FINAL REPORT

A Rigorous Demonstration of Permeability Enhancement Technology for In Situ Remediation of Low Permeability Media

ESTCP Project ER-201430

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CDM Smith

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14. ABSTRACT

This study demonstrated the use of permeability enhancement technology (i.e., environmental fracturing) to facilitate enhanced amendment delivery and distribution in low-permeability materials. The overall objective of this project is to compare the performance and cost benefits of hydraulic and hybrid pneumatic permeability enhancement for *in situ* treatment at low-permeability sites. The technology demonstration was performed at three separate sites with low-permeability lithologies including the Marines Corps Base – Camp Pendleton (MCB-CP) Site 1115 located in Oceanside, California; the Lake City Army Ammunition Plant (LCAAP) Site 17D located in Independence, Missouri; and the Grand Forks Air Force Base (GFAFB) site TU504 located in Grand Forks, North Dakota. The hydraulic approach to permeability enhancement was performed at all three aforementioned sites. In addition, hybrid pneumatic permeability enhancement was performed at LCAAP to provide a direct comparison between the hydraulic and the hybrid pneumatic approach to permeability enhancement. Advanced geophysics monitoring tools including tilt meter monitoring, electrical conductivity logging (EC logging), and electrical resistivity tomography (ERT) were used to evaluate the vertical and horizontal extent of amendment distribution resulting from permeability enhancement, and conventional soil confirmation and groundwater performance monitoring were used to validate the geophysics monitoring tools. At all three sites, qualitative assessment of amendment distribution was confirmed. Specifically, depth-discrete intervals where fractures were initiated and treatment amendment introduced via permeability enhancement were identified via visual observations of the emplaced materials (40/50 sand) at MCB-CP and LCAAP in the hydraulic demonstration area and/or field/analytical verification of amendment distribution via analysis of TOC (LCAAP and GFAFB), sulfate and persulfate (MCB-CP), and fluorescein (GFAFB). Despite the challenging subsurface conditions, more than 70% of the target injection volume was introduced into the subsurface via hydraulic permeability enhancement at LCAAP. Between 99 and 100% of the target injection volume was achieved within the treatment area at MCB-CP and GFAFB. No statistically significant changes in hydraulic conductivities were observed at demonstrations sites where a sand proppant was not added, by design, including GFAFB and the hybrid pneumatic demonstration area at LCAAP. The lack of changes in hydraulic conductivities following hydraulic permeability enhancement at LCAAP is likely attributable to presence of voids, vertical and horizontal preferential pathways, and other uncertainties in the subsurface due to past disturbances within the hydraulic demonstration area. At MCB-CP, where a sand proppant was hydraulically emplaced, significant increases in hydraulic conductivities ranging between approximately 3 and 40 times were observed. The accuracy and precision of tilt meter monitoring in predicting depth-discrete intervals where fractures were initiated and amendment delivered were verified using soil confirmation sampling results. On the other hand, data collected indicated that while potentially useful in some applications, ERT was a partially effective geophysics monitoring tool for monitoring fracture initiation and subsequent amendment distribution. Data collected at GFAFB rendered evaluation of EC logging as a potentially applicable geophysics tool for fracture monitoring inconclusive. At all three sites, significant changes in geochemistry and contaminant profile were observed at existing or new monitoring wells strategically placed within the anticipated radius of influence of the hydraulic permeability enhancement initiation points. In addition, orders-of-magnitude higher injection rates and volumes were achieved using hydraulic permeability enhancement than conventional injection approaches. Note that at LCAAP where a side-by-side comparison of hydraulic and hybrid pneumatic permeability enhancement was performed, the purely pneumatic approach to permeability enhancement could not be performed due to surfacing and thus fracture initiation was performed pneumatically while amendment delivery was achieved hydraulically (hybrid pneumatic technology).

Despite the use of this more advanced hybrid approach, significantly higher TOC concentrations were observed in soil and groundwater within the hydraulic demonstration cell than in the pneumatic cell. A cost comparison exercise was performed, which indicated that permeability enhancement techniques can be more or significantly more competitive than conventional injection techniques that are susceptible to unreasonably low injection rate and injection radius of influence, uncontrolled fracturing of the subsurface, and high reinjection frequency.

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ACRONYMS AND ABBREVIATIONS

%	percent
µg/L	microgram per liter
2D	two dimensional
3D	three dimensional
amsl	above mean sea level
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylene
cis-1,2-DCE	cis-1,2-dichloroethene
cm/s	centimeter per second
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	United States Department of Defense
DoE	United States Department of Energy
DPI	direct-push injection
DPT	direct-push drilling technology
EAB	enhanced anaerobic bioremediation
EC	electrical conductivity
EPA	United States Environmental Protection Agency
ERT	electrical resistivity tomography
ESTCP	Environmental Security Technology Certification Program
EVO	emulsified vegetable oil
Frac Rite	Frac Rite Environmental Limited
GFAFB	Grand Forks Air Force Base, Site TU504
gpm	gallon per minute
HAS	hollow-stem auger
ID	inner diameter
IDW	investigation-derived waste
ISCO	*in situ* chemical oxidation
KCl	potassium chloride
LCAAP	Lake City Army Ammunition Plant, Site 17D
LNAPL	light non-aqueous phase liquid
LTM	long-term monitoring

MCB-CP	Marines Corps Base-Camp Pendleton, Site 1115
MCL	maximum contaminant level
MEE	methane, ethane, and ethene
mg/kg	milligrams per kilogram
mg/L	milligram per liter
O&M	operation and maintenance
ORP	oxidation-reduction potential
PRW	permeable reactive wall
psi	pound per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
ROI	radius of influence
RPM	remediation project manager
TCE	trichloroethene
TOC	total organic carbon
TPH	total petroleum hydrocarbons
USACE	United States Army Corps of Engineers
UST	underground storage tank
VC	vinyl chloride
VOC	volatile organic compound
ZVI	zero-valent iron

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ACKNOWLEDGEMENTS

This project was funded by the Environmental Security Technology Certification Program (ESTCP). We are very appreciative of the support and encouragement from Dr. Andrea Leeson. We also wish to thank and recognize the support provided by Hunter Anderson of the Air Force Civil Engineer Center; Theresa Morley of the US Navy; Gord Guest, Cole Kaiser, Andreea Mogos, and Heather Sturm of GeoTactical Remediation; Robert Kelley and Eric Moskal of Cascade Drilling; Lee Slater and Judith Robinson of Rutgers University; and CDM Smith staff including Dung Nguyen, Nathan Smith, Ryan Wymore, and Michael Lamar. Finally, the project would not have been successful without the support from site representatives including Larry Olderbak (Grand Forks Air Force Base), Luis Ledesma, Ralph Pearce, and Steve Griswold (Marine Corps Camp Pendleton), and Sarah Clark (Lake City Army Ammunition Plant); the Army Corps of Engineers – Kansas City District and the Center of Expertise personnel including Mark Rothas, Dave Becker, Chuck Coyle, Phil Rosewicz, and Jodi Gentry; dedicated field support of IO staff including Karen Collins, Gary Vargas, and Chris Marino; LRS Federal staff including Kaye Guille, William Gray, and Dan Parker; and ECC staff including Michael Klosky and Ray Stallbaumer. US EPA Region 8 staff including Sam Garcia and Ian Bowen also assisted with the implementation of permeability enhancement and use of data from the Bountiful/Woods Cross Superfund site. Contact information for key individuals involved in this project is provided in **Appendix A**.

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ABSTRACT

INTRODUCTION & OBJECTIVES

This study demonstrated the use of permeability enhancement technology (i.e., environmental fracturing) to facilitate enhanced amendment delivery and distribution in low-permeability materials. The overall objective of this project was to compare the performance and cost benefits of hydraulic and hybrid pneumatic permeability enhancement for *in situ* treatment at low-permeability sites, as well as advanced monitoring techniques that can be used during implementation.

TECHNOLOGY DESCRIPTION

Hydraulic Permeability Enhancement

Invented by the oil and gas industry, hydraulic permeability enhancement technology was modified to aid remediation of soil and groundwater in the late 1980s (United States Environmental Protection Agency [EPA] 1993 and 1994). The goal of permeability enhancement technology is to increase bulk hydraulic conductivity and radius of amendment delivery to facilitate enhanced *in situ* remediation in low-permeability formations. A low- or high-viscosity fluid is introduced into a borehole at a rate and pressure high enough to overcome the *in situ* confining stress and the material strength of a geologic formation, resulting in the formation of a fracture. In high-viscosity permeability enhancement applications, sand can be injected simultaneously with a solid amendment such as zero-valent iron (ZVI) to maintain the integrity of the propagated fractures that can otherwise become restricted or collapsed entirely, particularly in plastic geologic materials (U.S. Patent No. 7,179,381). The emplaced fracture network typically results in an increase in hydraulic conductivity by about an order of magnitude and allows for more effective injections or extractions. Hydraulic permeability enhancement can be performed using almost any drilling technique, including direct-push.

Pneumatic Permeability Enhancement

Pneumatic permeability enhancement technology utilizes a gas at flow volumes exceeding the natural permeability of the formation to generate high enough pressures to overcome the *in situ* confining stress and the material strength of a formation such that fractures are formed (EPA 1995). The result is the enhancement of existing fractures and planes of weakness (e.g., bedding planes) and the propagation of a dense fracture network surrounding the *in situ* delivery well. Once a geologic zone has been fractured, the injection of the amendment can be performed in an integrated process. For example, the amendment liquid or slurry can be blended into a nitrogen gas stream above ground and become atomized, and then introduced into the formation at relatively low pressures. The atomization apparatus is a down-hole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the target interval. Using this method, the amendment might be distributed 10 to 25 radial feet depending on site-specific conditions. As with hydraulic permeability enhancement, this fracture network extends the radius of influence for injection, thus enhancing *in situ* treatment. For this demonstration, a hybrid approach to pneumatic permeability enhancement was applied, where the nitrogen gas stream was used to generate the fracture network, followed by hydraulic delivery of the aqueous amendment.

Advanced Geophysics Monitoring Tools

Although much more sophisticated, tilt meters operate on the same principle as a carpenter's level (Dunnicliff 1993). Tilt meters contain two tilt sensors (on orthogonal axes) and precision electronics. As the tilt meter tilts, the gas bubble must move to maintain its alignment with the local gravity vector. The movement of the gas bubble within the conductive liquid causes a change in the total resistance between the electrodes. This resistance change is measured with a resistance bridge or voltage divider circuit to precisely detect the amount of tilt. While simple in theory, the instruments are remarkably sensitive. Tilt data collected can be processed, analyzed, and converted into a dynamic, 3D graphical output that can be viewed in any perspective in space, and can be manipulated to view individual fracture configurations or the fracture network as a whole.

Electrical conductivity (EC) logging is utilized for high-resolution characterization of hydrostratigraphic conditions in unconsolidated media (Schulmeister et al. 2007). Direct-push EC probes typically operate using a four-electrode Wenner array, passing current through the outer two electrodes and measuring voltage across the inner two electrodes. The sensors can collect 20 measurements per second and collect data at a vertical resolution of 0.05 foot. Clayey materials tend to have higher electrical conductivity and charge characteristics compared to sandy or gravelly soils. The high vertical resolution of the probe readings allows the user to identify fine-scale features such as low-permeability clay or silt lenses or sand stringers, which are important for transport of injected amendments in the subsurface. T

Electrical resistivity tomography (ERT) is a geophysical visualization technique used to study hydrogeological characteristics of the subsurface. Resistivity, an inherent property of all materials, measures the degree to which a material resists the flow of an electrical current. As resistivity depends on chemical and physical properties such as saturation, concentration, and temperature, ERT can be used to monitor natural and anthropogenic processes responsible for changes in such properties (Daily et al.1992). In the context of environmental engineering, ERT can aid in monitoring active remedial progress and provide insights into material emplacement and deformational processes, both of which are very relevant to *in situ* treatment technologies in general and the permeability enhancement technology in particular (Halihan et al. 2005 and Wilkinson et al. 2008). In the context of this demonstration, ERT has the potential to aid in visualization of the 3D distribution of an injected fluid if the resistivity of that fluid is significantly different from the groundwater.

PERFORMANCE & COST ASSESSMENT

The technology demonstration was performed at three separate sites with low-permeability lithologies including the Marines Corps Base – Camp Pendleton (MCB-CP) Site 1115 located in Oceanside, California; the Lake City Army Ammunition Plant (LCAAP) Site 17D located in Independence, Missouri; and the Grand Forks Air Force Base (GFAFB) site TU504 located in Grand Forks, North Dakota. The hydraulic approach to permeability enhancement was performed at all three aforementioned sites. In addition, hybrid pneumatic permeability enhancement was performed at LCAAP to provide a direct comparison between the hydraulic and the hybrid pneumatic approach to permeability enhancement. Advanced geophysics monitoring tools including tilt meter monitoring, EC logging, and ERT were used to evaluate the vertical and horizontal extent of amendment distribution resulting from permeability enhancement, and conventional soil confirmation and groundwater performance monitoring were used to validate the geophysics monitoring tools.

At all three sites, qualitative assessment of amendment distribution was confirmed. Specifically, depth-discrete intervals where fractures were initiated and treatment amendment introduced via permeability enhancement were identified via visual observations of the emplaced materials (40/50 sand) at MCB-CP and LCAAP in the hydraulic demonstration area and/or field/analytical verification of amendment distribution via analysis of total organic carbon (LCAAP and GFAFB), sulfate and persulfate (MCB-CP), and fluorescein (GFAFB). Despite the challenging subsurface conditions, more than 70% of the target injection volume was introduced into the subsurface via hydraulic permeability enhancement at LCAAP. Between 99 and 100% of the target injection volume was achieved within the treatment area at MCB-CP and GFAFB. No statistically significant changes in hydraulic conductivities were observed at demonstration sites where a sand proppant was not added, by design, including GFAFB and the hybrid pneumatic demonstration area at LCAAP. The lack of changes in hydraulic conductivities following hydraulic permeability enhancement at LCAAP is likely attributable to presence of voids, vertical and horizontal preferential pathways, and other uncertainties in the subsurface due to past disturbances within the hydraulic demonstration area. At MCB-CP, where a sand proppant was hydraulically emplaced, significant increases in hydraulic conductivities ranging between approximately 3 and 40 times were observed. At all three sites, significant changes in geochemistry and contaminant profile were observed at existing or new monitoring wells strategically placed within the anticipated radius of influence of the hydraulic initiation points. In addition, orders-of-magnitude higher injection rates and volumes were achieved using hydraulic permeability enhancement than conventional injection approaches. Note that at LCAAP where a side-by-side comparison of hydraulic and hybrid pneumatic technologies was performed, the purely pneumatic approach to permeability enhancement could not be performed due to surfacing and thus fracture initiation was performed pneumatically while amendment delivery was achieved hydraulically (hybrid pneumatic technology). Despite the use of this more advanced hybrid approach, significantly higher TOC concentrations were observed in soil and groundwater within the hydraulic demonstration cell than in the pneumatic cell.

The accuracy and precision of tilt meter monitoring in predicting depth-discrete intervals where fractures were initiated and amendment was delivered were verified using soil confirmation sampling results. On the other hand, data collected indicated that while potentially useful in some applications, ERT was a partially effective geophysics monitoring tool for monitoring fracture initiation and subsequent amendment distribution. Data collected at GFAFB was inconclusive regarding evaluation of EC logging as a potentially applicable geophysics tool for fracture monitoring.

A cost comparison exercise was performed, which indicated that permeability enhancement techniques can be more or significantly more competitive than conventional injection techniques that are susceptible to unreasonably low injection rate and injection radius of influence, uncontrolled fracturing of the subsurface, and high reinjection frequency.

IMPLEMENTATION ISSUES

A variety of regulatory, procurement, and end-user issues may be encountered during permeability enhancement implementation. Regulatory issues may include overcoming the often-negative connotation associated with hydraulic fracturing for oil and gas and concerns regarding vertical migration of site contaminants as a potential unintended result of permeability enhancement.

Procurement issues regarding permeability enhancement implementation generally center around the use of specialized equipment, chemistry, and technical knowledge that are only offered by few commercial vendors as well as the patented nature of certain permeability enhancement applications. End-user concerns with respect to the technologies include the use of nonstandard equipment required for implementation, hazards associated with high-pressure injections, and amendment surfacing. Note that in nearly all cases, proper planning and engineering controls can be used to mitigate concerns associated with field implementation of permeability enhancement technologies.

PUBLICATIONS

It is anticipated that several peer-reviewed journal articles will be published to document the findings of this ESTCP project.

EXECUTIVE SUMMARY

INTRODUCTION

When reagents that stimulate biological or chemical destruction of contaminants can be mixed uniformly with target contaminants in the subsurface, remediation practitioners can have a high degree of confidence that the treatment will be reasonably effective. While this represents an enormous opportunity for the industry, the formidable challenge remains of ensuring that mixing and/or contact of biological or chemical treatment reagents with target contaminants occurs in a reasonable timeframe in low-permeability or fractured geological settings.

Conventional injection wells are typically adequate for delivering reagents in homogeneous geologic formations with a bulk hydraulic conductivity of 10^{-4} centimeters per second (cm/s) or greater; however, practitioners are well acquainted with the shortcomings of amendment injection using conventional wells in lower permeability settings (United States Department of Energy [DoE] 1996). Another problem with conventional injection wells in low-permeability settings is that a high degree of heterogeneity typically exists even within a 10-foot well screen, often ranging over multiple orders of magnitude of permeability. Given that the volumetric flow rate entering different vertical horizons in the injection well screen is proportional to the hydraulic conductivities of those horizons, the vertical distribution of injected amendment can be highly preferential; that is, 90% or more of the total volume might easily be pushed out into soils adjacent to less than 10% of the well screen interval.

In recent years, several technologies have been developed to address the challenge of achieving a uniform and effective distribution of treatment amendments in low-permeability and fractured media. These advances include hydraulic and pneumatic permeability enhancement technologies, both of which can emplace amendments into low-permeability media. Emplacing treatment amendments using these techniques can help overcome the aforementioned limitations of traditional amendment injection techniques where low-permeability soils can impede delivery. Significant confusion currently exists in the industry as to the differences among hydraulic and pneumatic permeability enhancement technologies and permeation injections. While one technology may be more warranted for a particular application, practitioners often do not have the information required to make good decisions regarding which delivery technique to use. Definitive guidance for selecting the most appropriate technique is needed.

In addition, significant advances have been made in technologies that can provide high-resolution mapping of the subsurface distribution of amendments. However, a rigorous comparison of such methods in different geologies of low hydraulic conductivity has never been made, in part because the high-resolution mapping and data processing tools are proprietary and have not been widely commercialized and implemented. Consequently, no guidance is available for practitioners or site managers to assist in the selection or specification of amendment distribution and monitoring techniques for assessing amendment delivery within low-permeability media.

OBJECTIVE

The overall objective of this project is to compare the performance and cost benefits of hydraulic and pneumatic permeability enhancement for *in situ* treatment at low-permeability sites. The technical objectives of this demonstration/validation project are to:

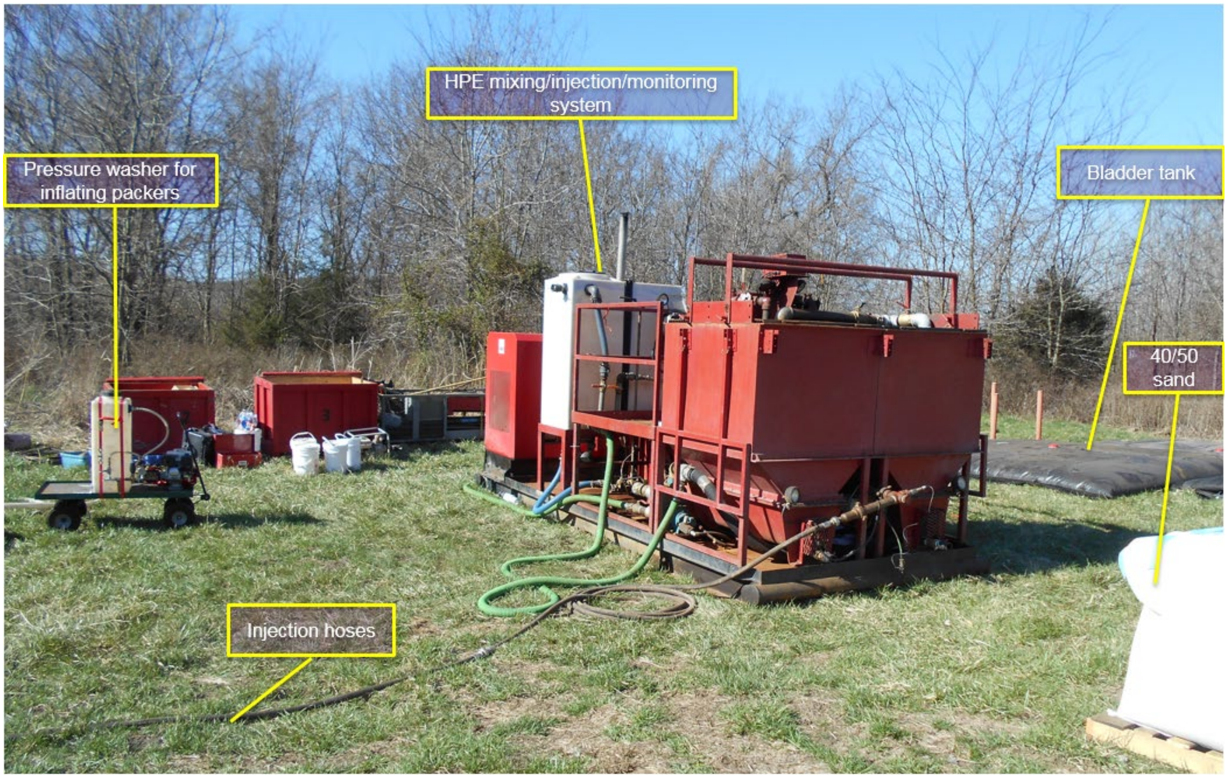
- Demonstrate the amendment distribution capabilities of permeability enhancement techniques in three different geologic settings with low permeability;
- Demonstrate and validate the use of tilt meter monitoring as a novel, high-resolution, and non-invasive mapping technique to aid in evaluating the performance of permeability enhancement technology;
- Collect sufficient performance and cost data to develop a concise guidance document to help RPMs and practitioners select and/or specify the optimal *in situ* delivery technique for a given low-permeability site, and the monitoring approach to quickly validate its performance; and
- If possible, compare *in situ* delivery performance results using permeability enhancement techniques to those of more conventional injection approaches.

The technology demonstration was performed at three separate sites with low-permeability lithologies including the Marines Corps Base – Camp Pendleton (MCB-CP) Site 1115 located in Oceanside, California; the Lake City Army Ammunition Plant (LCAAP) Site 17D located in Independence, Missouri; and the Grand Forks Air Force Base (GFAFB) site TU504 located in Grand Forks, North Dakota. The hydraulic approach to permeability enhancement was performed at all three aforementioned sites. In addition, hybrid pneumatic permeability enhancement was performed at LCAAP to provide a direct comparison between the hydraulic and the hybrid pneumatic approach to permeability enhancement. Advanced geophysics monitoring tools including tilt meter monitoring, electrical conductivity logging (EC logging), and electrical resistivity tomography (ERT) were used to evaluate the vertical and horizontal extent of amendment distribution resulting from permeability enhancement, and conventional soil confirmation and groundwater performance monitoring were used to validate the geophysics monitoring tools.

TECHNOLOGY DESCRIPTION

Hydraulic Permeability Enhancement

Invented by the oil and gas industry, permeability enhancement technology was modified to aid remediation of soil and groundwater in the late 1980s (United States Environmental Protection Agency [EPA] 1993 and 1994). The goal of permeability enhancement technology is to increase bulk hydraulic conductivity and amendment delivery radius of influence (ROI) to facilitate enhanced *in situ* remediation in low-permeability formations. A low- or high-viscosity fluid is introduced into a borehole at a rate and pressure high enough to overcome the *in situ* confining stress and the material strength of a geologic formation, resulting in the formation of a fracture. In high-viscosity permeability enhancement applications, sand can be injected simultaneously with a solid amendment such as zero-valent iron (ZVI) to maintain the integrity of the propagated fractures that can otherwise become restricted or collapsed entirely, particularly in plastic geologic materials (U.S. Patent No. 7,179,381). The emplaced fracture network typically results in an increase in hydraulic conductivity by about an order of magnitude and allows for more effective injections or extractions. Hydraulic permeability enhancement can be performed using almost any drilling technique, including direct-push.



Pneumatic Permeability Enhancement

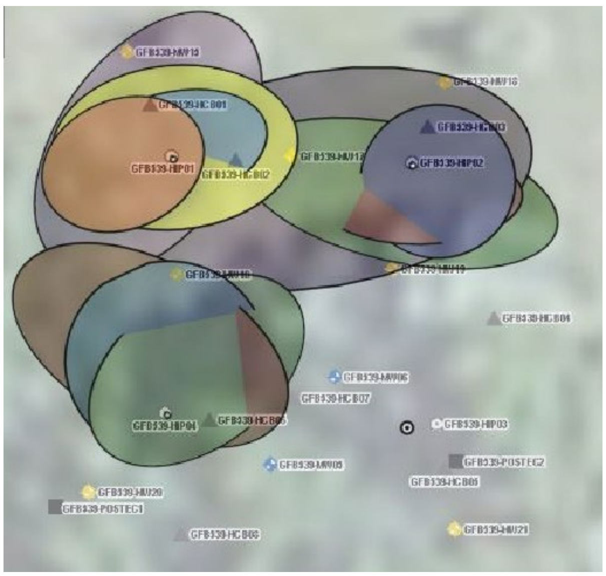
Pneumatic permeability enhancement technology utilizes a gas at flow volumes exceeding the natural permeability of the formation to generate high enough pressures to overcome the *in situ* confining stress and the material strength of a formation such that fractures are formed (EPA 1995). The result is the enhancement of existing fractures and planes of weakness (e.g., bedding planes) and the propagation of a dense fracture network surrounding the *in situ* delivery well. Once a geologic zone has been fractured, the injection of the amendment can be performed in an integrated process. For example, the amendment liquid or slurry can be blended into a nitrogen gas stream above ground and become atomized. Relatively low pressures are required to sustain the flow into the formation. The atomization apparatus is a down-hole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the target interval. Using this method, the amendment might be distributed 10 to 25 radial feet depending on site-specific conditions. As with hydraulic permeability enhancement, this fracture network extends the ROI for injection, thus enhancing *in situ* treatment. For this demonstration, a hybrid approach to pneumatic permeability enhancement was applied, where the nitrogen gas stream was used to generate the fracture network, followed by hydraulic delivery of the aqueous amendment.

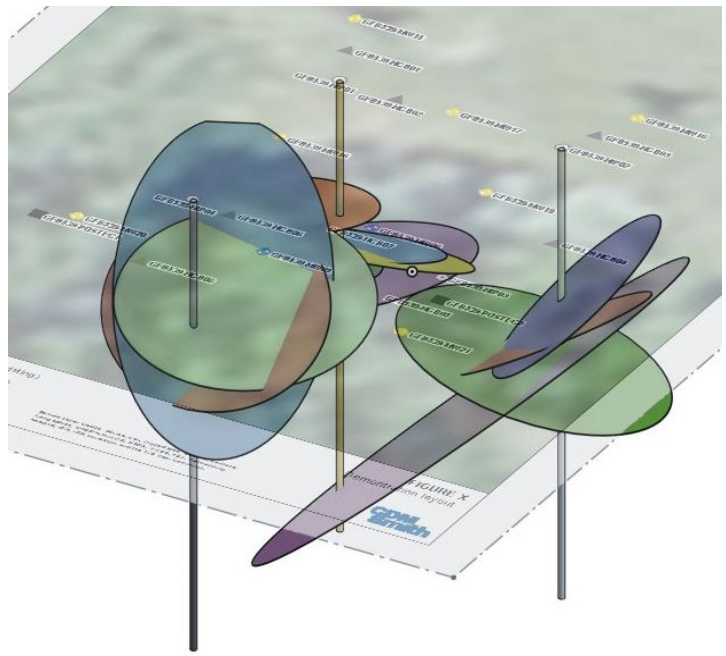
The nature of permeability enhancement induced by pneumatic techniques is thought to be quite different from hydraulically induced fractures. Conventional wisdom suggests that hydraulic permeability enhancement has the advantage of a larger *in situ* delivery radius and propped fractures that can be used for multiple injections or extractions, while pneumatic permeability enhancement is expected to produce a denser fracture network for the same cost but within a smaller zone. However, no studies have been published comparing and documenting the performance of either of these techniques at multiple low-permeability sites (ESTCP 2014).

Advanced Geophysics Monitoring Tools

Although much more sophisticated, tilt meters operate on the same principle as a carpenter's level (Dunnicliff 1993). Tilt meters contain two tilt sensors (on orthogonal axes) and precision electronics. As the tilt meter tilts, the gas bubble must move to maintain its alignment with the local gravity vector. The movement of the gas bubble within the conductive liquid causes a change in the total resistance between the electrodes. This resistance change is measured with a resistance bridge or voltage divider circuit to precisely detect the amount of tilt. While simple in theory, the instruments are remarkably sensitive. Proper installation and operation of the instruments are required to utilize this resolution. The instruments must be adequately coupled to solid earth and significantly isolated from the large thermal fluctuations of the earth's surface. This is accomplished by setting up ground surface-mounted tilt meters in a concentric array. The changes in resistance created by tilting the bubble sensor are electronically converted to a voltage that is proportional to the tilt of the instrument.

The voltage is then recorded either by a local data acquisition unit at each tilt meter site or via cable to a central data acquisition system for the whole tilt meter array. Data collection is most often accomplished with remote data acquisition at each tilt meter site because it removes the need to run cables over the surface area surrounding the wellbore. Real-time monitoring and analysis can still be performed with remote data acquisition units using radio telemetry to send the data to a central computer system for display and analysis. Remote data acquisition units have sufficient storage capabilities to allow periodic data acquisition with a portable computer. Tilt data collected can be processed, analyzed, and converted into a dynamic, 3D graphical output that can be viewed in any perspective in space, and can be manipulated to view individual fracture configurations or the fracture network as a whole. An example 3D visualization of the fracture network generated from the tiltmeter data at GFAFB is shown below.





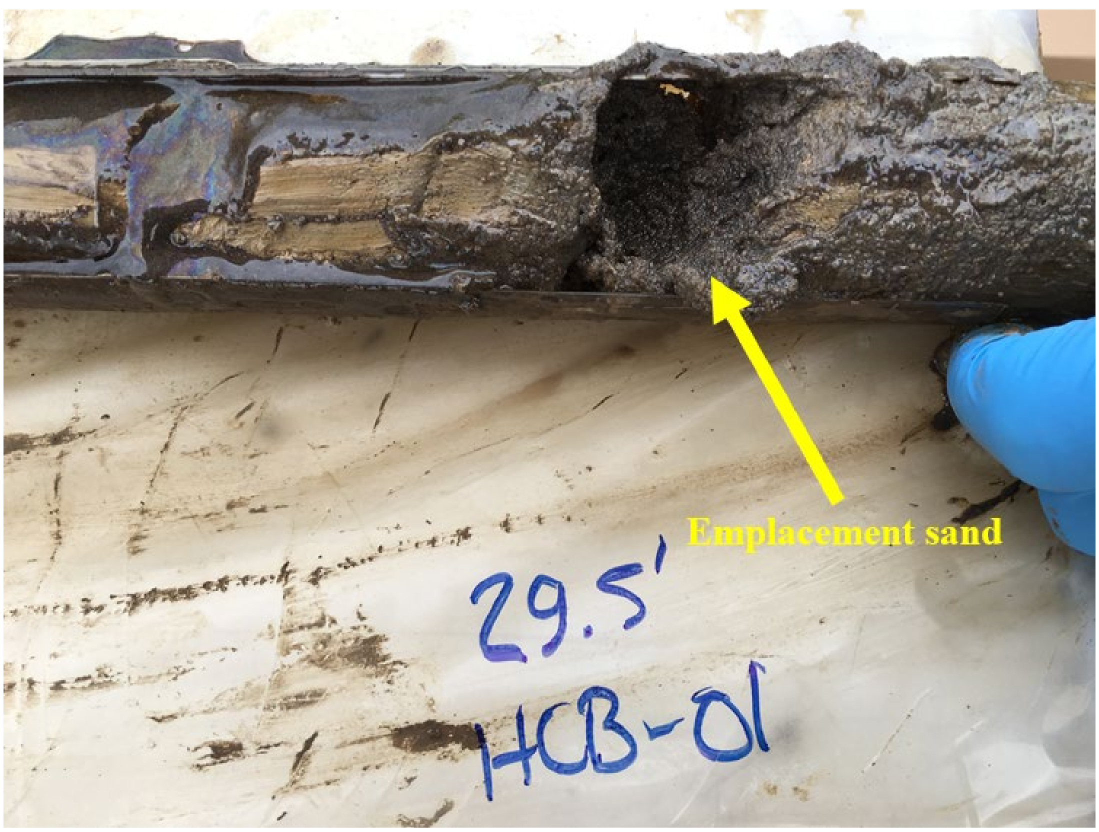
EC logging is utilized for high-resolution characterization of hydrostratigraphic conditions in unconsolidated media (Schulmeister et al. 2007). Direct-push EC probes typically operate using a four-electrode Wenner array, passing current through the outer two electrodes and measuring voltage across the inner two electrodes. The sensors can collect 20 measurements per second and collect data at a vertical resolution of 0.05 foot. Clayey materials tend to have higher electrical conductivity and charge characteristics compared to sandy or gravelly soils. The high vertical resolution of the probe readings allows the user to identify fine-scale features such as low-permeability clay or silt lenses or sand stringers, which are important for transport of injected amendments in the subsurface. The electrical conductivity of the groundwater also affects the conductivity measurements, but the conductivity of groundwater is typically relatively constant over the scale of a shallow, unconsolidated aquifer. By injecting an electrically conductive tracer or amendment solution and measuring electrical conductivity before and after injection activities, intervals impacted by the tracer can be evaluated using the direct-push probes, thereby delineating the vertical distribution of injected amendments.

ERT is a geophysical visualization technique used to study hydrogeological characteristics of the subsurface. Resistivity, an inherent property of all materials, measures the degree to which a material resists the flow of an electrical current. As resistivity depends on chemical and physical properties such as saturation, concentration, and temperature, ERT can be used to monitor natural and anthropogenic processes responsible for changes in such properties (Daily et al.1992). In the context of environmental engineering, ERT can aid in monitoring active remedial progress and provide insights into material emplacement and deformational processes, both of which are very relevant to *in situ* treatment technologies in general and the permeability enhancement technology in particular (Halihan et al. 2005 and Wilkinson et al. 2008). In the context of this demonstration, ERT has the potential to aid in visualization of the 3D distribution of an injected fluid if the resistivity of that fluid is significantly different from the groundwater.

PERFORMANCE ASSESSMENT

Quantifying Fracture Distribution

Visual observations of fractures and emplaced materials were generally observed during confirmation sampling at all three demonstration sites; an example of such observation is shown in the figure below. In some instances, monitoring wells strategically placed within the target ROI of permeability enhancement were directly impacted by the high-pressure injections. At sites where a solid amendment or permeability enhancement reagents were not used, direct or indirect analyses of the added aqueous treatment reagents (i.e., total organic carbon [TOC], persulfate, or fluorescein) were used to quantify the horizontal and vertical distribution of amendment within the anticipated ROI of permeability enhancement.

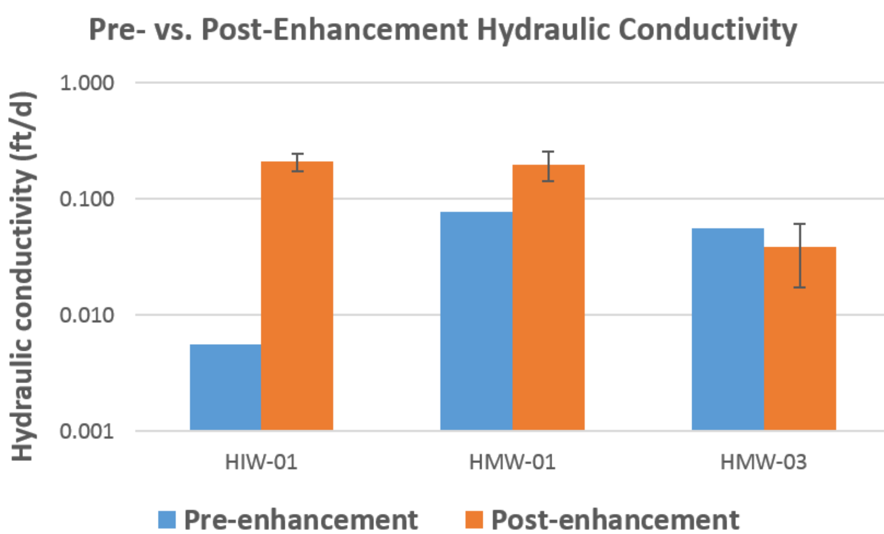


Amendment Delivery

Despite the challenging subsurface conditions, more than 70% of the target injection volume was introduced into the subsurface via HPE at LCAAP. 100% of the target injection volume was achieved using PPE at LCAAP. Between 99 and 100% of the target injection volume was achieved within the treatment area at the MCB-CP and GFAFB sites.

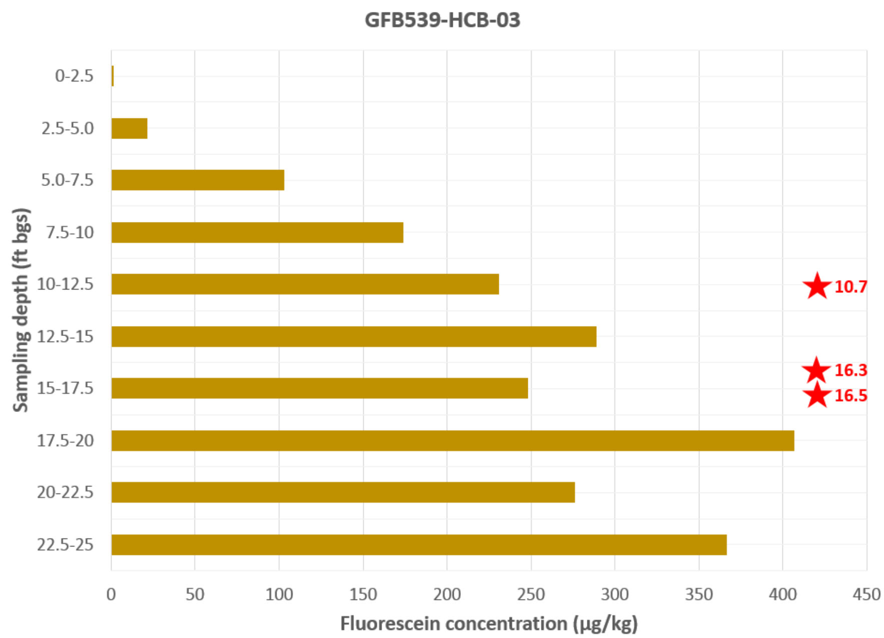
Impacts of Permeability Enhancement on Bulk Hydraulic Conductivity

Increases in hydraulic conductivity were expected at MCB-CP and LCAAP because a sand proppant was used at both sites. Orders of magnitude increases in hydraulic conductivities were observed at MCB-CP at the permeability location following emplacement of the sand proppant (as shown in below figure). However, no changes in hydraulic conductivities were observed within the hydraulic demonstration area at LCAAP even though a sand proppant was used. It was discovered midway through the project the demonstration area for hydraulic permeability enhancement had unknown subsurface conditions that significantly impacted the amendment emplacement.

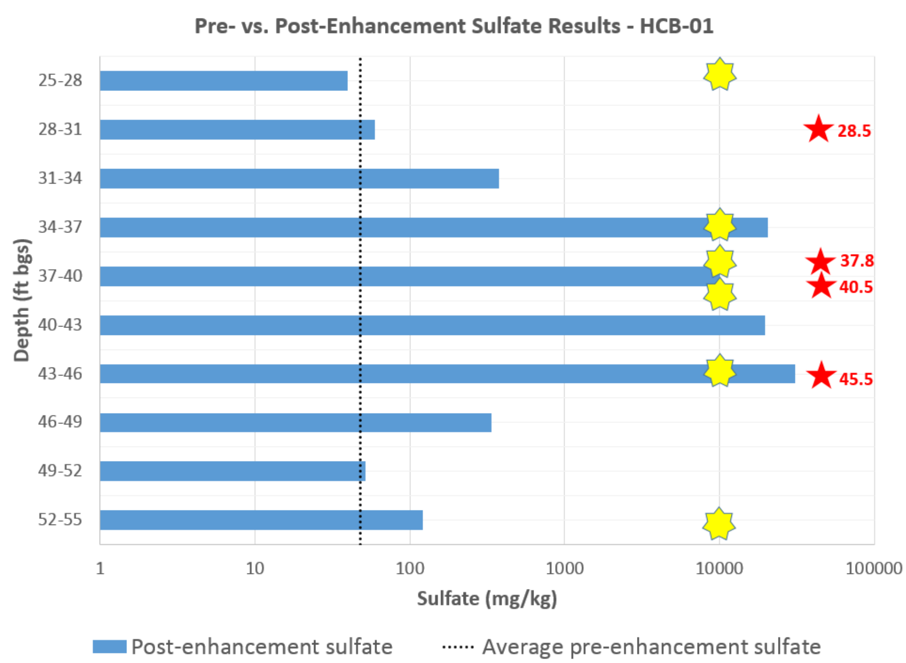


Effectiveness and Accuracy of Tilt Meter Monitoring

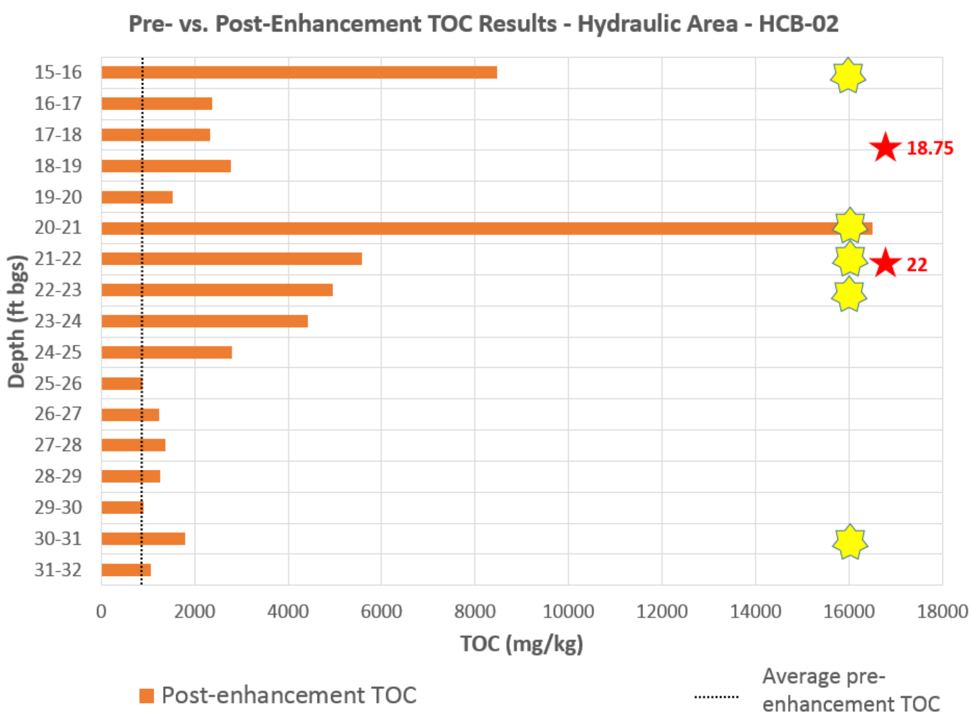
At all three demonstration sites where tilt meter monitoring technique was employed, post-enhancement confirmation boring locations impacted by the permeability enhancement work were generally located within the predicted horizontal extent of the fracture network. In addition, the predicted fracture-intercepting depths provided by modeling (denoted by the red stars in the below figure) correlated very well with the actual depths where fractures were visually observed or confirmed analytically. At GFAFB, elevated fluorescein concentrations indicative of amendment delivery were observed within 1 to 2 feet of the tilt meter-predicted depth-discrete intervals where the initiated fracture network intercepts the confirmation borehole; an example of this correlation is shown in the below figure. At the other confirmation boreholes (GFB539-HCB-04, -05, and -08) located outside the ROI of permeability enhancement (as verified by the lack of fluorescein in depth-discrete composite soil samples), the lack of fracture interception was also predicted by tilt meters.



At MCB-CP, three of the four fracture-intercepting depth-discrete intervals predicted by tilt meter (denoted by the red stars in the below figure) coincided with intervals where fractures were visually observed during post-enhancement confirmation sampling and lithologic logging. Also, orders-of-magnitude increases in total sulfate concentrations were analytically verified at one (HCB-01) of the two post-enhancement confirmation boreholes as shown in the figure below. At the other confirmation borehole (HCB-02), no fractures were visually observed, consistent with the 3D visualization (which shows that this boring location is at the edge of the fracture network) and the absence of the orders-of-magnitude increases in total sulfate concentrations observed at HCB-01.



At both post-enhancement confirmation boreholes within the hydraulic demonstration area at LCAAP, all six tilt meter-predicted fracture-intercepting depth intervals (denoted by the red stars) were within 1 to 3 feet of those where fractures were either visually observed or the highest increases in TOC concentrations were observed; an example of this correlation is shown in the below figure. Similar correlations between tilt meter modeling predictions and confirmation sampling results were observed at two of the three post-enhancement boreholes within the pneumatic demonstration area. Specifically, at PCB-01 and PCB-02, the fracture-intercepting depths predicted by tilt meter were generally within 1 to 2 feet of the highest increases in TOC concentrations. Such correlation was not observed at PCB-03; however, the predicted fracture interceptions thereof might have emanated from the nearby PIW-01 that was not monitored by tilt metering. Collectively, these results indicated that tilt meter monitoring is a non-intrusive and cost-effective geophysics technique for fracture monitoring during permeability enhancement.



Effectiveness and Accuracy of EC Logging

No significant increases in EC were observed within the target treatment depth interval at GFAFB. However, no evidence of amendment delivery into the two EC locations was observed. This lack thereof was also analytically confirmed via soil confirmation sampling and subsequent fluorescein analysis. Specifically, no significant detection of fluorescein was detected at the two post-enhancement confirmation boreholes located in the vicinity of the two EC locations. Collectively, the limited data collected at this site renders the evaluation of EC as an effective geophysics tool for fracture monitoring inconclusive.

Effectiveness and Accuracy of ERT

Significant changes in ERT signals were generally correlated with other observations at each of the three demonstration areas (hydraulic and pneumatic areas at LCAAP and hydraulic at GFAFB). For the pneumatic cell at LCAAP, little change was observed following amendment emplacement, which was consistent with the TOC groundwater data. For the hydraulic cell at LCAAP, modest changes were observed following enhancement activities, with such changes generally localized around the monitoring well locations where the electrodes were deployed. At GFAFB, ERT imaging showed the most dramatic changes pre- and post-injection, and these changes were generally correlated with increases in TOC and fluorescein as measured from the groundwater monitoring network. ERT was also able to show a time-lapse evolution of the injected amendment over time. Overall, while ERT visualization of post-enhancement amendment distribution was not of sufficiently high enough resolution throughout the target areas to map and identify individual fractures, it was useful for assessing overall distribution of the emplaced amendment.

Ease of Use

Proper applications of hydraulic permeability enhancement require proprietary injection equipment and materials and therefore highly specialized personnel to aid in project planning, design, execution, and evaluation. Most of the equipment required to perform hydraulic permeability enhancement is generally commercially available although some modification and optimization are necessary. On the other hand, proprietary chemical reagents are required to properly inject a solid amendment into the subsurface. Therefore, there are very few vendors that have consistently demonstrated the ability to successfully perform hydraulic permeability enhancement. Similar to hydraulic permeability enhancement, the aboveground and downhole equipment used to facilitate pneumatic permeability enhancement is mostly commercially available. Injection skids are often constructed in a modular configuration to allow for ease of transport, access, and adaptability to site-specific settings. There are several vendors in North America that have commercialized permeability services.

Real-time decision-making is often required during implementation of both hydraulic and pneumatic permeability enhancement. Therefore, the personnel providing the technical oversight need to be familiar with the site conceptual model, understand the overall objective of the injection program, communicate any issues encountered to the project team, and help make the necessary adjustments. In addition, because some applications of permeability enhancement are performed under relatively high pressures, it is imperative that these personnel be familiar with the health and safety concerns associated with permeability enhancement and are qualified to supervise and provide input as necessary.

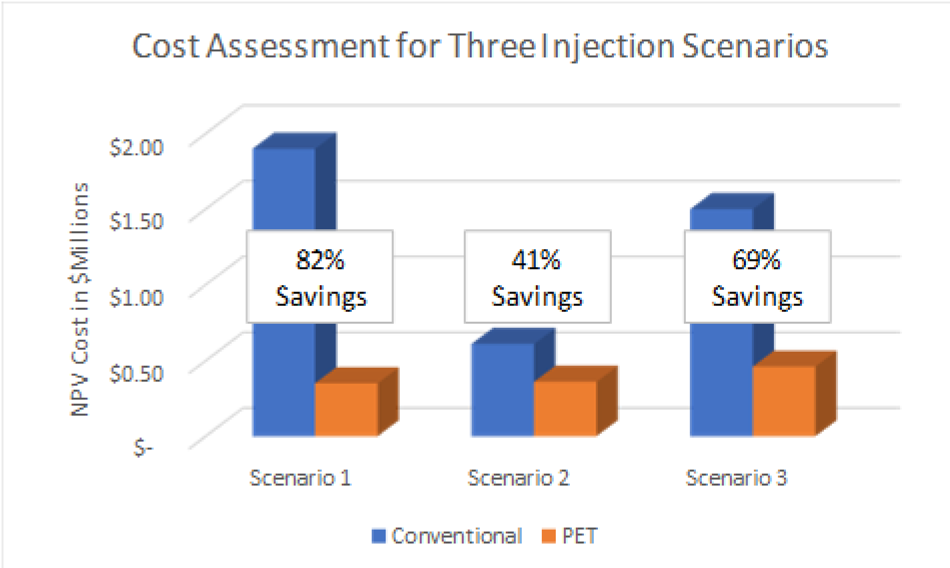
There are several types of issues that may be encountered throughout the different stages of a permeability enhancement project including planning, design, implementation, and evaluation. Despite its recent commercialization as an in situ delivery technique at sites with challenging lithologies, permeability enhancement is still a relatively novel technique in the remediation industry. In addition, the technology, especially the hydraulic approach to permeability, also suffers from the poor public perception of hydraulic fracturing in the oil and gas industry, although the two techniques differ vastly. In several instances during the planning phase of this demonstration project, it was necessary to communicate the differences between the permeability enhancement techniques employed for environmental purposes versus oil and gas recovery applications.

In other cases, concerns regarding vertical contaminant migration, damages to existing nearby infrastructure, and amendment surfacing had to be alleviated by detailed discussion in planning documents, webinar presentations, and/or telephone conferences among the parties of interest. Overall, concerns were resolved relatively promptly and easily by modifying the approved demonstration plan and preparing additional site-specific planning documents, conducting additional performance monitoring or slightly changing the injection approach. Another issue encountered at several sites during demonstration of permeability enhancement was the lack of site-specific information—some information was not known even to the onsite points of contact. For example, past disturbances and presence of DNAPL observed at the hydraulic demonstration area at LCAAP was not known by any party involved, thus rendering the direct comparison between the hydraulic and the pneumatic approach to permeability enhancement incomplete, as the two demonstration areas are vastly different in terms of lithology and contaminant profile. Similarly, the need to be escorted by a government officer for all non-U.S. citizens at LCAAP was not apparent until arrival at the site. This issue was immediately resolved with the help of the regulatory agencies involved in environmental restoration efforts at LCAAP.

COST ASSESSMENT

The primary cost drivers in implementation of permeability enhancement include site-specific lithology and treatment depth; site location as it directly impacts equipment mobilization charges which may account for a significant portion of the overall cost; and material cost for the remedial amendment to be emplaced. For monitoring technologies, including tilt-meter, ERT, and EC, cost drivers vary by technology due to their implementation approach. For tilt-meter, cost components include mobilization, onsite support, and data interpretation. Cost drivers for ERT and EC primarily are related to lithology and depth. Because ERT requires installation of electrodes on the outside of well casing, the type of drilling and depth of the target formation are of key importance. EC is only applicable in unconsolidated formations that can be drilled using DPT; the cost for mobilization of the EC tooling is minimal (assuming a DPT rig is already onsite), and overall cost for use is typically tied to a daily rate for use of the DPT rig. Therefore, EC cost drivers are primarily tied to formation depth and ease of DPT drilling; deeper or denser formations will likely require more field time to obtain data due to slower drilling conditions than shallower, less dense formation types.

Comparisons of implementation costs for real-life examples of conventional injection techniques (i.e., injection wells) versus permeability enhancement as applied at the sites were completed. Three specific scenarios were considered. Scenario 1 was the clay/weathered shale source area at Lake City Army Ammunition Plant, and compared permeability enhancement technology to gravity-fed injection in convention wells actually performed at the site. The cost to achieve a similar percent reduction of contaminants via conventional injection as achieved using permeability enhancement technology was used as the basis for comparison. The cost assessment showed an estimated cost savings of 82% for this case. Scenario 2 considered the glacial till source area at Grand Forks Air Force Base (see figure below). The “conventional” injection in this case comprised the use of 1-inch wells with pre-packed screens installed via DPT for injection. A similar analysis as for Scenario 1 revealed an estimated cost savings of 41% using permeability enhancement for Scenario 2. This was considered highly conservative for reasons discussed in the body of the report. As we did not have good comparative data for conventional injections at Marine Corps Base Camp Pendleton, Scenario 3 considered an interbedded sand/silt/clay source area at the Bountiful/Woods Cross Superfund Site where a direct comparison could be made between permeability enhancement technology and slightly pressurized injections in conventional injection wells. The analysis showed an estimated 69% reduction in costs relative to conventional injection to achieve the same contaminant reduction.



IMPLEMENTATION ISSUES

A variety of regulatory, procurement, and end-user issues may be encountered during permeability enhancement implementation. Regulatory issues may include overcoming the often-negative connotation associated with hydraulic fracturing for oil and gas and concerns regarding vertical migration of site contaminants as a potential unintended result of permeability enhancement technology. Procurement issues regarding permeability enhancement technology implementation generally center around the use of specialized equipment, chemistry, and technical knowledge that are only offered by few commercial vendors as well as the patented nature of certain permeability enhancement technology applications. End-user concerns with respect to permeability enhancement technology include the use of nonstandard equipment required for implementation, hazards associated with high-pressure injections, and amendment surfacing. Note that in nearly all cases, proper planning and engineering controls can be used to mitigate concerns associated with field implementation of permeability enhancement technology.

PUBLICATIONS

It is anticipated that several peer-reviewed journal articles will be published to document the findings of this ESTCP project.

1.0 INTRODUCTION

Environmental Security Technology Certification Program (ESTCP) Project Number ER-201430 involved the demonstration and validation of hydraulic and pneumatic permeability enhancement technologies (i.e., environmental fracturing) to improve the delivery of remediation amendments to low-permeability zones. This demonstration project provided a rigorous comparison of the costs and benefits of the hydraulic and pneumatic approaches for enhanced amendment delivery and distribution in low-permeability media, as well as an analysis of the state-of-the-art tilt meter and other advanced geophysics monitoring tools to delineate the emplaced fracture networks. The ultimate goal of this demonstration project was to develop a guidance document that outlines the technical and financial advantages and disadvantages of each of the permeability enhancement technologies, as well as the monitoring technologies. The guidance document was made available in a format to help remediation project managers (RPMs) better assess the applicability of this technology for amendment distribution and verification for a given site, as well as to help practitioners select and procure the optimal remediation technique. The guidance was also intended document the value of real-time tilt meter and electrical resistivity tomography (ERT) monitoring in remedial application, verification, and optimization.

This document details the field activities that were conducted at three sites selected for this technology demonstration, the detailed results, and the cost implications for application of these technologies. The three sites and the rationale for their selection are discussed in the Site Selection Memorandum provided in **Appendix B**. This introductory section includes a summary of the project background, objectives, and associated regulatory drivers relevant to the project.

1.1 BACKGROUND

When reagents that stimulate biological or chemical destruction of contaminants can be mixed uniformly with target contaminants in the subsurface, remediation practitioners can have a high degree of confidence that the treatment will be reasonably effective. While this represents an enormous opportunity for the industry, the formidable challenge remains of ensuring that mixing and/or contact of biological or chemical treatment reagents with target contaminants occurs in a reasonable timeframe in low-permeability or fractured geological settings.

Conventional injection wells are typically adequate for delivering reagents in homogeneous geologic formations with a bulk hydraulic conductivity of 10^{-4} centimeters per second (cm/s) or greater; however, practitioners are well acquainted with the shortcomings of amendment injection using conventional wells in lower permeability settings (United States Department of Energy [DoE] 1996). For instance, in a silty formation with a bulk hydraulic conductivity of approximately 10^{-5} cm/s and assuming a 50 percent (%) efficient injection well with a 10-foot screen and 30 feet of head, one can calculate an injection rate of approximately 0.02 gallon per minute (gpm). Assuming an effective porosity of 10%, 587 gallons of amendment would be required to achieve a radius of influence (ROI) of 5 feet. That means the injection time required to achieve the target ROI of 5 feet for a single well would be 19 days, assuming 24-hour operation. Another problem with conventional injection wells in low-permeability settings is that a high degree of heterogeneity typically exists even within a 10-foot well screen, often ranging over multiple orders of magnitude of permeability.

Given that the volumetric flow rate entering different vertical horizons in the injection well screen is proportional to the hydraulic conductivities of those horizons, the vertical distribution of injected amendment can be highly preferential; that is, 90% or more of the total volume might easily be pushed out into soils adjacent to less than 10% of the well screen interval.

In recent years, several technologies have been developed to address the challenge of achieving a uniform and effective distribution of treatment amendments in low-permeability and fractured media. These advances include hydraulic and pneumatic permeability enhancement technologies, both of which can emplace amendments into low-permeability media. Emplacing treatment amendments using these techniques can help overcome the aforementioned limitations of traditional amendment injection techniques where low-permeability soils can impede delivery. Significant confusion currently exists in the industry as to the differences among hydraulic and pneumatic permeability enhancement technologies and permeation injections. While one technology may be more warranted for a particular application, practitioners often do not have the information required to make good decisions regarding which delivery technique to use. Definitive guidance for selecting the most appropriate technique is needed.

In addition, significant advances have been made in technologies that can provide high-resolution mapping of the subsurface distribution of amendments. However, a rigorous comparison of such methods in different geologies of low hydraulic conductivity has never been made, in part because the high-resolution mapping and data processing tools are proprietary and have not been widely commercialized and implemented. Consequently, no guidance is available for practitioners or RPMs to assist in the selection or specification of amendment distribution and monitoring techniques for assessing amendment delivery within low-permeability media.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project was to compare the performance and cost benefits of hydraulic and pneumatic permeability enhancement for *in situ* treatment at low-permeability sites. The technical objectives of this demonstration/validation project were to:

- Demonstrate the amendment distribution capabilities of permeability enhancement techniques in three different geologic settings with low permeability;
- Demonstrate and validate the use of tilt meter monitoring as a novel, high-resolution, and non-invasive mapping technique to aid in evaluating the performance of permeability enhancement technology;
- Collect sufficient performance and cost data to develop a concise guidance document to help RPMs and practitioners select and/or specify the optimal *in situ* delivery technique for a given low-permeability site, and the monitoring approach to quickly validate its performance; and
- If possible, compare *in situ* delivery performance results using permeability enhancement techniques to those of more conventional injection approaches.

1.3 REGULATORY DRIVERS

The United States Department of Defense (DoD) has many contaminated sites in complex hydrogeological settings and with unique contaminant characteristics where aquifer restoration to maximum contaminant levels (MCLs) or other cleanup criteria within a reasonable timeframe may be extremely difficult. For example, in the presence of a dense non-aqueous phase liquid (DNAPL), technologies specific to treatment of the dissolved components of the contaminants are limited by the DNAPL dissolution rates. This can result in contaminant persistence on the order of hundreds of years. In geologic settings of low hydraulic conductivity such as tight clays and fractured rocks, effective and uniform delivery of remediation amendments to the zones of interest is rarely achieved using conventional techniques. Collectively, these sites present significant technical and financial challenges to DoD (and other federal site owners) due to the long remedial timeframe and high cleanup costs.

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2.0 TECHNOLOGY

Permeability enhancement technology offers unique benefits to address the many challenges present at contaminated sites with low hydraulic conductivity. This section provides a description of the technology and presents its advantages and limitations.

2.1 TECHNOLOGY DESCRIPTION

At sites with low hydraulic conductivities of approximately 10^{-5} cm/s or lower, specialized *in situ* delivery techniques are required to distribute amendments effectively. The three most prevalent methods in use today are pressurized direct-push injection (DPI), hydraulic permeability enhancement, and pneumatic permeability enhancement (ESTCP 2014). Pressurized DPI is commonly used because of its low initial cost. However, distribution of amendments using this technique is often uncontrolled and unverified. Unfortunately, the high life-cycle cost of poor amendment distribution is seldom considered when selecting an appropriate *in situ* delivery strategy. In addition, rapid diagnostic tools for assessing amendment distribution to facilitate real-time optimization of the selected strategy have not been well documented. In recent years, several technologies have been developed in an attempt to address the challenge of achieving and measuring effective distribution of treatment amendments in low-permeability and fractured media. These advances include hydraulic and pneumatic permeability enhancement technologies, both of which emplace amendments into low-permeability media, as well as advancements in tilt meter monitoring for high resolution mapping of the subsurface distribution of amendments.

2.1.1 Hydraulic Permeability Enhancement

Invented by the oil and gas industry, permeability enhancement technology was modified to aid remediation of soil and groundwater in the late 1980s (United States Environmental Protection Agency [EPA] 1993 and 1994). The goal of permeability enhancement technology is to increase bulk hydraulic conductivity and amendment delivery ROI to facilitate enhanced *in situ* remediation in low-permeability formations. A low- or high-viscosity fluid is introduced into a borehole at a rate and pressure high enough to overcome the *in situ* confining stress and the material strength of a geologic formation, resulting in the formation of a fracture. In high-viscosity permeability enhancement applications, sand can be injected simultaneously with a solid amendment such as zero-valent iron (ZVI) to maintain the integrity of the propagated fractures that can otherwise become restricted or collapsed entirely, particularly in plastic geologic materials (U.S. Patent No. 7,179,381). The emplaced fracture network typically results in an increase in hydraulic conductivity by about an order of magnitude and allows for more effective injections or extractions. Hydraulic permeability enhancement can be performed using almost any drilling technique, including direct-push. **Figure 2.1** provides an idealized visual perspective on the processes involving hydraulic permeability enhancement where a series of long, depth-discrete fractures were initiated using the top-down approach.

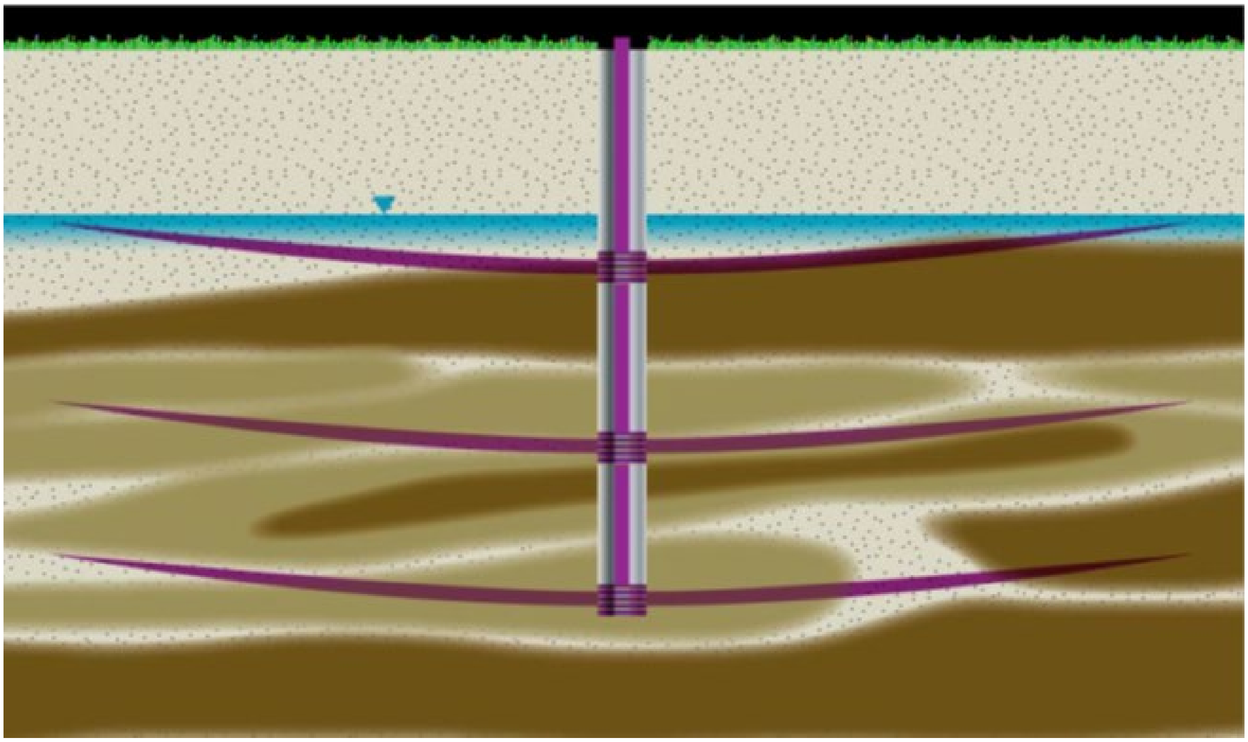

Figure 2.1. An Illustration of Hydraulic Permeability Enhancement Technology

2.1.2 Pneumatic Permeability Enhancement

Pneumatic permeability enhancement technology utilizes a gas at flow volumes exceeding the natural permeability of the formation to generate high enough pressures to overcome the *in situ* confining stress and the material strength of a formation such that fractures are formed (EPA 1995). The result is the enhancement of existing fractures and planes of weakness (e.g., bedding planes) and the propagation of a dense fracture network surrounding the *in situ* delivery well. Once a geologic zone has been fractured, the injection of the amendment can be performed in an integrated process. For example, the amendment liquid or slurry can be blended into a nitrogen gas stream above ground and become atomized. Relatively low pressures are required to sustain the flow into the formation. The atomization apparatus is a down-hole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the target interval. Using this method, the amendment might be distributed 10 to 25 radial feet depending on site-specific conditions. As with hydraulic permeability enhancement, this fracture network extends the ROI for injection, thus enhancing *in situ* treatment. **Figure 2.2** provides a visual perspective on the processes involving pneumatic permeability enhancement where a series of hairline fractures are initiated at the depths of interest. In the case of this demonstration project, a hybrid approach to pneumatic permeability enhancement was used, where fractures are generated pneumatically by application of high-pressure nitrogen gas, followed by hydraulic delivery of the aqueous amendment.

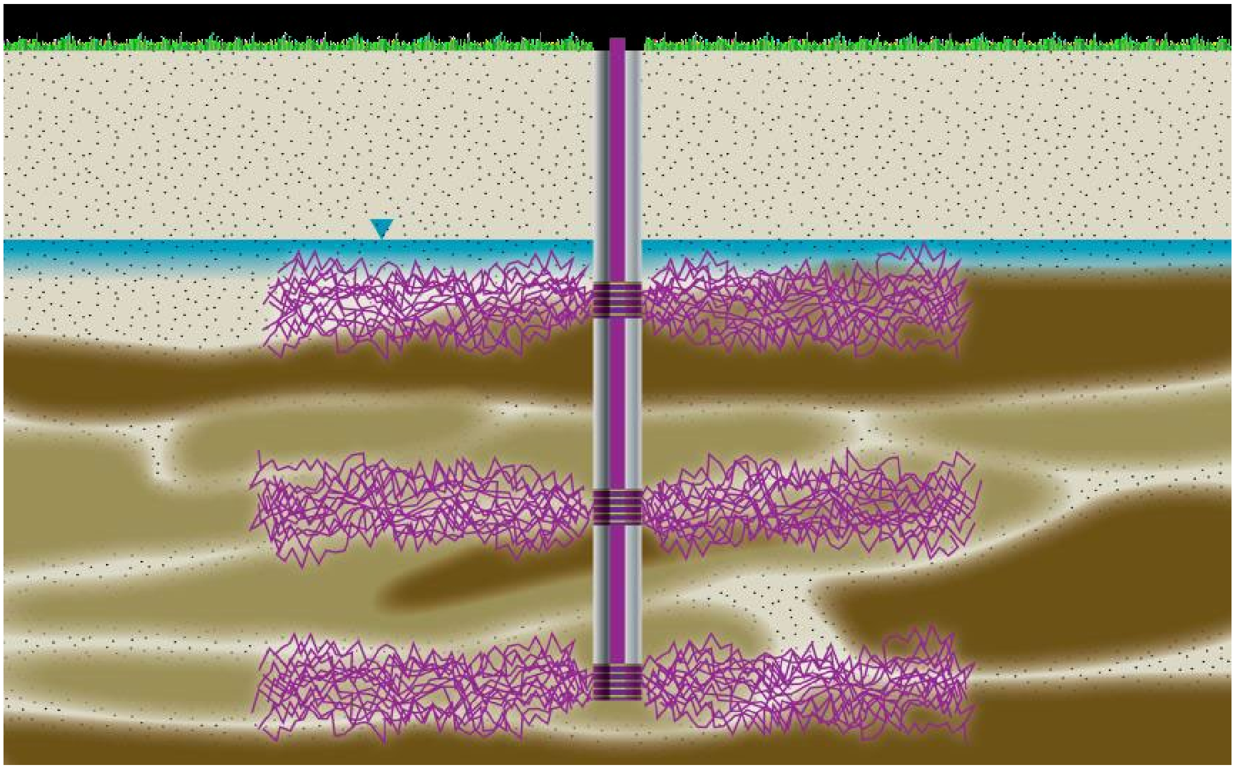

Figure 2.2. An Illustration of Pneumatic Permeability Enhancement Technology

The nature of permeability enhancement induced by pneumatic techniques is thought to be quite different from hydraulically induced fractures. Conventional wisdom suggests that hydraulic permeability enhancement has the advantage of a larger *in situ* delivery radius and propped fractures that can be used for multiple injections or extractions, while pneumatic permeability enhancement is expected to produce a denser fracture network for the same cost but within a smaller zone. However, no studies have been published comparing and documenting the performance of either of these techniques at multiple low-permeability sites (ESTCP 2014).

2.1.3 Tilt-Metering

A perhaps unrecognized advantage of using permeability enhancement technologies is the potential ability to measure three-dimensional (3D) amendment distribution in real time using tilt meters. Although much more sophisticated, tilt meters operate on the same principle as a carpenter's level (Dunnicliff 1993). Tilt meters contain two tilt sensors (on orthogonal axes) and precision electronics. As the tilt meter tilts, the gas bubble must move to maintain its alignment with the local gravity vector. The movement of the gas bubble within the conductive liquid causes a change in the total resistance between the electrodes. This resistance change is measured with a resistance bridge or voltage divider circuit to precisely detect the amount of tilt. While simple in theory, the instruments are remarkably sensitive. Utilizing sophisticated electronics and signal processing, tilt meters can achieve a resolution on the order of nanoradians. This is equivalent to the tilt produced by lifting one end of a rigid beam spanning from New York to San Francisco by less than 1 inch. Proper installation and operation of the instruments are required to utilize this resolution. The instruments must be adequately coupled to solid earth and significantly isolated from the large thermal fluctuations of the earth's surface. This is accomplished by setting up ground surface-mounted tilt meters in a concentric array.

The changes in resistance created by tilting the bubble sensor are electronically converted to a voltage that is proportional to the tilt of the instrument. The voltage is then recorded either by a local data acquisition unit at each tilt meter site or via cable to a central data acquisition system for the whole tilt meter array. Data collection is most often accomplished with remote data acquisition at each tilt meter site because it removes the need to run cables over the surface area surrounding the wellbore. Real-time monitoring and analysis can still be performed with remote data acquisition units using radio telemetry to send the data to a central computer system for display and analysis. Remote data acquisition units have sufficient storage capabilities to allow periodic data acquisition with a portable computer.

After tilt data are collected and analyzed to determine the tilt vectors due to the fracture stimulation, an inverse problem is solved to determine the nature of the source that produced the observed tilt field. Various models exist that predict surface deformations due to subsurface disturbances. Currently, a dislocation model is used to calculate the theoretical surface deformation (and therefore tilt field) due to hydraulic fractures with arbitrary orientation, dimensions, and location. The resulting output is then converted into a dynamic, 3D graphical output that can be viewed in any perspective in space and can be manipulated to view individual fracture configurations or the fracture network as a whole.

2.1.4 Other High-Resolution Characterization Tools

Other high-resolution characterization tools including direct-push electrical conductivity (EC) and ERT have been used to aid validation of amendment delivery via permeability enhancement. A brief summary of each technology is provided in the subsequent sections.

2.1.4.1 Direct-Push Electrical Conductivity

EC logging is utilized for high-resolution characterization of hydrostratigraphic conditions in unconsolidated media (Schulmeister et al. 2007). Direct-push EC probes typically operate using a four-electrode Wenner array, passing current through the outer two electrodes and measuring voltage across the inner two electrodes. The sensors are capable of collecting 20 measurements per second and collect data at a vertical resolution of 0.05 foot. Clayey materials tend to have higher electrical conductivity and charge characteristics compared to sandy or gravelly soils. The high vertical resolution of the probe readings allows the user to identify fine-scale features such as low-permeability clay or silt lenses or sand stringers, which are important for transport of injected amendments in the subsurface. The electrical conductivity of the groundwater also affects the conductivity measurements, but the conductivity of groundwater is typically relatively constant over the scale of a shallow, unconsolidated aquifer. By injecting an electrically conductive tracer or amendment solution and measuring electrical conductivity before and after injection activities, intervals impacted by the tracer can be evaluated using the direct-push probes, thereby delineating the vertical distribution of injected amendments.

2.1.4.2 Electrical Resistivity Tomography

ERT is a geophysical visualization technique used to study hydrogeological characteristics of the subsurface. Resistivity, an inherent property of all materials, measures the degree to which a material resists the flow of an electrical current. As resistivity depends on chemical and physical properties such as saturation, concentration, and temperature, ERT can be used to monitor natural and anthropogenic processes responsible for changes in such properties (Daily et al.1992).

In the context of environmental engineering, ERT can aid in monitoring active remedial progress and provide insights into material emplacement and deformational processes, both of which are very relevant to *in situ* treatment technologies in general and the permeability enhancement technology in particular (Halihan et al. 2005 and Wilkinson et al. 2008). In the context of this demonstration, ERT has the potential to aid in visualization of the 3D distribution of an injected fluid if the resistivity of that fluid is significantly different from the groundwater.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGIES

Advantages of the permeability enhancement technology include:

- In many instances, permeability enhancement represents the best practice remediation approach for subsurface delivery of treatment amendments, especially at low-permeability sites. The technology is a cost-effective, environmentally sustainable, and non-disruptive alternative to conventional delivery practices.
- Effective delivery of treatment amendments into the target zones can be achieved and verified with a high degree of confidence, thus minimizing the potential for failed in situ remediation attempts and lowering life-cycle remediation costs.
- Permeability enhancement is a very versatile technology; its various applications range from aggressive source treatment to enhancement of monitored natural attenuation in a variety of geologic media.
- The ability to visualize the 3D distribution of injected amendments in a fracture network through tilt meter monitoring is a unique advantage over any other delivery technique that can facilitate rapid and highly effective optimization of in situ remediation strategies.
- Equipment used in permeability enhancement generally has a small footprint, making the technology applicable at sites with limited working space.

Limitations associated with the permeability enhancement technology include:

- Highly specialized equipment and chemicals are often used in permeability enhancement technology, resulting in a higher initial cost relative to some conventional *in situ* remedial technologies.
- A potential risk for vertical migration of contaminants exists as a result of permeability enhancement. This risk can be mitigated by properly implementing these technologies based on a comprehensive understanding of site hydrogeological conditions.
- High-pressure injection requires proper planning and adherence to health and safety protocols to mitigate associated health and safety concerns.
- Permeability enhancement sometimes suffers from the poor public perception of the applications of hydraulic fracturing in the oil and gas industry. As adapted for environmental applications, the technology is significantly different than that used in the oil and gas industry. The primary differences include the much lower pressures and the lack of potentially toxic chemicals used for remediation purposes. Education of the regulatory authorities and interested community stakeholders might be required in some cases to address concerns arising from this perception.

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3.0 SITE DESCRIPTION

This section provides background information pertinent to the three contaminated low-permeability sites selected for this technology demonstration. The approved site selection memorandum is presented in **Appendix B**. Specifically, site locations and history, previous remedial work performed, geology and hydrogeology, and contaminant distribution are described.

3.1 CAMP PENDLETON SITE 1115

Site conceptual model information including site location and history, previous remedial work performed, site geology and hydrogeology, and contaminant distribution pertinent to the Marine Corps Base-Camp Pendleton, Site 1115 (referred herein as MCB-CP) is presented in this section.

3.1.1 Site Location and History

MCB-CP is located in Oceanside, California on the eastern portion of Camp Pendleton, southwest of the intersection of Vandegrift Boulevard and 16th Street. The site is approximately 14.5 acres in size. The site map is provided in **Figure 3.1** and the building and well layouts are shown in **Figure 3.2**. MCB-CP is relatively flat and mostly slopes at a 5 to 7% grade toward the north. Elevations of the site range from 325 to 365 feet above mean sea level (amsl). There is no permanent surface water present; rainfall drains to the west and to the swales along 16th Street, which lies north of the site.

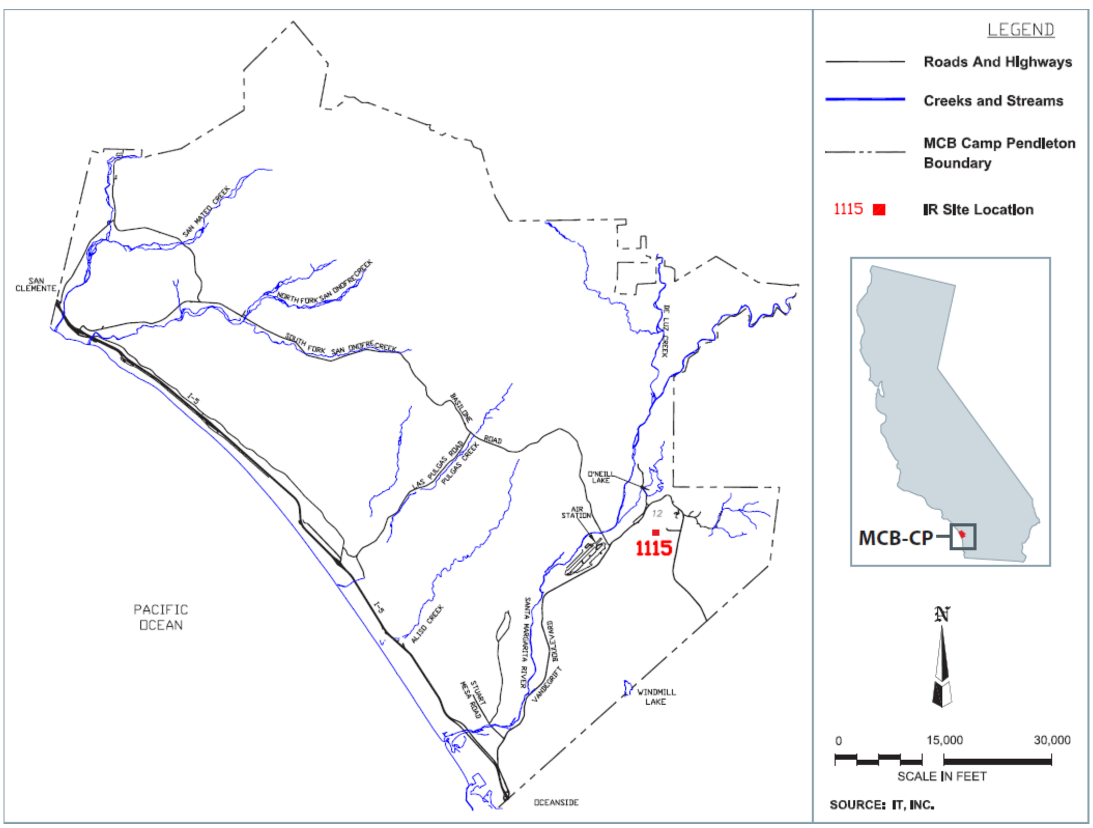

Figure 3.1. MCB-CP Site Location Map

The site once served as a motor pool for vehicle maintenance and a repair, painting, washing, and fuel service station for the base. A total of nine underground storage tanks (USTs), which stored a variety of fuels and solvents, were used to support activities at the site. All buildings and USTs have been removed or closed in place. The site is currently paved with asphalt and is used for vehicle and equipment staging (Parsons 2012).

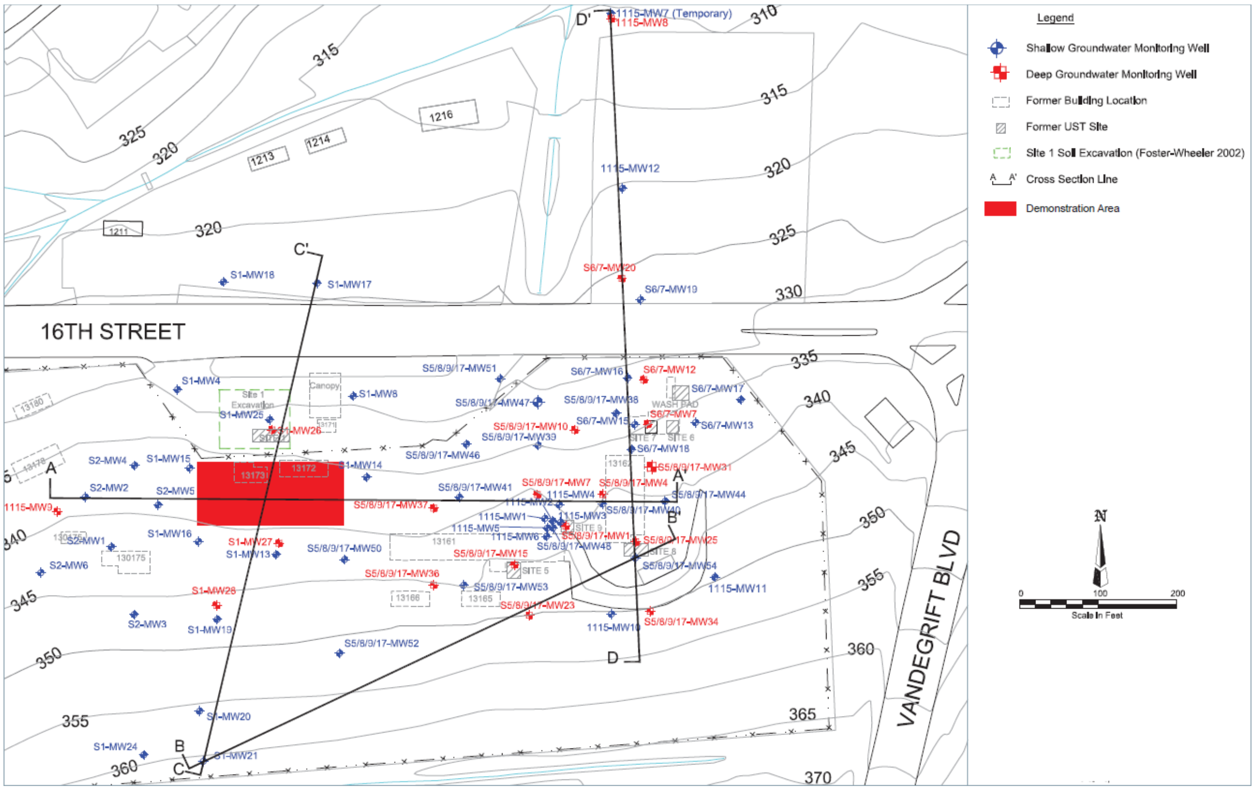

Figure 3.2. MCB-CP Site 1115 Building and Well Layout Map

3.1.2 Previous Remedial Work

Previous treatment activities at MCB-CP include UST removals, soil excavation (UST Site 1 in January 2002), pilot study soil-vapor extraction investigations, light non-aqueous phase liquid (LNAPL) recovery, and pilot studies for delivery of organic substrates in 2010 and 2011. Removal of 5,000 cubic yards of soil from the UST 1 area in 2002 resulted in marginal impact to water quality, as leachable concentrations of total petroleum hydrocarbons (TPH) gasoline range, benzene, toluene, ethylbenzene, and xylene (BTEX), and naphthalene were still found in the sidewalls of the excavation. Performance monitoring following the delivery of organic substrates in 2010 indicate that reductive dechlorination of chlorinated solvents was occurring where substrate was successfully delivered. However, the delivery of treatment amendment was severely restricted due to the site's low permeability and thus minimal remedial success was observed downgradient of the injection sites.

3.1.3 Site Geology/Hydrogeology

Figure 3.3 presents a west-to-east geologic cross section of MCB-CP soil lithology. The Santiago Formation is ubiquitous throughout the site and consists of mostly interbedded, low-permeability, lightly cemented siltstone, sandstone, and mudstone (Cranham et al.1994). This formation has the characteristic of not being strongly indurated or cemented. The soils in the western part of the site consist of yellowish-brown to very pale brown silty sand, greenish gray lean clay or silty lean clay with sand, light olive brown or olive yellow clayey silt, and dark grayish brown sandy silt. Sand units in this part of the site consist of very fine to coarse-grained, poorly graded sand, silty sand, and clayey sand. Silt and clay beds also contain sand and are very stiff to hard. Shallow soils in this portion of the site consist of a fill material that is a yellow-brown, fine to medium-grained, and poorly graded sand. In the eastern part of the site, bedrock consists of clay and silt beds. These clay and silt zones are mostly at depths between 15 and 30 feet below ground surface (bgs). The shallow, low-permeability units consist of silt and lean clay, whereas deeper units consist of fat and lean clays with fine laminations with interbedded lenses of unsaturated sand. At approximately 50 to 60 feet bgs, poorly graded sands, silty sands, and clayey sands are present; these are underlain by silt and clay.

A shallow groundwater zone exists across the site. It varies considerably in depth due to surface topography and contains an array of contaminants at roughly an order of magnitude higher in concentration than a deeper groundwater zone (Parsons 2012). In the eastern portion of the site, the shallow groundwater generally occurs in low-permeability water bearing zones. These zones include silts and clays with thin saturated sand lenses. The western portion of the site has more permeable sand or silty sands. The saturated thickness of the western portion of the shallow aquifer is estimated to be 5 to 20 feet, with an average of 13 feet. The average thickness of the shallow aquifer on the eastern portion of the site is estimated to be 5 feet. The average thickness of the deeper aquifer is estimated to be 5 to 10 feet at a minimum. **Figure 3.3** also depicts the observed depths to the shallow and deeper water tables.

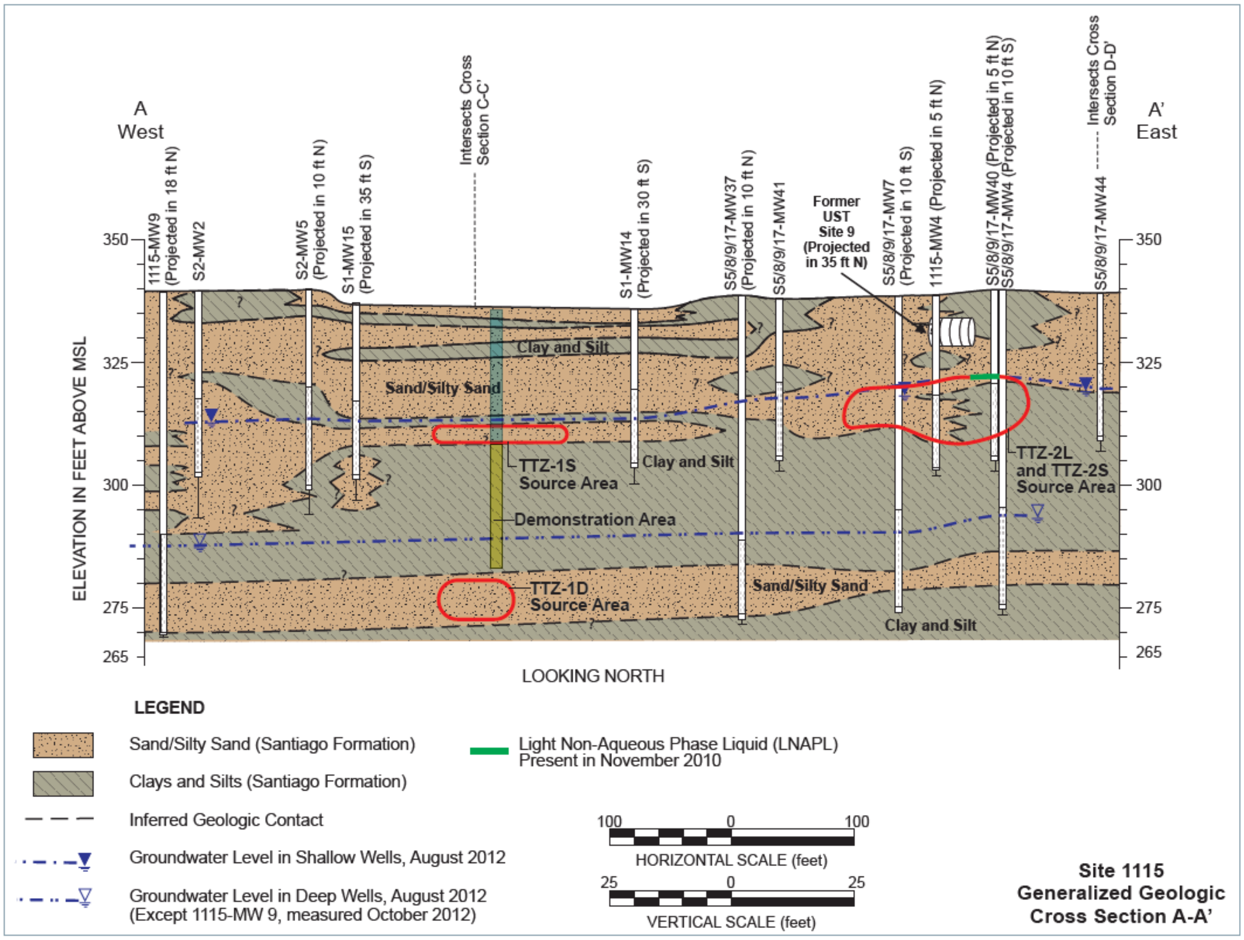

Figure 3.3. MCB-CP Site 1115 Cross Section

3.1.4 Contaminant Distribution

Contaminant migration from three distinct source areas has resulted in an extensive groundwater plume, as shown in **Figure 3.4**. This plume extends from a northwestern plume associated with UST Site 1 (former fuel service station), and a comingled plume associated with UST Sites 6/7 and 5/8/9, and former pipeline 17 on the eastern side of the site. Presently, the plumes have migrated several hundred feet from these source areas. Approximately 30% (4 acres) of the site is underlain by groundwater with contaminants above their respective MCLs.

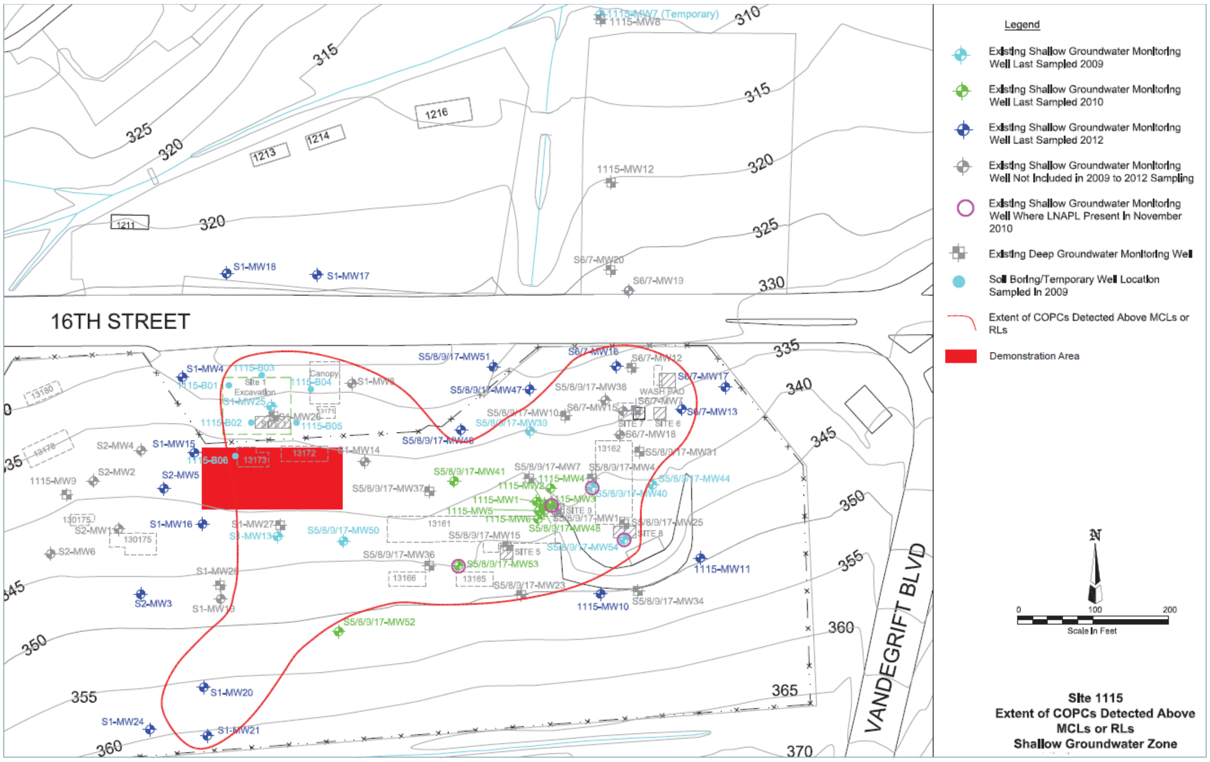

Figure 3.4. MCB-CP Site 1115 Demonstration Layout

From a total of 25 previous site investigations dating from 1986 to 2012, commonly detected contaminants in soil and groundwater above risk-screening levels include 1,2-dichloroethane, 1,2-dibromoethane, arsenic, benzene, carbon tetrachloride, cis-1,2-dichloroethene (cis-1,2-DCE), ethylbenzene, methylene chloride, methyl tertiary butyl ether, naphthalene, toluene, trichloroethene (TCE), and vinyl chloride (VC). These contaminants are mostly found in the vicinities of the former USTs. Benzene is the primary groundwater contaminant in the northwestern part of the site (area of UST 1d), while fuel-related compounds and chlorinated solvents are present on the eastern and central portions of the site. The presence of TCE degradation products, including cis-1,2-DCE and VC, and low oxidation-reduction potential (ORP) indicate potential attenuation of chlorinated solvents within the plume. Total dissolved solids above 5,000 milligrams per liter (mg/L) are also typically encountered in the monitoring wells.

LNAPL has historically been observed in monitoring wells near former UST 1 on the western side of the site and near USTs 5, 6, 7, 8, and 9 on the eastern portion of the site (Parsons 2012). LNAPL has been observed in excess of 1 foot thick in six monitoring wells next to former USTs 5, 6, 7, 8, and 9, as well as near former buildings 13162 and 13165. In February 1996, 16 feet of LNAPL was observed in the shallow monitoring well MW40—the most observed at MCB-CP. As of 2013, most of the visible LNAPL in these wells has been reduced to just sheens, with the exception of MW53, for which 0.42 feet of LNAPL was reported. Observed LNAPL is thought to exist in isolated pools perched above the shallow groundwater, providing a continued source of contamination to the groundwater. Diesel- and gasoline-range petroleum hydrocarbons were observed during a series of soil borings in 2009; these ranged in concentrations from non-detect to 14,000 milligrams per kilogram (mg/kg). The contaminant plume extent seen in **Figure 3.4** is supported by data from the 64 monitoring wells at the site.

It should be noted that based on the contaminant profile discussion, the primary contaminants of concern requiring treatment at MCB-CP were originally chlorinated solvents. However, following installation of a new monitoring well in the vicinity of the proposed demonstration area, it was determined that there were minimal levels of chlorinated solvents within the demonstration area. On the contrary, elevated benzene concentrations were found and thus the original permeability enhancement approach for MCB-CP had to be revised as appropriate, with the amendments changing from enhanced anaerobic bioremediation using an electron donor to *in situ* chemical oxidation (ISCO) using persulfate. Details pertinent to the test design at this site are provided in **Section 5.2**.

3.2 LAKE CITY ARMY AMMUNITION PLANT SITE 17D

Site conceptual model information including site location and history, previous remedial work performed, site geology and hydrogeology, and contaminant distribution pertinent to the Lake City Army Ammunition Plant, Site 17D (referred herein as LCAAP) is presented in this section.

3.2.1 Site Location and History

LCAAP is located in northeastern Independence, Missouri. The site consists of 3,935 acres with 458 buildings as shown in **Figure 3.5**. The small community of Lake City, which relies on private groundwater wells, is located adjacent to the northern boundary of LCAAP.

The site was established in December 1940 for manufacturing and testing of small caliber ammunition for the United States Army (EPA 2008). The site has been in continuous operation except for a single 5-year period following World War II. On average, the plant has produced almost 1.4 billion rounds of ammunition per year. The site is a government-owned, contractor-operated facility. Remington Arms operated the facility until 1985, when Olin Corporation took over operations. Management changed to Alliant Techsystems in 2001.

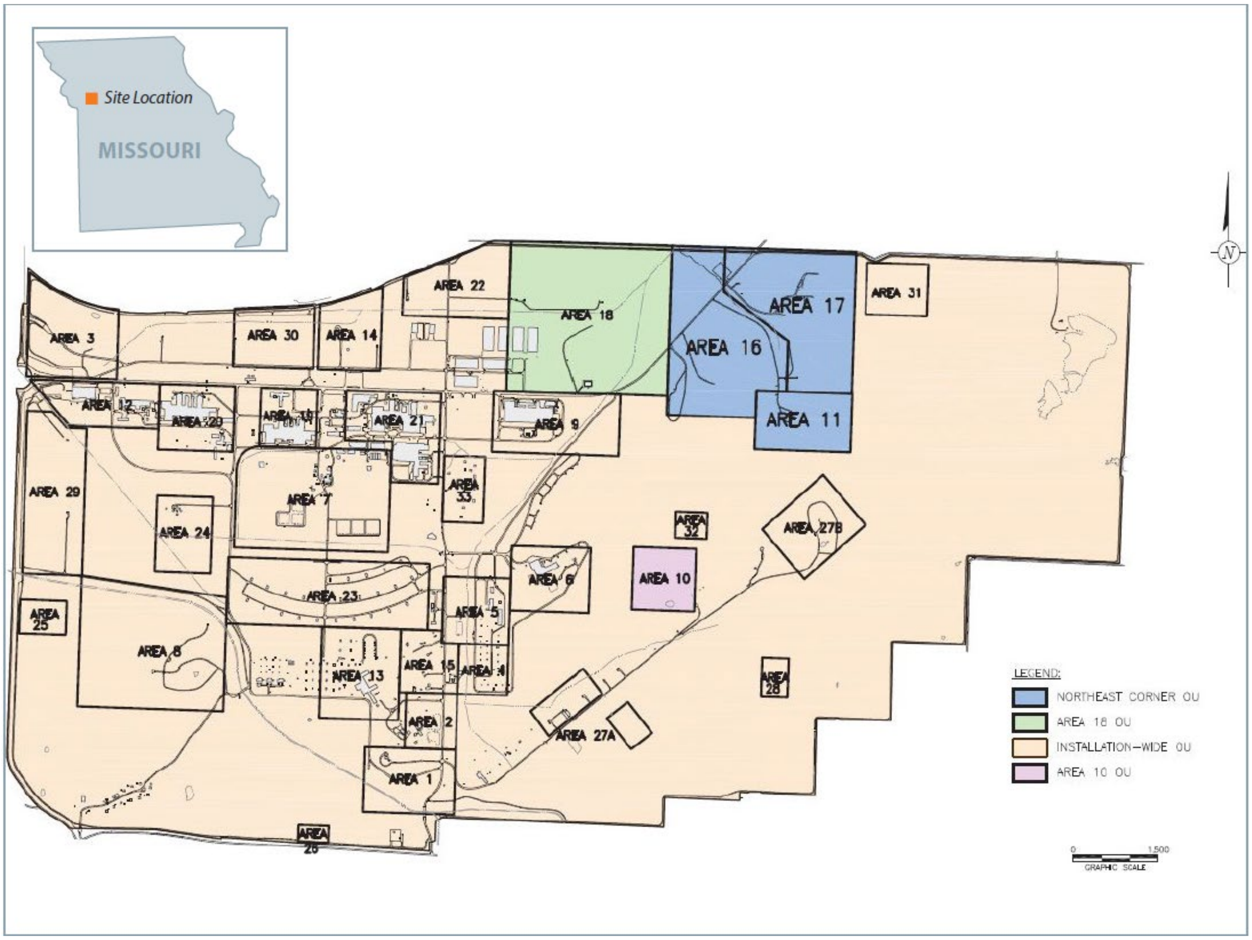

Figure 3.5. LCAAP Site Location Map

3.2.2 Previous Remedial Work

Following an interim 1998 remedial action record of decision, a subsurface permeable reactive wall (PRW) containing ZVI was installed in 2000 to treat dissolved-phase contaminants emanating from the source area (United States Army Corps of Engineers [USACE] 2013). The PRW is located approximately 500 feet upgradient of the area selected for the permeability enhancement technology demonstration. Concentrations of volatile organic compounds (VOCs) are higher on the upgradient side of the PRW than on the downgradient side, indicating that degradation of these compounds is occurring.

In 2007, Arcadis installed multiple injection wells within an area of the plume with the highest concentrations of VOCs to facilitate injection of an organic carbon substrate and to promote enhanced anaerobic bioremediation (EAB). These injections have been ongoing since the installation and monitoring wells were installed throughout the LCAAP 17D area plume to assess the impact of this treatment.

3.2.3 Site Geology/Hydrogeology

Previous investigations indicate that three distinct hydrostratigraphic units exist at the 17D area, as shown in **Figure 3.6** (Arcadis 2006). A silty clay overburden consisting of both alluvial silty clays and fine silty sands is approximately 20 to 30 feet thick in this area. Hydraulic conductivity for the silty clay colluvium unit has been estimated to be approximately 4 x 10^{-5} cm/s. Underlying this unit is a silty clay and weathered shale residuum with a thickness of approximately 10 to 15 feet. The water table in the 17D source area is approximately 5 to 10 feet bgs. This water table is most likely influenced by Abshier Creek, which is approximately 400 feet to the north of the source area.

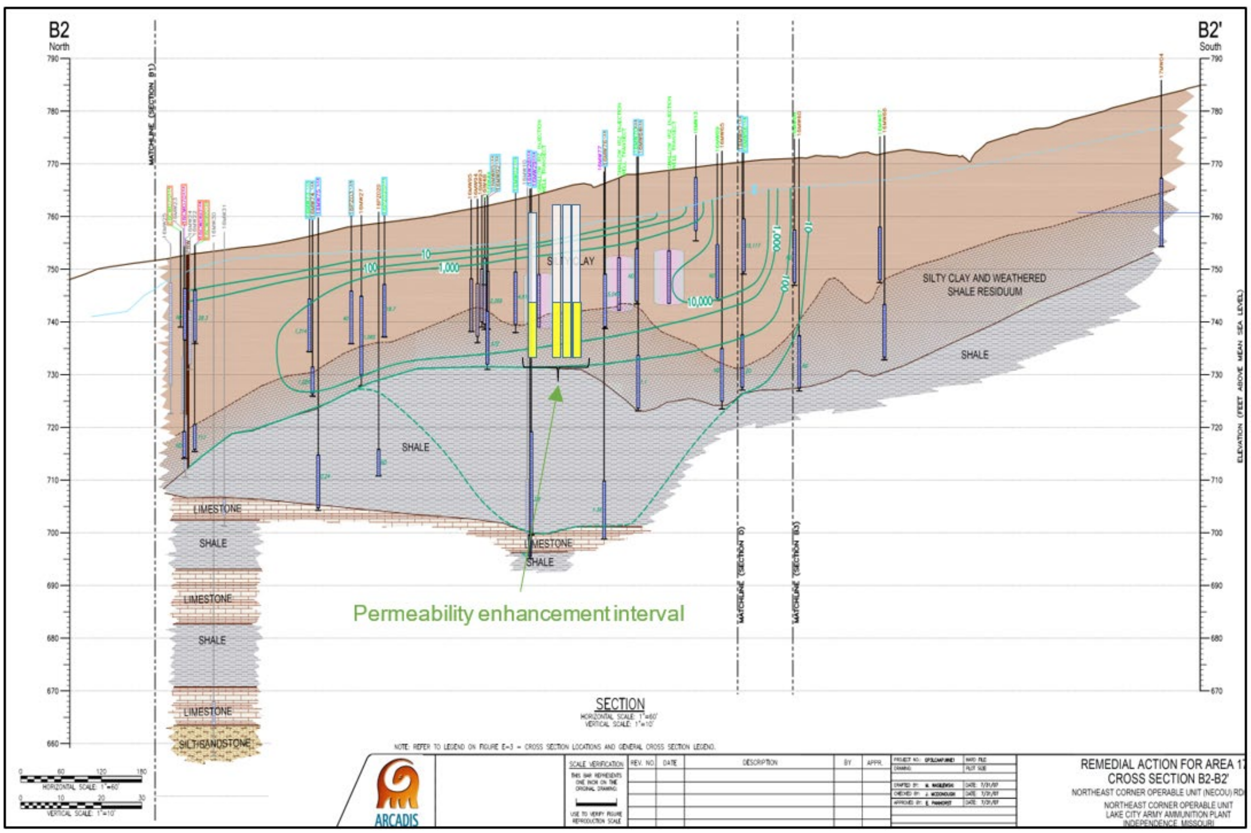

Figure 3.6. LCAAP 17D Area Cross Section

The LCAAP area selected for this technology demonstration is illustrated in **Figure 3.7**. The area's lithologic low permeability in the saturated and contaminated zone along with its nearby monitoring network of appropriate screen intervals provide an excellent opportunity for a side-by-side comparison of hydraulic versus pneumatic permeability enhancement. In addition, the demonstration area is located between two rows of biobarriers that have been actively receiving emulsified vegetable oil (EVO) injections and thus will allow for performance comparisons between the permeability enhancement technology and conventional injection technologies. The primary contaminants of concern at this site are the aforementioned chlorinated ethenes. Details regarding the test design for this site are provided in **Section 5.**

It should be noted that, unbeknownst to CDM Smith and other parties involved in remediation work at LCAAP, the hydraulic demonstration area was a historical dump pit for TCE DNAPL. Although backfilled, this area was likely heavily disturbed during past disposal activities. On the contrary, native materials were present in the pneumatic demonstration area and DNAPL was not present. These discrepancies were likely attributable to several unanticipated permeability enhancement performance results at LCAAP, which will be discussed in further in **Section 6**.

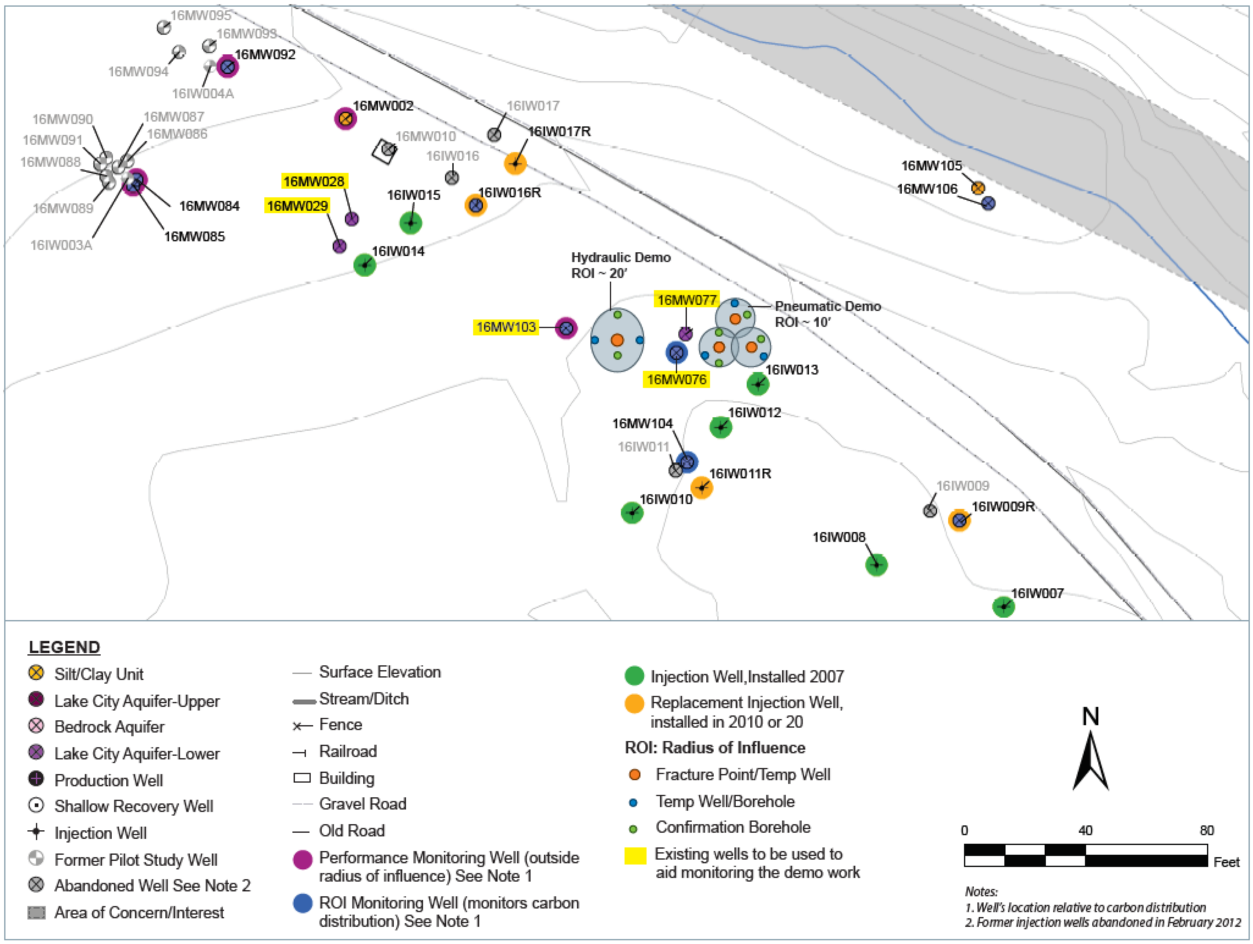

Figure 3.7. LCAAP 17D Area Demonstration Layout

3.2.4 Contaminant Distribution

Waste treatment and disposal occurred on site in unlined lagoons, landfills, and burn pits (EPA 2008a). These disposal processes released solvents, oils, explosives, radionuclides, VOCs, and metals to the local environment. Contaminated groundwater has migrated offsite in the northeastern part of LCAAP. A groundwater extraction well is currently used to control further offsite migration of contaminants. As shown in **Figure 3.8**, Area 17D was used for waste storage of glass, paint, and solvents.

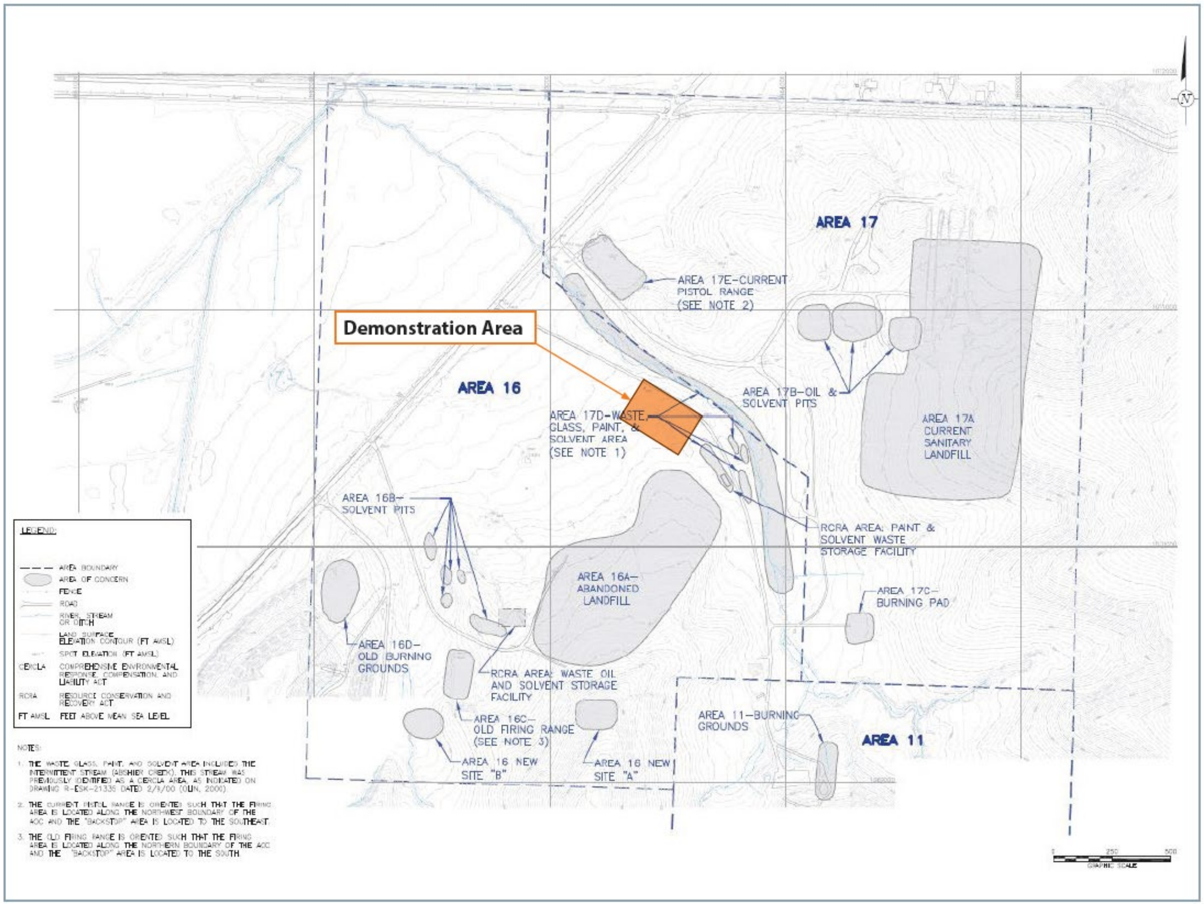

Figure 3.8. LCAAP Area 17 Layout

Area 17D is long and narrow, located on relatively flat terrain, and has the Abshier Creek (identified as a Comprehensive Environmental Response, Compensation, and Liability Act of 1980 area) running through it (EPA 2008b). The LCAAP 17D area was used from 1960 to 1975 for a variety of waste disposal activities. These activities included disposal of fluorescent tubes, oil, grease, bleach cans, ammunition cans, and paint cans. The area has a chlorinated solvent plume that extends over 2,000 feet from the southeastern source area to the northwest, effectively following the groundwater flow that moves in a west-northwest direction from the source area. Chlorinated solvent concentrations are between approximately 1 and 10 mg/L in the source area near the southeast end of the plume. The area of the 17D plume is estimated to be 7 acres, with an estimated impacted saturated interval of up to 30 feet. In the surficial soil, concentrations of lead exceed cleanup goals. In groundwater, VOCs including TCE, cis-1,2-DCE, and VC are present. Aromatic hydrocarbons are not present in sufficient quantities at the site to feed microbes that would support natural degradation of the contaminants.

3.3 GRAND FORKS AIR FORCE BASE SITE TU504

Site conceptual model information including site location and history, previous remedial work performed, site geology and hydrogeology, and contaminant distribution pertinent to the Grand Forks Air Force Base, Site TU504 (referred herein as GFAFB) is presented in this section.

3.3.1 Site Location and History

GFAFB is located 12 miles west of Grand Forks, North Dakota, near the state line with Minnesota as shown in **Figure 3.9**. The site contains 4,830 acres of land, which are partially surrounded by the farming communities of Emerado, Arvilla, and Mekinock (ARGO/LRS JV 2014).

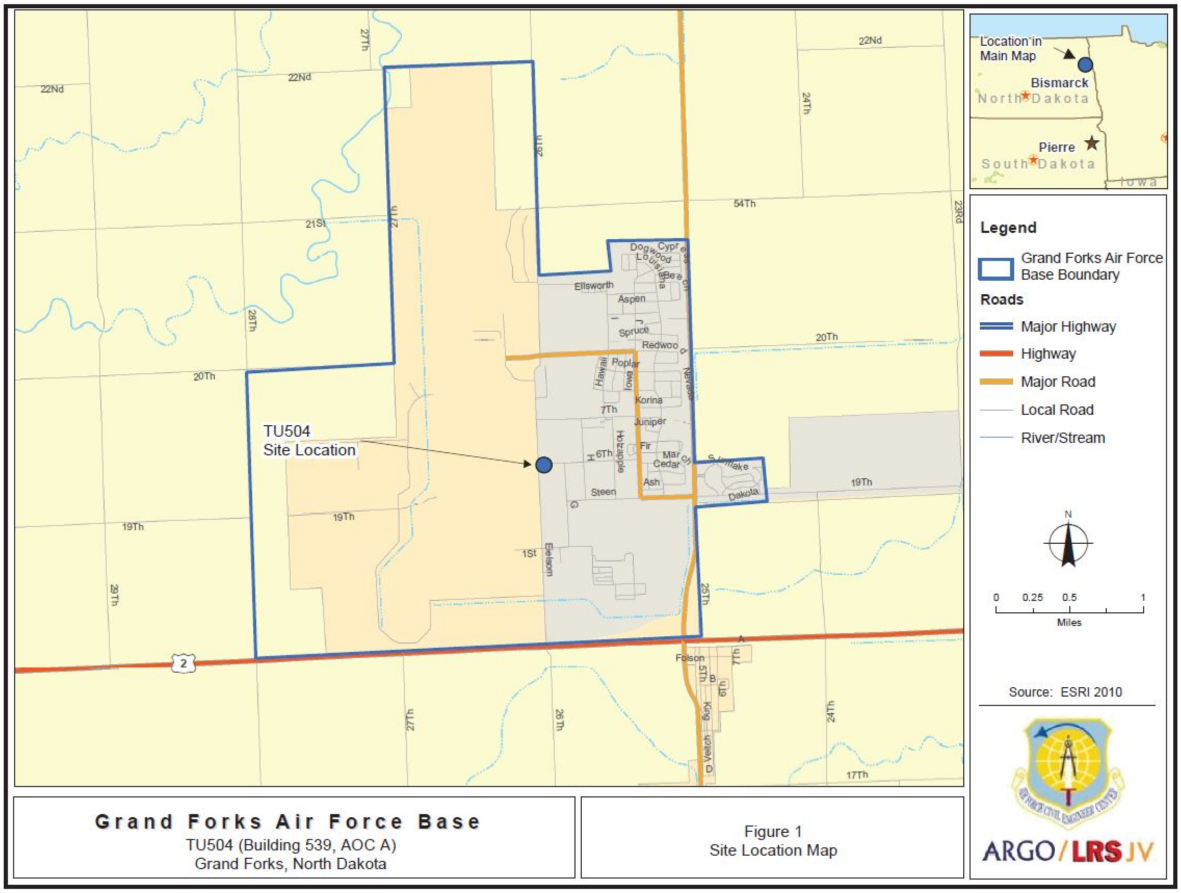

Figure 3.9. GFAFB Site Location Map

The site was historically used as an air defense command base that housed KC-135 Stratotankers, B-52 bombers, and B-1B bombers. The area selected for this demonstration is TU504, shown in **Figure 3.10**, which is located in the central portion of the base. Building 539 is located within this area and it was used for jet engine testing from the 1950s through 1992.

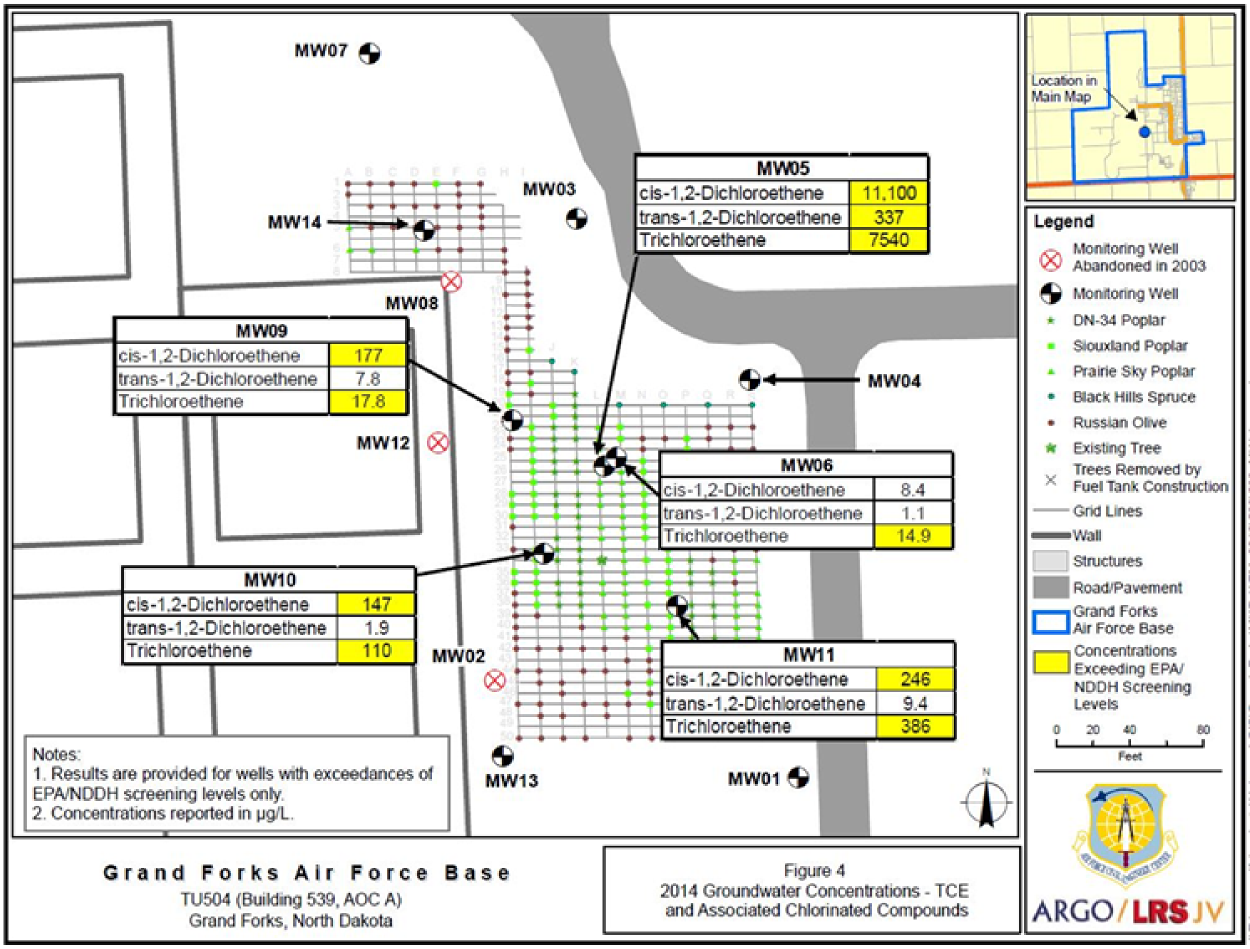

Figure 3.10. Groundwater VOC Results in the Vicinity of the Demonstration Area

3.3.2 Previous Remedial Work

In 2002, a phytoremediation project was implemented to hydraulically control and mitigate the plume contamination. The groundwater surface in the vicinity of the plume has been depressed due to limited surface recharge and evapotranspiration. This has caused the groundwater to flow towards the center of TU504. Long-term monitoring (LTM) of 10 monitoring wells has been conducted on an annual basis since 2003. During the 2014 LTM, tree canopy heights ranged from 7.5 to 62.1 feet, with an average height of 26.9 feet, indicating potentially extensive subsurface root structures (ARGO 2014). Groundwater sampling at this time showed maximum concentrations of TCE and cis-1,2-DCE of 7.54 and 11.1 mg/L, respectively. The maximum benzene concentration was measured at 0.657 mg/L, while diesel- and gasoline-range organics were measured at 0.973 and 6.25 mg/L, respectively. Exceedances of MCLs in the 2014 groundwater sampling results for the 10 monitoring wells are shown in **Figure 3.10**.

In July 2014, 6,625 pounds of LactOil® and 4,323 gallons of a LactOil®/water solution were injected into 30 locations, in addition to a bioaugmentation of *Dehalococcoides spp*. The spacing of the trees and the temporary injection well scheme at the TU504 area are shown in **Figure 3.10**.

An illustration of the temporary well installation is presented in **Figure 3.11**. Results from the 2014 LTM report indicate that this injection was successful at degrading contaminants in locations where the bioaugmentation and substrate addition had migrated, but exceedances of MCLs in multiple wells for VOCs and TPH still remain. It was concluded that considerable time may be necessary to fully realize the impact of the bioaugmentation and LactOil® treatment.

Figure 3.11. Temporary Injection Well Installation at the GFAFB Site TU504

3.3.3 Site Geology/Hydrogeology

The base lies on interbedded lacustrine and glacial units, which were deposited during interglacial and glacial periods (EA Engineering, Science, and Technology, Inc. 2010). The shallow soil contains a pale brown coarse sand and silty clay fill ranging from 2.5 to 6 feet thick. Below this lies a till unit of brown and gray mottled silty clay with decayed vegetation between 15 and 40 feet thick. Below this is a gray clay unit containing gravel and cobbles, which ranges in thickness from 25 to 58 feet. This is followed by a gray silty clay unit approximately 16 to 32 feet thick. Underlying these soils is the Emerado Sand, a gray sand unit approximately 30 feet thick. The interval targeted for the permeability enhancement technology demonstration lies within the clay zone extending from 3 to 30 feet bgs.

A shallow water table observed at the site between 4 and 8 feet bgs overlies the Emerado Aquifer. A confining unit above such an aquifer is present at approximately 60 feet bgs. The potentiometric surface of the Emerado Aquifer is observed to be higher in elevation than the shallow perched water surface. Hydraulic conductivities of the shallow zones of interest for this demonstration have been measured on the order of 2×10^{-5} cm/s, but measurements for deeper soils have not been found. A hydraulic gradient of 0.025 is observed on the site, suggesting a groundwater flow velocity of 13 feet per year in the shallow groundwater unit. The lower permeability of the shallow soils suggests that significant migration of contaminants away from the source area is not expected.

Unfilled soil fractures have been observed in the shallower portions of the soils, which may contribute to preferential flow.

3.3.4 Contaminant Distribution

In 1996, a petroleum odor was detected in soils removed from an excavated water line. Subsequent analysis of compounds in the site soil and groundwater included detections of JP-4 fuel, hydraulic fluid, engine oil, solvents, TCE, and methyl ethyl ketone. A Resource Conservation and Recovery Act (RCRA) facility investigation was conducted in 1999 and found VOC and TPH above MCLs for soil and groundwater. In 2000 and 2001, a phase II RCRA facility investigation completed the horizontal and vertical delineation of the TU504 area plume. This phase II activity also found other VOCs above MCLs and determined that the soil contamination extended to a depth of 10 feet bgs.

GFAFB, selected for this technology demonstration, is illustrated in **Figure 3.12**. The area's low permeability in the saturated zone, its nearby monitoring network of appropriate screen intervals, and previous remedial work provides an excellent opportunity for a side-by-side comparison between hydraulic permeability enhancement and standard in-well injection. The primary contaminants of concern at this demonstration site are the chlorinated ethenes. Details regarding the test design for this site are provided in **Section 5**.

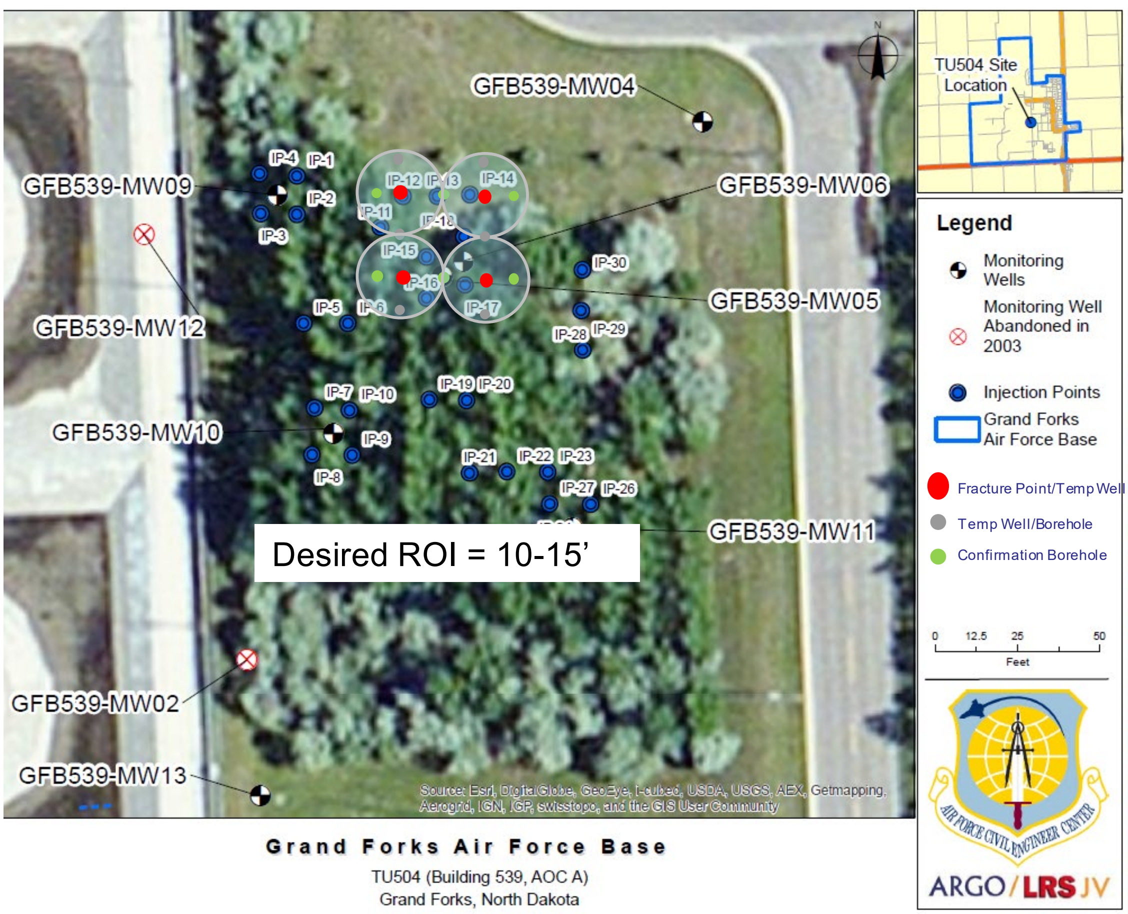

Figure 3.12. GFAFB Site TU504 Demonstration Layout

4.0 PERFORMANCE OBJECTIVES

A description of each performance objective [also presented in the approved demonstration work plan (**Appendix B**)] pertinent to this technology demonstration, specific data requirements, success criteria, and whether the performance objective was met is summarized in **Table 4.1** and described in more detail in the subsequent subsections. It should be noted that just because the collected field and analytical data did not categorically satisfy a set of pre-defined success criteria does not necessarily mean that the associated performance objective was not met, or the demonstrated technology was unsuccessful. In some cases, an inconclusive evaluation or an unanticipated result can serve as an important data point or provide useful insights. A detailed discussion of the results and interpretation is provided in **Section 6**.

Table 4.1. Overall Summary of Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Performance Objective Met?
#1 – Quantify horizontal and vertical distribution of emplaced fractures within target treatment volume	• Two soil cores for each fracture initiation boring to a depth equaling the deepest fracture interval	• Visual/analytical presence/absence of emplaced materials (e.g., zero-valent iron or sand) in soil cores will constitute success as these data will allow for qualitative assessment of amendment distribution.	Met
	• Tilt meter mapping in a 360-degree concentric array around fracture borehole	• Successful application of tilt meters will result in mapped injection planes of emplaced amendment within the target treatment volume. These data provide measurements of fracture orientation, extent, and thickness.	Met
	• Continuous down-hole EC logging (one site only)	• Successful application of EC will result in statistically different EC results in vertical intervals where fractures are present.	Marginally met
	• ERT (one or two sites)	• Successful application of surface ERT will result in a mapping of the aerial distribution of emplaced fractures. • Successful application of ERT may also result in observation of vertical distribution of fractures, although this will likely be masked by multiple vertical fractures in each borehole.	Marginally met
#2 – Deliver target amendment dose within the target treatment volume	• Amendment volume emplaced • Soil cores • Tilt meter mapping • EC logging • ERT	• 75% of the target injection volume is delivered within the treatment area of interest.	Met
#3 – Evaluate increase in aquifer permeability resulting from permeability enhancement technology	• Aquifer pumping/slug testing conducted in treatment area before and after permeability enhancement	• Successful conductivity enhancement is viewed as a statistically significant increase, defined herein as an increase of approximately one order of magnitude, in bulk hydraulic conductivity that allows for improved use of wells for injection and/or extraction.	Met

Table 4.1. Overall Summary of Performance Objectives (Continued)

Performance Objective	Data Requirements	Success Criteria	Performance Objective Met?
#4 – Evaluate effectiveness and accuracy of tilt meter geophysics monitoring	• Tilt meter fracture plane maps • Soil coring data • Direct-push EC data (one site only)	• Visual observation and/or analytical detection of fractures/treatment amendment against predicted tilt meter results.	Met
#5 – Evaluate effectiveness and accuracy of EC	• Pre-fracture EC values • Post-fracture EC values • Soil coring data	• Statistically significant increase in EC value at predicted depth intervals against actual visual observations and/or analytical detection of fractures/treatment amendment.	Met
#6 – Evaluate effectiveness and accuracy of ERT	• Pre-fracture surface ERT • Post-fracture surface ERT • Soil coring data	• Statistically significant increase in ERT value at predicted depth intervals against actual visual observations and/or analytical detection of fractures/treatment amendment.	Met
#7 – Evaluate efficacy of improved amendment delivery for treatment of site contaminants	• Contaminant and geochemistry data from existing groundwater monitoring wells	• Desired geochemical changes are observed in groundwater consistent with the type of treatment.	Met
	• Previous injection data	• Concentrations of the site-specific contaminants of concern in groundwater are reduced by at least 50% at the last performance monitoring event relative to historical trends and most recent groundwater quality data.	
	• Newly installed monitoring wells	• Permeability enhancement techniques are demonstrated to be more cost-effective over the life cycle of the remedy than conventional techniques based on site-specific data.	
#8 – Evaluate the ease of use/ implementation of each permeability enhancement technology and performance monitoring strategy	• Level of effort (including availability of equipment) necessary to perform each injection technique • Reporting of problems encountered in the field (including surfacing), and ability to resolve problems quickly	• Documentation of the relative availability of equipment and access to appropriate expertise, the level of oversight required, and the types of problems encountered, as well as the ease of resolution for each permeability enhancement technology and/or monitoring technique.	Met
#9 – Evaluate cost performance of each permeability enhancement technology	• Costs for equipment, subcontractors, drilling, field oversight, and data evaluation of each permeability enhancement technology	• Documented cost comparisons for equipment, subcontractors, oversight, and data evaluation for each permeability enhancement technology; the costs will be interpreted in the context of the actual distribution of amendments achieved.	Met

4.1 PERFORMANCE OBJECTIVE #1

This objective is focused on quantifying the fracture distribution in the low-permeability zones of interest at the three demonstration sites.

4.1.1 Data Requirements

Data collected to quantify the distribution of the emplaced fractures within the target treatment volume included at least two soil cores from each fracture initiation boring to a depth equaling the deepest fracture interval at each demonstration site, tilt meter mapping using a 360-degree concentric array around the fracture borehole at all three sites, continuous down-hole EC logging at GFAFB, and ERT at LCAAP and GFAFB.

4.1.2 Success Criteria

Success was determined based on visual and/or analytical presence or absence of emplaced materials (e.g., sand or EVO). Successful application of tilt meters was defined as accurately mapped injection planes of emplaced amendment within the target treatment volume to provide measurements of fracture orientation, extent, and thickness. Successful application of EC and ERT activities would further aid in achieving this performance objective. Amendment detections using all visual, analytical, and geophysics methodologies were also compared to determine whether they provided consistent data and to enable use of multiple lines of evidence to estimate distribution.

4.1.3 Outcome/Interpretation Overview

Visual observations of fractures and emplaced materials were generally observed during confirmation sampling at all three demonstration sites. In some instances, monitoring wells strategically placed within the target ROI of permeability enhancement were directly impacted by the high-pressure injections. At sites where a solid amendment or permeability enhancement reagents were not used, direct or indirect analyses of the added aqueous treatment reagents (i.e., TOC, persulfate, or fluorescein) were used to quantify the horizontal and vertical distribution of amendment within the anticipated ROI of permeability enhancement. Note that only marginal success was observed with the use of advanced geophysics monitoring techniques including EC and ERT to aid in quantifying fracture distribution within the low-permeability zone of interest at each of the demonstration sites, as further discussed in **Section 6**. Overall, based on the collected field and analytical data, this performance objective was met.

4.2 PERFORMANCE OBJECTIVE #2

This objective is focused on evaluating the accuracy of amendment delivery using the hydraulic and pneumatic permeability enhancement technologies within the target contaminated zones at the three selected sites.

4.2.1 Data Requirements

Analysis of the amendment volume emplaced, as well as post-demonstration confirmation sampling of soil cores, tilt meter mapping, EC logging, and ERT, was to determine the extent of the propagated fracture networks within and (potentially) outside the target treatment zone.

4.2.2 Success Criteria

The success criterion associated with this performance objective was defined as delivery of 75% or more of the target injection volume within the treatment area of interest.

4.2.3 Outcome/Interpretation Overview

Despite the challenging subsurface conditions, more than 70% of the target injection volume was introduced into the subsurface via hydraulic permeability enhancement at LCAAP as shown in **Table 4.2**. Between 99 and 100% of the target injection volume was achieved within the treatment area at the MCB-CP and GFAFB sites. Overall, this performance objective was met.

Table 4.2. Target vs. Actual Injection Volume

Site ID	Number of target permeability enhancement intervals	Target injection volume per interval (gallons)	Total target injection volume (gallons)	Total actual injection volume (gallons)	Percent of target injection volume achieved
LCAAP - Pneumatic	15	210	3150	3249	103
LCAAP - Hydraulic	1	2900	2900	2017	70
GFAFB	12	130	1560	1542	99
MCB-CP	5	580	2900	3095	107

4.3 PERFORMANCE OBJECTIVE #3

This objective is focused on quantifying the impacts of permeability enhancement technology on bulk hydraulic conductivity.

4.3.1 Data Requirements

Data collected to evaluate the increase in permeability from the permeability enhancement activities included results of slug tests conducted in the target treatment area before and after permeability enhancement.

4.3.2 Success Criteria

A success criterion for the enhancement of aquifer hydraulic conductivity was defined as approximately an order of magnitude increase in hydraulic conductivity following permeability enhancement activities. This would improve contact with the emplaced amendment and would also allow for improved performance of future injection and/or extraction performed using these wells.

4.3.3 Outcome/Interpretation Overview

An increase in hydraulic conductivity was not anticipated at GFAFB and within the pneumatic demonstration area at LCAAP where, at both sites, a sand proppant was not used to create permanent, high-permeability pathways. Therefore, the insignificant changes in pre- and post-permeability enhancement hydraulic conductivities at these demonstration sites were expected.

Increases in hydraulic conductivity were expected at MCB-CP and LCAAP because a sand proppant was used at both sites. Orders of magnitude increases in hydraulic conductivities were observed at MCB-CP following emplacement of the sand proppant. However, no changes in hydraulic conductivities were observed within the hydraulic demonstration area at LCAAP even though a sand proppant was used. It was discovered midway through the project the demonstration area for hydraulic permeability enhancement had unknown subsurface conditions that significantly impacted the amendment emplacement (namely the presence of DNAPL and subsurface disturbances as a result of past remedial activities as discussed further in **Section 6** below).

It should be noted that slug testing was used to assess changes in hydraulic conductivity rather than the more desirable aquifer performance testing. This adjustment was needed because of the low permeability and slow recovery rates observed at all three sites, as well as the presence of NAPL at LCAAP. Overall, based on the data collected, this performance objective was met.

4.4 PERFORMANCE OBJECTIVE #4

This objective is focused on evaluating the effectiveness and accuracy of the tilt metering tool in measuring and estimating fracture emplacement.

4.4.1 Data Requirements

Data collected to evaluate the effectiveness and accuracy of tilt metering for estimating fracture emplacement included visual and/or analytical detection of emplaced amendment and confirmation of fractures and/or amendment during post-enhancement soil confirmation sampling.

4.4.2 Success Criteria

Post-permeability enhancement soil confirmation sampling was used to evaluate the effectiveness and accuracy of tilt meter technology. Two evaluation criteria were considered including the vertical and horizontal extent of the initiated fracture networks. Preliminary tilt meter results were used to guide the soil confirmation sampling locations. Visual observations and analytical sampling of post-enhancement soil cores allowed for determination of actual depth intervals of fracture initiation and the horizontal extent of the fracture networks. Specifically, 3D visualization of the fracture network developed analytically using the tilt meter data was used to qualitatively determine whether post-enhancement confirmation boreholes that were impacted by the permeability enhancement were located within the horizontal extent of the modeled fracture network. In addition, the modeling results were used to predict the depths at which the fracture network intercepted the confirmation boreholes. Subsequently, field observations and analytical measurements indicative of amendment delivery such as TOC or total sulfate were used to determine the accuracy of the predicted depths of interception.

4.4.3 Outcome/Interpretation Overview

At all three demonstration sites where tilt meter monitoring technique was employed, post-enhancement confirmation boring locations impacted by the permeability enhancement work were generally located within the predicted horizontal extent of the fracture network. In addition, the predicted fracture-intercepting depths provided by modeling correlated very well with the actual depths where fractures were visually observed or confirmed analytically. At GFAFB, elevated fluorescein concentrations indicative of amendment delivery were observed within 1 to 2 feet of the tilt meter-predicted depth-discrete intervals where the initiated fracture network intercepts the confirmation borehole. At the other confirmation boreholes (GFB539-HCB-04, -05, and -08) located outside the ROI of permeability enhancement (as verified by the lack of fluorescein in depth-discrete composite soil samples), the lack of fracture interception was also predicted by tilt meters. At MCB-CP, three of the four fracture-intercepting depth-discrete intervals predicted by tilt meter coincided with intervals where fractures were visually observed during post-enhancement confirmation sampling and lithologic logging. Also, orders-of-magnitude increases in total sulfate concentrations were analytically verified at one (HCB-01) of the two post-enhancement confirmation boreholes. At the other confirmation borehole (HCB-02), no fractures were visually observed, consistent with the 3D visualization (which shows that this boring location is at the edge of the fracture network) and the absence of the orders-of-magnitude increases in total sulfate concentrations observed at HCB-01. At both post-enhancement confirmation boreholes within the hydraulic demonstration area at LCAAP, all six tilt meter-predicted fracture-intercepting depth intervals were within 1 to 3 feet of those where fractures were either visually observed or the highest increases in TOC concentrations were observed. Similar correlations between tilt meter modeling predictions and confirmation sampling results were observed at two of the three post-enhancement boreholes within the pneumatic demonstration area. Specifically, at PCB-01 and PCB-02, the fracture-intercepting depths predicted by tilt meter were generally within 1 to 2 feet of the highest increases in TOC concentrations. Such correlation was not observed at PCB-03; however, the predicted fracture interceptions thereof might have emanated from the nearby PIW-01 that was not monitored by tilt metering. Collectively, these results indicated that tilt meter monitoring is a non-intrusive and cost-effective geophysics technique for fracture monitoring during permeability enhancement.

4.5 PERFORMANCE OBJECTIVE #5

This objective is focused on evaluating the effectiveness and accuracy of EC in predicting fracture emplacement.

4.5.1 Data Requirements

Pre- and post-enhancement EC data collected were compared against depth intervals where fractures were visually observed and/or analytically detected during post-enhancement confirmation sampling of TOC and fluorescein.

4.5.2 Success Criteria

Similar to the aforementioned evaluation of tilt metering, the effectiveness and accuracy of EC was determined by comparing the estimated fracture depth interval and extent against the actual values obtained during post-enhancement soil confirmation sampling. Changes in post-enhancement conductivity following injections of an amendment solution with high conductivity were evaluated against the pre-enhancement values and depth-discrete field observations and analytical measurements.

4.5.3 Outcome/Interpretation Overview

No significant increases in EC were observed within the target treatment depth interval at GFAFB. However, no evidence of amendment delivery into the two EC locations was observed. This lack thereof was also analytically confirmed via soil confirmation sampling and subsequent fluorescein analysis. Specifically, no significant detection of fluorescein was detected at the two post-enhancement confirmation boreholes located in the vicinity of the two EC locations. Collectively, the limited data collected at this site renders the evaluation of EC as an effective geophysics tool for fracture monitoring inconclusive. Overall, this performance objective was only marginally met.

4.6 PERFORMANCE OBJECTIVE #6

This objective is focused on evaluating the effectiveness and accuracy of ERT in predicting fracture emplacement.

4.6.1 Data Requirements

Pre- and post-enhancement ERT data were collected and compared against depth intervals where fractures were visually observed and/or analytically detected during post-enhancement confirmation sampling.

4.6.2 Success Criteria

The effectiveness and accuracy of ERT were determined by comparing pre- and post-enhancement ERT data as well as correlating ERT data with post-enhancement soil confirmation sampling results including TOC at LCAAP and fluorescein at GFAFB. The success criteria for ERT for predicting the horizontal and vertical extent of amendment distribution was evaluated using the correlation between ERT data and the post-enhancement depth-discrete soil sampling data as well as post-enhancement groundwater sampling results, as appropriate.

4.6.3 Outcome/Interpretation Overview

At both LCAAP and GFAFB where ERT was implemented, significant changes (increases of up to 35%) were observed following permeability enhancement.

Along these lines, significant changes in ERT signals were generally correlated with other observations at each of the three demonstration areas (hydraulic and pneumatic areas at LCAAP and hydraulic at GFAFB). For the pneumatic cell at LCAAP, little change was observed following amendment emplacement, which was consistent with the TOC groundwater data. For the hydraulic cell at LCAAP, modest changes were observed following enhancement activities, with such changes generally localized around the monitoring well locations where the electrodes were deployed. At GFAFB, ERT imaging showed the most dramatic changes pre- and post-injection, and these changes were generally correlated with increases in TOC and fluorescein as measured from the confirmation borings and the groundwater monitoring network. ERT was also able to show a time-lapse evolution of the injected amendment following emplacement.

Overall, while ERT visualization of post-enhancement amendment distribution was not of sufficiently high enough resolution throughout the target areas to map and identify individual fractures, it was useful for assessing overall distribution of the emplaced amendment. Therefore, this performance objective was satisfactorily met.

4.7 PERFORMANCE OBJECTIVE #7

This objective is focused on evaluating the remedial enhancement gained by applying the permeability enhancement technologies at the contaminated sites.

4.7.1 Data Requirements

Data collected to aid evaluating the efficacy of improved amendment delivery for the removal of site contaminants included pertinent geochemical parameters and contaminant profiles in groundwater at monitoring wells located within and near the demonstration area both pre- and post-permeability enhancement. Where possible, data from previous conventional amendment injections were also obtained to evaluate injection performance improvements attributable to permeability enhancement.

4.7.2 Success Criteria

Success criteria for this objective were defined as attainment of geochemical conditions conducive for the intended treatment, and that the historically known contaminants in the groundwater within the vicinity of the permeability enhancement emplacement are reduced by at least 50% in the last performance monitoring events. Additionally, for sites with previous *in situ* injection data, cost comparisons should show that *in situ* delivery via permeability enhancement technology is demonstrably more cost effective (over the life-cycle) than conventional injections.

4.7.3 Outcome/Interpretation Overview

At GFAFB, orders-of-magnitude increases in TOC were observed in nearly all monitoring wells located and screened within the target treatment zone following permeability enhancement, resulting in development of highly reducing conditions conducive to reductive dechlorination. Significant reduction in TCE concentrations by as much as a factor of 9 was observed. At MCB-CP, aerobic conditions characterized by elevated dissolved oxygen (DO) and high ORP were observed at several wells located upgradient, downgradient, and cross-gradient from the permeability-enhanced injection well following amendment injection. At these locations, including 1115-HMW-01 through -03, complete degradation of BTEX compounds were observed. Similar to GFAFB, development of a highly reducing environment conducive to reductive dechlorination of TCE was observed at several monitoring wells located within the hydraulic permeability enhancement demonstration area at LCAAP. While no reduction in chlorinated solvent concentrations was observed at two of the three monitoring wells located within the ROI of hydraulic permeability enhancement, it should be noted that DNAPL was unexpectedly present in this area, which led to baseline TCE concentrations of greater than 100,000 µg/L at all three monitoring wells. However, at one of the monitoring locations (HMW-01), TCE concentrations decreased significantly from 160,000 to 810 µg/L. Such decreases in TCE concentrations were accompanied by an increase in VC from approximately 3,000 to 11,000 µg/L and a slight increase in ethene from 5.3 to 430 µg/L.

Following permeability enhancement, a strongly reducing environment typical of sulfate reduction was developed within the pneumatic demonstration area at LCAAP. In monitoring wells that were directly impacted by the pneumatic permeability enhancement, including PMW-01 through -04, significant changes in contaminant concentrations were observed in addition to changes in geochemical conditions. In many instances, complete degradation of TCE, transient accumulation then removal of daughter products cis-1,2-DCE and VC, and accumulation of ethene, resulting in more than 99% removal of chlorinated VOCs, were observed. Overall, this performance objective was satisfactorily met.

4.8 PERFORMANCE OBJECTIVE #8

This objective is focused on evaluating the ease of use of the permeability enhancement technologies.

4.8.1 Data Requirements

As permeability enhancement activities were completed, data on the level of effort (including the availability of equipment) necessary to perform each injection technique were collected. These data included reporting of problems encountered in the field and the ability of field crews to resolve problems quickly.

4.8.2 Success Criteria

Success in this case depends simply on documenting the issues related to ease of use. The intent was to use these data to evaluate whether permeability enhancement and pertinent monitoring activities can be performed with a level of effort similar to conventional injection techniques and whether improvements in remedial performance as a result of permeability enhancement are sufficient to justify whatever additional level of effort is required.

4.8.3 Outcome/Interpretation Overview

Issues encountered and lessons learned during the various phases of permeability enhancement at each of the three demonstration sites related to planning, procurement, field execution, and management were documented as detailed in **Section 6**. Overall, this performance objective was met.

4.9 PERFORMANCE OBJECTIVE #9

This objective is focused on evaluating the cost performance of the permeability enhancement technologies.

4.9.1 Data Requirements

Data collected for evaluating the cost performance of each permeability enhancement technology included costs for equipment, subcontractors, drilling, field oversight, and data evaluation.

4.9.2 Success Criteria

The success of this objective required that the costs for equipment, subcontractors, oversight, and data evaluation be captured and compared for each permeability enhancement technology. The costs were interpreted in the context of the actual distribution of amendments achieved and compared against those associated with the conventional remediation techniques previously employed at the demonstrated sites.

4.9.3 Outcome/Interpretation Overview

Cost elements that are key in the field execution of permeability enhancement were documented at all three demonstration sites. The obtained information was used to develop and justify several scenarios where permeability enhancement should be considered the preferred *in situ* amendment delivery technique to conventional methods from both a technical and a financial standpoint. Results from this cost estimating exercise, which is detailed in **Section 7**, indicate that permeability enhancement provides cost savings over conventional technologies some remedial scenarios.

5.0 TEST DESIGN

This section provides a brief summary of the overall experimental design, field activities performed that were common to all three demonstration sites, site-specific field implementation activities, and results of the permeability enhancement demonstration performed at MCB-CP, LCAAP, and GFAFB.

5.1 OVERALL EXPERIMENTAL DESIGN

This technology demonstration was performed to (1) demonstrate the efficacy of permeability enhancement techniques to emplace *in situ* treatment amendments in low-permeability media, and (2) compare the effectiveness of such techniques to that of conventional injection techniques. This overall project objective was achieved by utilizing the permeability enhancement techniques at three different DoD sites (MCB-CP, LCAAP, and GFAFB). Each of the three sites selected for this technology demonstration exhibited a different low-permeability geologic setting, as well as varying contaminants and past remedial activities. Pre-enhancement activities performed at each of the demonstration sites include utility location, unexploded ordinance clearance, and baseline soil/groundwater characterization. A variety of permeability enhancement techniques was performed depending on the type of amendments being emplaced as well as site-specific hydrogeological conditions, contaminants present, and past remedial activities. Permeability enhancement was monitored using a combination of conventional and innovative techniques to demonstrate amendment distribution using multiple lines of evidence. Following permeability enhancement, depth-discrete soil confirmation sampling was performed to evaluate amendment distribution; visual observation of soil samples was also conducted to assess presence of fractures. Post-enhancement hydraulic testing and performance monitoring were also performed to evaluate changes in hydraulic conductivity, geochemistry, and contaminant concentrations attributable to permeability enhancement. Details pertinent to the site-specific demonstration layout, field activities, sampling protocol, and field and analytical laboratory results are provided in the subsequent sections.

5.2 COMMON FIELD ACTIVITIES

Several field activities were performed at multiple demonstration sites, including the following:

- **Utility location**: a local subcontractor was procured to provide underground utility location and subsurface feature identification using ground-penetrating radar within and near the anticipated demonstration area at each of the three sites prior to commencement of any subsurface intrusive work. The utility location reports are presented in **Appendix C**.
- **Pre-enhancement well installation**: at each demonstration site, in conjunction with existing onsite monitoring wells, a number of new monitoring wells were installed to facilitate performance monitoring and evaluation of permeability enhancement. Sonic drilling technology was used to install three 2-inch inner diameter (ID), Schedule 40, polyvinyl chloride (PVC) monitoring wells and one 4-inch ID, Schedule 40, PVC injection well at MCB-CP. Hollow-stem auger (HSA) drilling technology was used for installation of six 2-inch ID, Schedule 40, PVC monitoring wells and one 2-inch ID, Schedule 40, PVC injection well at LCAAP. Similar to LCAAP, HSA drilling technology was also used to install seven 2-inch ID, Schedule 40, PVC monitoring wells at GFAFB.

Details pertinent to the well installation at MCB-CP, LCAAP, and GFAFB are presented in **Tables 5-1**, **5-2**, and **5-3**, respectively. It should be noted that, unlike traditional wells, all new wells installed for this technology demonstration at the three selected sites were completed with a grout seal consisting of approximately 5% bentonite powder for additional protection from the high pressure exerted during permeability enhancement. In a typical injection or monitoring well construction, only 2 to 3% bentonite powder is used.

- **Pre-enhancement soil sampling**: pre-enhancement soil samples were collected at each demonstration site to establish baseline measurements to which post-enhancement measurements can be compared. Sonic drilling technology was used to facilitate collection of soil samples at MCB-CP, whereas direct-push drilling technology (DPT)-aided dual-tube sampling methodology was used to collect samples at LCAAP and GFAFB.
- **Installation of ERT electrodes**: at LCAAP and GFAFB, where ERT monitoring was implemented, 2-inch, Schedule 40, PVC well casings and well screens equipped with electrodes made of low-profile, 201 stainless steel band clamps every 1.8 feet and single-stranded 20-gauge conductor wire leading to the surface were prepared in CDM Smith's Environmental Treatability Laboratory in Denver, Colorado. Each electrode wire was labeled and checked for continuity prior to being shipped to the demonstration sites. Details regarding the installation of the ERT electrodes are provided in **Appendix D.**
- **Pre- and post-enhancement hydraulic characterization**: slug testing was performed at each of the three demonstration sites to obtain estimated hydraulic conductivities pre- and post-permeability enhancement. The following procedures were used to conduct the slug tests:
  - A synoptic round of water level measurements was performed at all wells to be slug-tested prior to downhole deployment of pressure transducers.
  - Following the synoptic water level measurements, each LevelTroll 700 pressure transducer was programmed to allow for continuous recording of temperature, pressure, and depth at a frequency of 1 per second and in a fast-linear mode at each testing location.
  - Each programmed transducer was subsequently deployed to approximately 2 feet above the bottom of each well being tested.
  - Once the water level has stabilized to near the static level, a slug with a pre-measured length of cable was then carefully deployed into each well to initiate the "slug-in" test. The water level was again allowed to stabilize to approximately 90% of the static level.
  - Following establishment of approximately 90% of the static water level, the slug was then quickly removed from the well to initiate the "slug-out" test. The water level was then allowed to stabilize to approximately 90% of the static level.
  - At least one slug-in and one slug-out was performed at each of the testing locations.
  - Upon completion of each slug-in/slug-out test, the transducer data was downloaded onto a laptop computer and the transducer and the slug decontaminated for the next testing location.
  - Basic data processing was performed in Microsoft Excel on the downloaded slug test transducer data. Subsequently, the processed data was transferred to a computer equipped with AQTESOLV Pro software, where the hydraulic conductivity associated with each slug test was obtained using the Bouwer-Rice solution.

- **Survey**: following completion of all permeability enhancement and soil confirmation sampling, all new and relevant existing injection and monitoring wells as well as soil confirmation borings were surveyed. Specifically, the horizontal coordinates and vertical elevations at each of the locations of interest were measured to the nearest 0.1 and 0.01 foot, respectively. All measurements were made using the North American Vertical Datum. Details regarding survey activities performed at the three demonstration sites are provided in **Appendix E**.

- **Health and safety**: all field work was performed in accordance with the health and safety plan, subcontractor-specific health and safety plan, and/or accident prevention plan developed for each of the demonstration sites. A health and safety tailgate meeting was held with all field personnel prior to work each day.

- **Investigation-derived waste (IDW) management, characterization, and disposal**: except for GFAFB, where solid (drill cuttings) and aqueous (purged groundwater from sampling and well development and decontamination water) IDW were disposed of onsite, all IDW generated from the permeability enhancement work at MCB-CP and LCAAP was properly containerized pending waste profiling, characterized, and subsequently disposed of offsite.

- **Borehole abandonment**: as appropriate, boreholes were abandoned at the demonstration sites using a combination of medium-sized bentonite chip and grout in accordance with state-specific guidelines and regulations.

- **Quality assurance/quality control (QA/QC) sampling**: QA/QC samples, including trip blanks, field duplicates, and temperature blanks, were collected during baseline and post-enhancement groundwater performance monitoring event at all three demonstration sites. Specifically, field duplicates were collected at a frequency of 10% to evaluate the reproducibility of the sample collection and analytical procedure. A temperature blank was included in each sample cooler sent to the analytical laboratory and a trip blank was included in each sample cooler containing VOC samples to facilitate evaluation of cross-contamination during sample transport. Calibration of field equipment was conducted per manufacturers' instructions or subcontractors' standard operating procedures; calibration of analytical equipment was performed in accordance with the analytical laboratory's quality procedures.

Table 5.1. Well Construction Information at MCB-CP

Well ID	Well Type	Well material	Well ID (inches)	Top of screen (feet bgs)	Bottom of screen (feet bgs)	Slot size	Filter pack type	Annual seal type
1115-HIW-01	Injection well	Sched. 40 PVC	2	28	53	0.02	10/20 silica sand	Type II Portland cement with 5% bentonite powder
1115-HMW-01	Monitoring well	Sched. 40 PVC	2	30	50			
1115-HMW-02	Monitoring well	Sched. 40 PVC	2	30	50			
1115-HMW-03	Monitoring well	Sched. 40 PVC	2	30	50			

Table 5.2. Well Construction Information at LCAAP

Well ID	Well type	Well material	Well ID (inches)	Top of screen (feet bgs)	Bottom of screen (feet bgs)	Screen slot size (inches)	Length of blank PVC below screen (feet)	Filter pack type	Annual seal type
PMW-01*	Monitoring well	Sched. 40 PVC	2	20	35	0.020	5	10/20 silica sand	Type II Portland cement with 5% bentonite powder
PMW-02*	Monitoring well	Sched. 40 PVC	2	20	35		10		
PMW-03*	Monitoring well	Sched. 40 PVC	2	20	35		5		
PMW-04*	Monitoring well	Sched. 40 PVC	2	19	34		5		
HMW-01*	Monitoring well	Sched. 40 PVC	2	15	30		5		
HMW-02*	Monitoring well	Sched. 40 PVC	2	15	30		5		
HMW-03*	Monitoring well	Sched. 40 PVC	2	15	30		5		
PIW-01	Injection well	Sched. 40 PVC	2	20	35		0		
PIW-02	Injection well	Sched. 40 PVC	2	20	35		0		
PIW-03	Injection well	Sched. 40 PVC	2	20	35		0		
HIW-03	Injection well	Sched. 40 PVC	2	15	30		0		

*equipped with ERT electrodes and wires on the outside of well casings

Table 5.3. Well Construction Information at GFAFB

Well ID	Well type	Well material	Well ID (inches)	Top of screen (feet bgs)	Bottom of screen (feet bgs)	Screen slot size (inches)	Length of blank PVC below screen (feet)	Filter pack type	Annual seal type
GFB539-MW15*	Monitoring well	Sched. 40 PVC	2	10	20	0.010	5	10/20 silica sand	Type II Portland cement with 5% bentonite powder
GFB539-MW16*	Monitoring well	Sched. 40 PVC	2	10	20	0.010	5		
GFB539-MW17*	Monitoring well	Sched. 40 PVC	2	10	20	0.010	5		
GFB539-MW18*	Monitoring well	Sched. 40 PVC	2	10	20	0.010	5		
GFB539-MW19*	Monitoring well	Sched. 40 PVC	2	10	20	0.010	5		
GFB539-MW20	Monitoring well	Sched. 40 PVC	2	10	20	0.010	0		
GFB539-MW21	Monitoring well	Sched. 40 PVC	2	10	20	0.010	0		

*equipped with ERT electrodes and wires on the outside of well casings

5.3 MCB-CP SITE 1115

This section discusses the overall objective of the technology demonstration at MCB-CP. In addition, a summary of the technical approach, demonstration design and layout, details pertinent to field activities performed, and notable field observations and performance monitoring/geophysics monitoring results is provided herein.

5.3.1 Overall Objective and Technical Approach

The overall objective for the technology demonstration at MCB-CP was to evaluate the performance of the hydraulic approach to permeability enhancement at a low-permeability site with claystone/siltstone lithology. It should be noted that, originally, the primary contaminant of concern at MCB-CP was thought to be chlorinated solvents and therefore, permeability enhancement for emplacing ZVI and promoting *in situ* chemical reduction was planned. However, pre-mobilization performance monitoring results indicated that benzene, instead of chlorinated solvents, was the primary contaminant of concern in groundwater in the demonstration area. Given the high benzene concentrations observed, alkaline-activated persulfate, instead of ZVI, was selected as the treatment amendment at this site. However, unlike ZVI, persulfate cannot be injected simultaneous with other permeability enhancement reagents such as guar and polymer-based crosslinker, as these organic compounds exert relatively high oxidant demands. Therefore, the overall technical approach for permeability enhancement at MCB-CP was revised to allow for initiation of permeability enhancement with sand to create high-permeability pathways at five depth-discrete intervals between 30 and 50 feet bgs, followed by conversion of the enhancement borehole into an injection well screened across the five depth intervals to facilitate subsequent injections of alkaline-activated persulfate into the sand-propped, high-permeability pathways.

It was estimated that approximately 585 gallons of the fracture fluid consisting of sand and guar would be introduced to each fracture initiation zone to achieve the desired ROI of approximately 25 feet. Following the sand emplacement, the borehole would be completed as a 2-inch PVC injection well that would be screened to encompass all permeability enhancement intervals. At least 48 hours following well installation, well development would be performed to extract as much of the permeability enhancement fluid as attainable. Once developed, approximately 585 gallons of 5% (by weight) persulfate amended with sodium hydroxide would be injected into each enhancement interval, or a total of approximately 3,000 gallons would be injected into the injection well. It should be noted that a bench-scale pH buffering capacity test using site soil and groundwater was performed to determine the amount of sodium hydroxide required to sustain a pH value of approximately 10.5, which is necessary to activate the persulfate. The amount of hydroxide required for the post-enhancement persulfate injection was calculated using results from the bench-scale test, and assuming a 10% porosity and that 1% of the soil was contacted by the permeability enhancement work and subsequent persulfate injection.

5.3.2 Technology Demonstration Design and Layout

The layout of the permeability enhancement technology demonstration at MCB-CP is illustrated in **Figure 5.1**. Specifically, the permeability enhancement initiation point, HIW-01, was positioned such that existing monitoring wells 1115-MW-35 and -MW-37 were located just outside of the anticipated ROI of the permeability enhancement work of 25 feet.

This layout was implemented to reduce the potential risk of damaging the structural integrity of the existing monitoring wells, as they were not completed as typically recommended for permeability enhancement applications. In addition to the existing monitoring wells, three new monitoring wells were constructed by the U.S. Navy subcontractor, IOSDV, to facilitate performance monitoring and evaluation. The new monitoring wells were completed with a grout seal consisting of approximately 5% bentonite powder for additional strength. The new monitoring wells were strategically placed within the 25-foot ROI of permeability enhancement at different distances, as well as upgradient and downgradient relative to the general groundwater flow direction in this area (southwest direction), from the permeability enhancement point to facilitate a rigorous performance assessment of amendment distribution and treatment effectiveness.

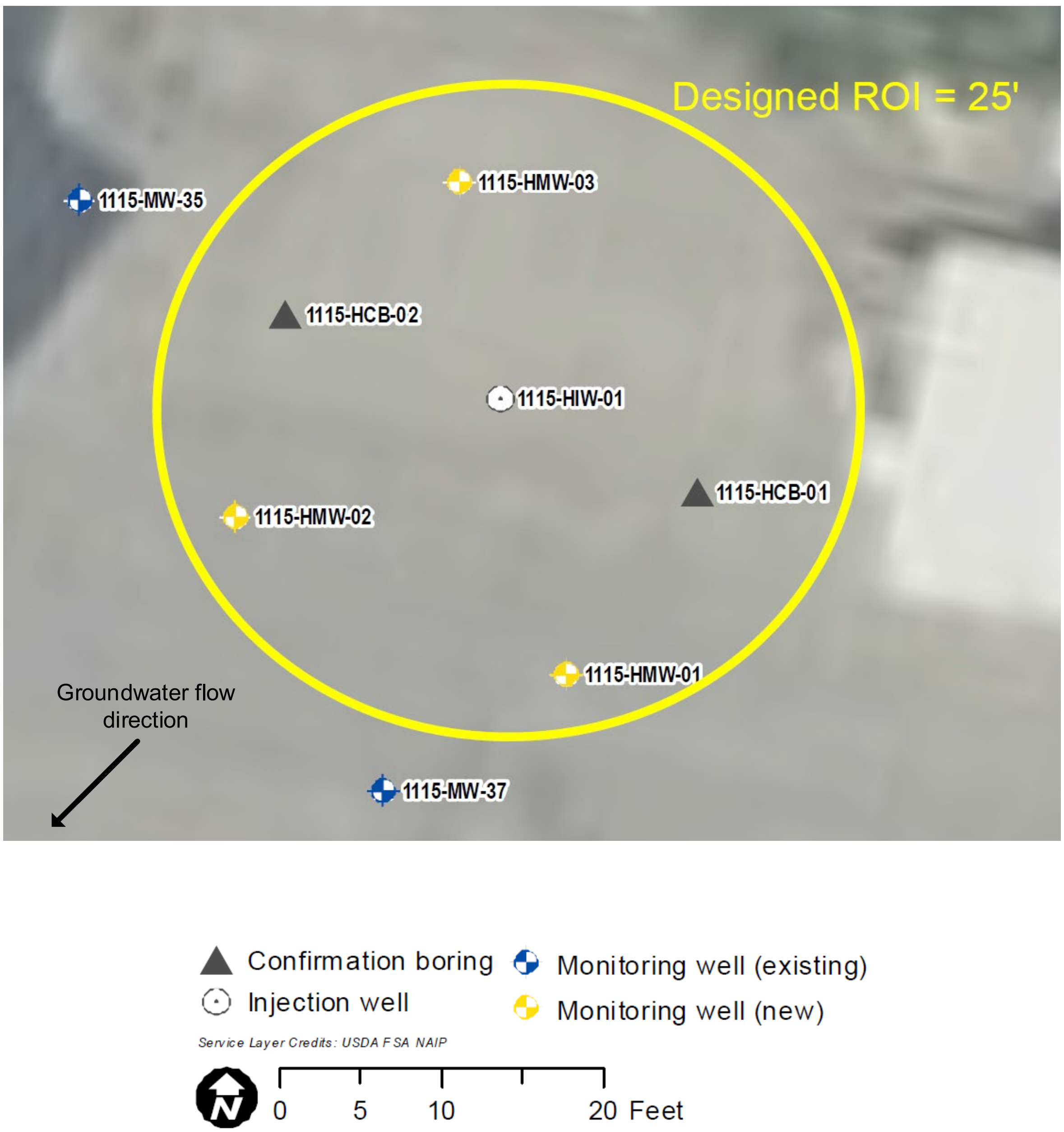

Figure 5.1. Detailed Demonstration Layout at MCB-CP

5.3.3 Baseline sampling

Upon completion of all pre-enhancement soil sampling, and well installation and development activities by IOS-DV, baseline sampling was performed at a number of existing monitoring wells located near the technology demonstration area and at the newly installed monitoring wells using low-stress, low-flow sampling techniques (bladder pumps). The existing monitoring wells were selected because they are located upgradient or downgradient of the demonstration area, screened approximately within the target permeability enhancement intervals, and in some cases, screened below the confining unit of the deepest permeability enhancement intervals to allow for monitoring of vertical impacts from permeability enhancement activities. During baseline sampling, the existing monitoring wells were sampled by IOS-DV whereas the newly installed monitoring wells were sampled by CDM Smith. Following parameter stabilization using a pre-calibrated YSI multi-parameter water quality indicator, formation-representative samples were collected and submitted to an analytical laboratory for analyses of BTEX and sulfate. The collected groundwater samples were also field analyzed for persulfate using a CHEMetrics test kit. The sampling and analysis plan for MCB-CP is presented in **Table 5-4**.

5.3.4 Permeability Enhancement Activities

This section describes field activities that were performed as part of the permeability enhancement technology demonstration at MCB-CP. Specifically, details pertinent to the overall technical approach, aboveground and underground setup, monitoring tools, and post-enhancement confirmation sampling are provided herein. Detailed permeability enhancement reports are presented in **Appendix F**.

5.3.4.1 Aboveground Setup

Frac Rite Environmental Limited's (Frac Rite's) proprietary EF9300 environmental hydraulic permeability enhancement unit was used for the technology demonstration at MCB-CP. The unit is self-contained with power, mixing tanks, and pumps mounted on a single skid. In addition, the EF9300 is outfitted with a high-output triplex pump capable of safely and efficiently pumping high solids, slurries, and reactive agents. A real-time data acquisition system is used to display and record permeability enhancement fluid pumping pressure and pump rate. The aboveground setup of the EF9300 permeability enhancement unit at MCB-CP is illustrated in **Figure 5.2**.

5.3.4.2 Underground Setup

Sonic drilling technology was used to create an open borehole to facilitate permeability enhancement at MCB-CP. A straddle packer assembly was used to isolate the zones of interest for permeability enhancement in a bottom-up emplacement methodology. The sonic drill rig's winch line was used to move the packer system in and out of the borehole. Once emplaced at the deepest depth interval targeted, the packer assembly was inflated to create an isolated zone within the borehole. Once permeability enhancement was initiated and the target permeability enhancement fluid volume was pumped into the zone of interest, the packer assembly was deflated and raised to the next depth, as appropriate.

Table 5.4. Sampling and Analysis Plan at MCB-CP

Well ID	Well Type	Sampling event				Analyte	Analytical method	Sampling method
		Baseline	2 months post-enhancement	5 months post-enhancement	9 months post-enhancement			
1115-HMW-01	Monitoring well (new)	✓	✓	✓	✓	Field parameters VOCs Sulfate Persulfate	YSI EPA 8260B EPA 300.1 Chemetrics	Low-flow with bladder pumps
1115-HMW-02	Monitoring well (new)	✓	✓	✓	✓			
1115-HMW-03	Monitoring well (new)	✓	✓	✓	✓			
1115-MW-35	Monitoring well (existing)	✓	✓	✓	✓			
1115-MW-37	Monitoring well (existing)	✓	✓					
S1-MW13	Monitoring well (existing)	✓	✓					
S1-MW16	Monitoring well (existing)	✓	✓					
S1-MW19	Monitoring well (existing)	✓	✓					
S2-MW5	Monitoring well (existing)	✓	✓					
S5/8/9/17-MW50	Monitoring well (existing)	✓	✓					
S1-MW27	Monitoring well (existing)	✓	✓					
S1-MW28	Monitoring well (existing)	✓	✓					

5.3.4.3 Field Activities

Sonic drilling technology was utilized to create a 6-inch ID borehole to a total depth of 57 feet bgs. Surface casing was installed to approximately 20 feet bgs to prevent borehole sloughing. Following leak testing, the straddle packer assembly with an injection port located between the two packers was lowered to the deepest depth interval targeted for permeability enhancement at 50 feet bgs. Two-inch ID galvanized drop pipes were used to connect to the top of the straddle packer system. It should be noted that the borehole was drilled 7 feet deeper than the deepest depth interval targeted for permeability enhancement to accommodate the bottom packer. Following setup at the deepest depth interval, the packers were inflated to approximately 200 pounds per square inch (psi) with a pressure washer, a wellhead assembly connected to the drop pipe at the surface, and 2-inch ID injection hoses used to connect between the wellhead assembly and the Frac Rite's EF9300 environmental hydraulic permeability enhancement unit.

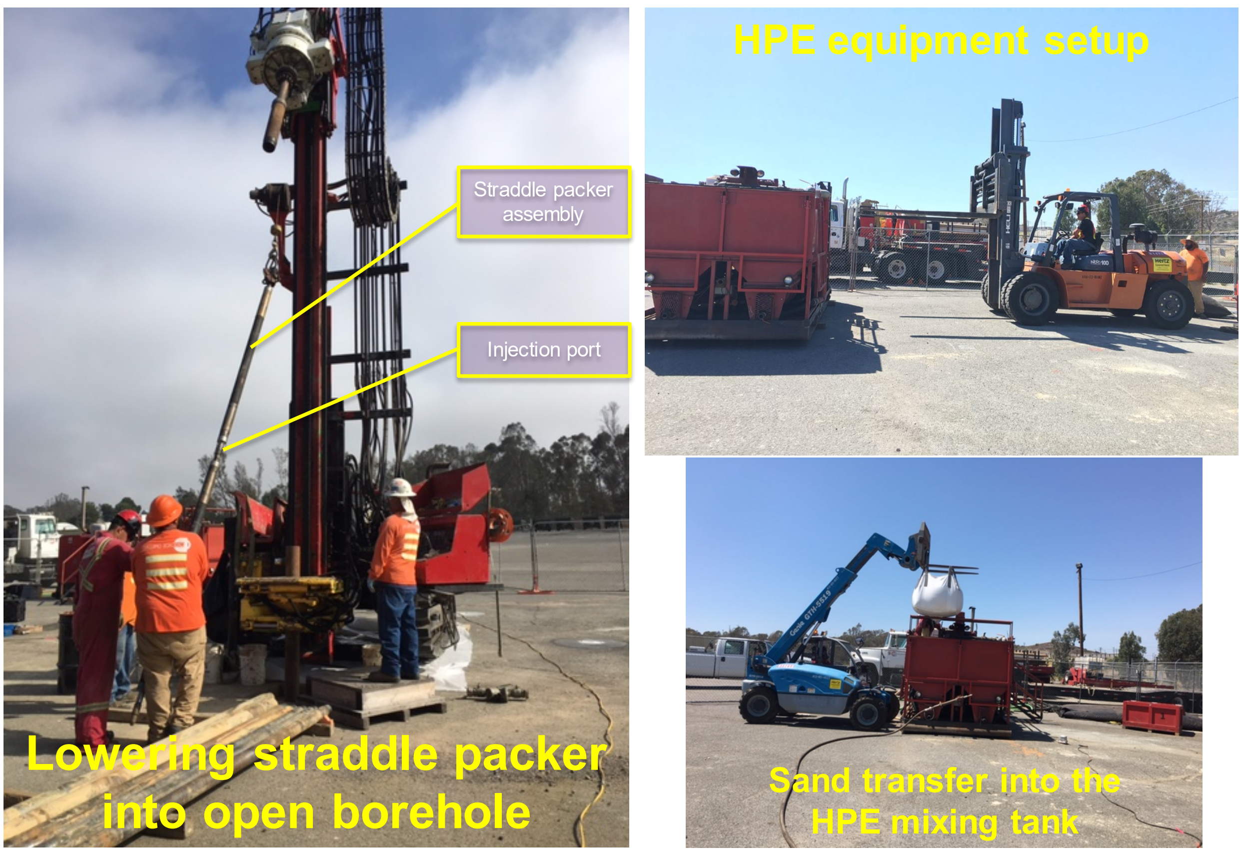

Figure 5.2. Aboveground Setup of Permeability Enhancement at MCB-CP

Permeability enhancement was initiated at each enhancement interval using a proprietary guar solution only. Following confirmation of fracture initiation via real-time monitoring of the injection vs. time curve (an example of which is shown in **Figure 5.3**), 40/50 silica sand was then mixed with the guar solution and a cross-linker added to ensure proper suspension of the solid material in solution. The target volume of the silica sand/guar solution was then introduced to each permeability enhancement interval. Upon achieving the target injection volume, the downhole pressure was monitored and allowed to dissipate before the packers were deflated, the straddle packer assembly was raised to the next depth interval of interest, and the entire procedure repeated.

Tilt meter monitoring was performed at each depth interval of interest during permeability enhancement.

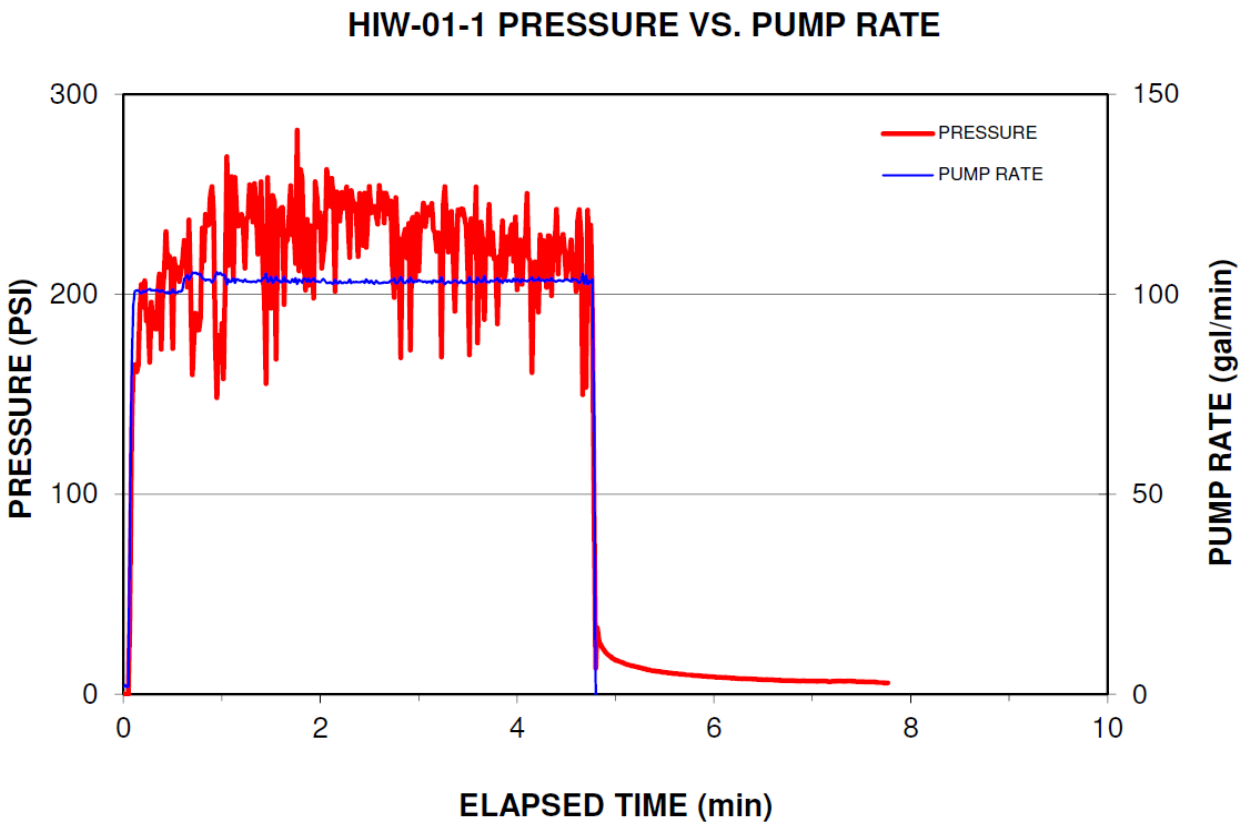

Figure 5.3. Example Injection Pressure and Rate Versus Time Curve During Permeability Enhancement at MCB-CP

Following completion of all permeability enhancement activities, post-enhancement hydraulic characterization was performed as described in **Section 5.2**. Subsequently, sonic drilling technology was utilized to ream out the enhancement borehole and facilitate installation of a 2-inch ID, Schedule 40, PVC injection well screened across all five permeability enhancement intervals. Approximately 48 hours following installation, the injection well was developed using a combination of surging and pumping to remove as much of the added guar solution as possible. The injection well was completed with a flush-mounted surface completion similar to other onsite wells. A slip-to-threaded adapter was installed at the top of the well casing to allow for installation of an injection wellhead assembly.

A Frac Rite's EFI2000 injection unit was used for batch injections of persulfate and sodium hydroxide into the injection well screened within the depth intervals subjected to hydraulic permeability enhancement. A stock solution of concentrated sodium hydroxide was prepared in one tank, whereas a 5% persulfate as sodium persulfate was prepared in another. The sodium hydroxide was injected in line with the persulfate solution rather than being mixed together prior to injection; this approach is used to minimize heat generation. The target injection volume was achieved within approximately 8 hours of injection.

Following the persulfate injection, preliminary tilt meter analysis results were used to guide confirmation sampling locations. Sonic drilling technology was used for continuous collection of soil samples at two locations between 25 and 55 feet bgs. Lithologic logging was performed at both confirmation borings; soil samples were composited every 3 feet and submitted to an analytical laboratory for sulfate analysis. A subset of the composited samples was also collected for field analysis of persulfate using a CHEMetrics test kit. Specifically, approximately 5 grams of soil from each composited sample were added to 20 mL of deionized water, vortexed, centrifuged, and filtered through a 0.45-micron syringe filter, diluted as necessary, and analyzed for persulfate.

Performance monitoring was performed by IOS-DV at select existing monitoring wells and at all newly installed monitoring wells approximately 2, 5, and 9 months following permeability enhancement and persulfate injections. As was done during baseline groundwater sampling, low-stress, low-flow sampling techniques utilizing bladder pumps were employed to facilitate collection of formation-representative samples. Following parameter stabilization monitored using a pre-calibrated multi-parameter water quality meter, the collected groundwater samples were submitted to an analytical laboratory for analyses of BTEX and sulfate. In addition, a subset of the collected samples was field analyzed for persulfate using a CHEMetrics test kit.

5.3.5 Notable Results

Based on field observations, and analytical and geophysics monitoring results, an evaluation of the project-specific performance objectives is provided in **Section 6**. A summary of notable field observations and analytical results with regard to amendment distribution and injection volume, changes in hydraulic conductivity and injectability, changes in geochemical conditions and contaminant profile, and effectiveness of geophysics and other monitoring tools employed at MCB-CP are provided below.

5.3.5.1 Amendment Distribution & Injection Volume

The target injection volume of approximately 590 gallons was achieved at all depth-discrete permeability intervals except for the deepest interval (at approximately 50 feet bgs), where only approximately 240 gallons of silica sand/guar slurry were injected before surfacing was observed. However, the total target injection volume of sand/guar of approximately 2,900 gallons was emplaced. Additional volume was injected into the 46-foot interval to compensate for the lower injection volume emplaced in the 50-foot interval. The emplacement volume is shown in **Table 5-5**. Following enhancement, 40/50 silica sand emplaced during permeability enhancement was visually observed, and elevated persulfate concentrations were detected at several depth-discrete intervals at one of the two confirmation borings guided by preliminary tilt meter analysis results. The target persulfate/sodium hydroxide injection volume of approximately 2,900 gallons was also achieved.

5.3.5.2 Changes in Hydraulic Conductivities and Injectability

Significant increases (up to 2 orders of magnitude) in hydraulic conductivity were observed at the permeability enhancement initiation point, as well as nearby monitoring wells, as illustrated in **Figures 5.4** and **5.5**.

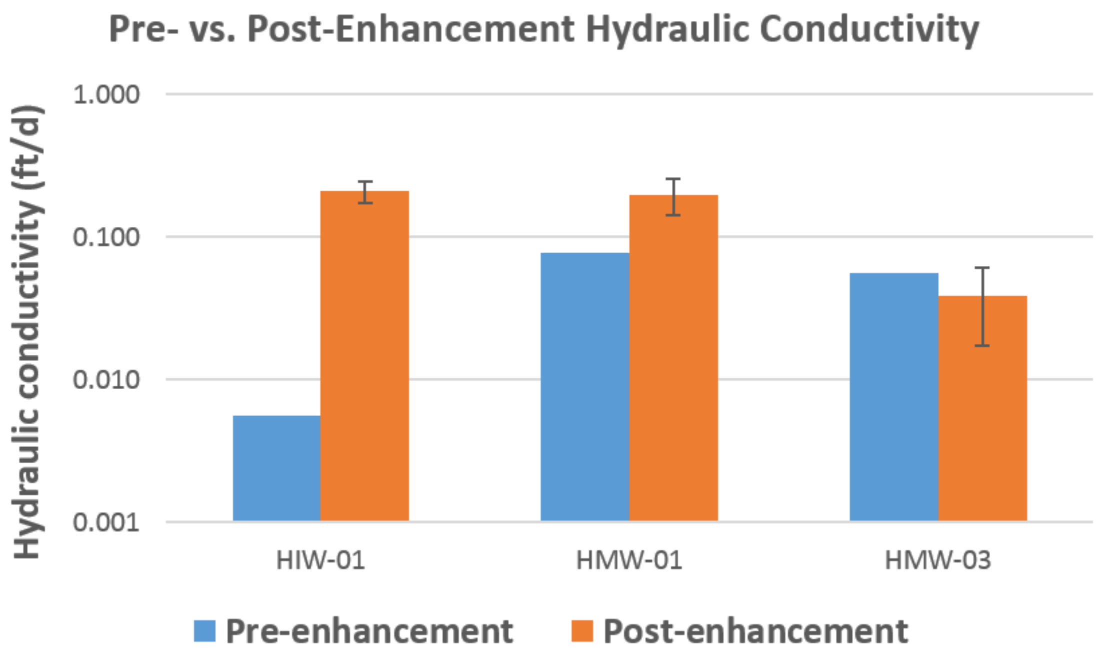

Figure 5.4. Pre- Versus Post-Enhancement Hydraulic Conductivity at MCB-CP

Figure 5.5. Pre- Versus Post-Enhancement Hydraulic Conductivity at MCB-CP (Plan View)

Following permeability enhancement, the target injection volume of approximately 2,900 gallons was introduced into an enhancement borehole that had been converted into an injection well within an approximate 8-hour period. Note that the average injection rate of 6 gpm without any pressure buildup was orders of magnitude higher than what was previously achieved at the site (0.1 gpm).

Table 5.5. Emplacement Volume at MCB-CP

Enhancement initiation point	Enhancement depth (ft bgs)	Volume of solution emplaced (gal)
HIW-01	50	608
HIW-01	46	608
HIW-01	40	608
HIW-01	36	1032
HIW-01	32	238
Total injection volume (gal)		**3095**
Target injection volume (gal)		**2900**

5.3.5.3 Changes in Geochemical Conditions and Contaminant Profile & Estimated ROI

Development of aerobic conditions characteristic of an ISCO injection was observed at monitoring wells located within the anticipated ROI of the permeability enhancement, including 1115-HMW-01 through -03. In addition, elevated sulfate and persulfate concentrations and reduction in BTEX compounds were observed at monitoring wells located within the anticipated ROI of the permeability enhancement. During the last groundwater performance monitoring event performed approximately 9 months following permeability enhancement, elevated persulfate concentrations and reduction in BTEX compounds were also observed at the existing downgradient monitoring wells located outside of the anticipated enhancement ROI. These results indicated that the effective ROI of the permeability enhancement was between approximately 22.5 to 25 feet. Performance monitoring results are tabulated in **Table 5.6** and the time-series plots are graphically depicted in **Figures 5.6** through **5.10**. Changes in persulfate and total BTEX concentrations are also presented in plan views in **Figures 5.11** and **5.12**.

Table 5.6. Summary of Performance Monitoring Results at MCB-CP

Well ID	Sampling date	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	O-xylene (µg/L)	Persulfate (mg/L)	Sulfate (mg/L)	Total sulfate (mg/L)
1115-HMW-01	8/22/2016	140	7.2 J	6.4 J	2.2 J	0.1	606	606
1115-HMW-01	10/6/2016	0.18 J	< 0.24	< 0.14	< 0.23	8400	780	10860
1115-HMW-01	1/18/2017	0.36 J	< 0.47	< 0.28	< 0.46	3800	1300	5860
1115-HMW-01	5/8/2017	0.39 J	< 0.24	< 0.14	< 0.23	3000	1300	4900
1115-HMW-02	8/22/2016	34	0.94 J	2.2	0.29 J	0.1	488	488
1115-HMW-02	10/6/2016	5.4 J	< 4.7	< 2.8	< 4.6	5600	1100	7820
1115-HMW-02	1/18/2017	6	< 0.24	0.91 J	2.1	0.7	680	681
1115-HMW-02	5/8/2017	5	0.37 J	0.19 J	1.6	10	390	402
1115-HMW-03	8/22/2016	150	1.7 J	8.4 J	1 J	0.1	610	610
1115-HMW-03	10/6/2016	0.45 J	< 0.24	< 0.14	< 0.23	7000	650	9050
1115-HMW-03	1/18/2017	0.29 J	< 0.24	< 0.14	< 0.23	112	430	564
1115-HMW-03	5/8/2017	0.93 J	< 0.24	< 0.14	< 0.23	60	460	532
1115-MW-35	8/22/2016	7400	35 J	380	< 10	0.1	247	247
1115-MW-35	10/6/2016	7300	77	610	27 J	0	110	110
1115-MW-35	1/18/2017	8700	70	530	28 J	0.7	100	101
1115-MW-35	5/8/2017	8000	86	470	52	0	110	110
1115-MW-37	8/22/2016	10000	1100	480	310	0.1	230	230
1115-MW-37	10/6/2016	8800	1200	410	350	0	80	80
1115-MW-37	1/18/2017	9500	480	400	170	56	230	297
1115-MW-37	5/8/2017	7700	190	290	64	600	530	1250

Table 5.6. Summary of Performance Monitoring Results at MCB-CP (Continued)

Well ID	Sampling date	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	O-xylene (µg/L)	Persulfate (mg/L)	Sulfate (mg/L)	Total sulfate (mg/L)
S1-MW13	8/23/2016	2.4	< 0.24	< 0.14	1.1	0.1	140	140
S1-MW13	10/6/2016	3.5	< 0.24	< 0.14	0.79 J	6	160	167
S1-MW16	8/23/2016	0.78 J	< 0.24	< 0.14	< 0.23	0.1	130	130
S1-MW16	10/6/2016	120	8.6	1.4	2.3	#N/A	110	#N/A
S1-MW16	1/19/2017	540	12	2.9 J	31	#N/A	#N/A	#N/A
S1-MW19	8/23/2016	5.1	0.42 J	< 0.14	< 0.23	0.1	320	320
S1-MW19	10/6/2016	4.2	0.35 J	< 0.14	< 0.23	0.7	280	281
S1-MW27	8/23/2016	1.3	< 0.24	< 0.14	< 0.23	0.1	1900	1900
S1-MW27	10/6/2016	2.2	< 0.24	< 0.14	< 0.23	0.7	2100	2101
S1-MW28	8/23/2016	< 0.14	< 0.24	< 0.14	< 0.23	0.1	1900	1900
S1-MW28	10/6/2016	< 0.14	< 0.24	< 0.14	< 0.23	1	1800	1801
S2-MW5	8/23/2016	< 0.14	< 0.24	< 0.14	< 0.23	0.1	280	280
S2-MW5	10/6/2016	< 0.14	< 0.24	< 0.14	< 0.23	#N/A	250	#N/A
S5/8/9/17-MW50	8/23/2016	3.8	0.41 J	0.2 J	3.3	0.1	260	260
S5/8/9/17-MW50	10/6/2016	2.6	0.28 J	< 0.14	4	7	220	228

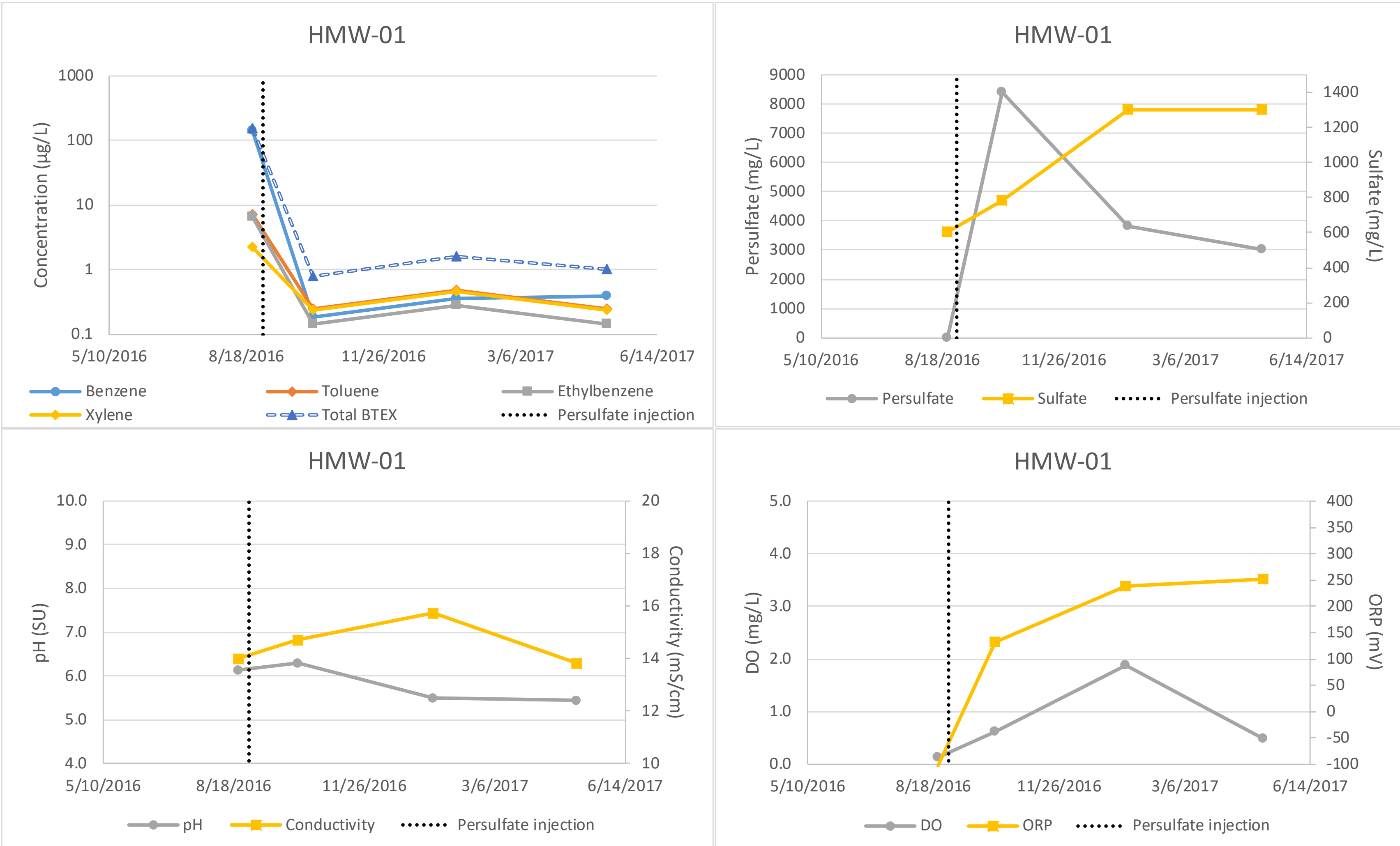

Figure 5.6. Trend Charts – 1115-HMW-01

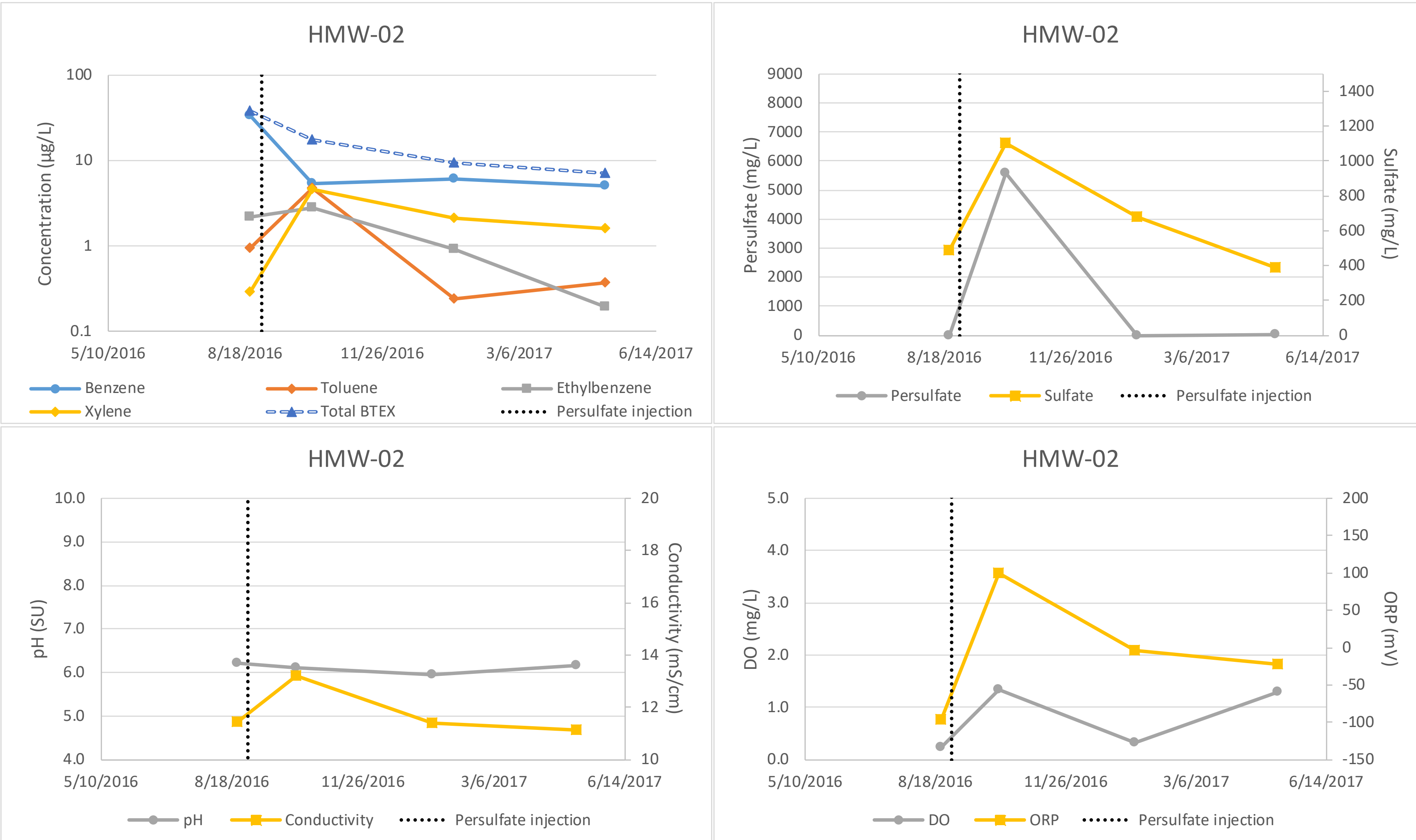

Figure 5.7. Trend Charts – 1115-HMW-02

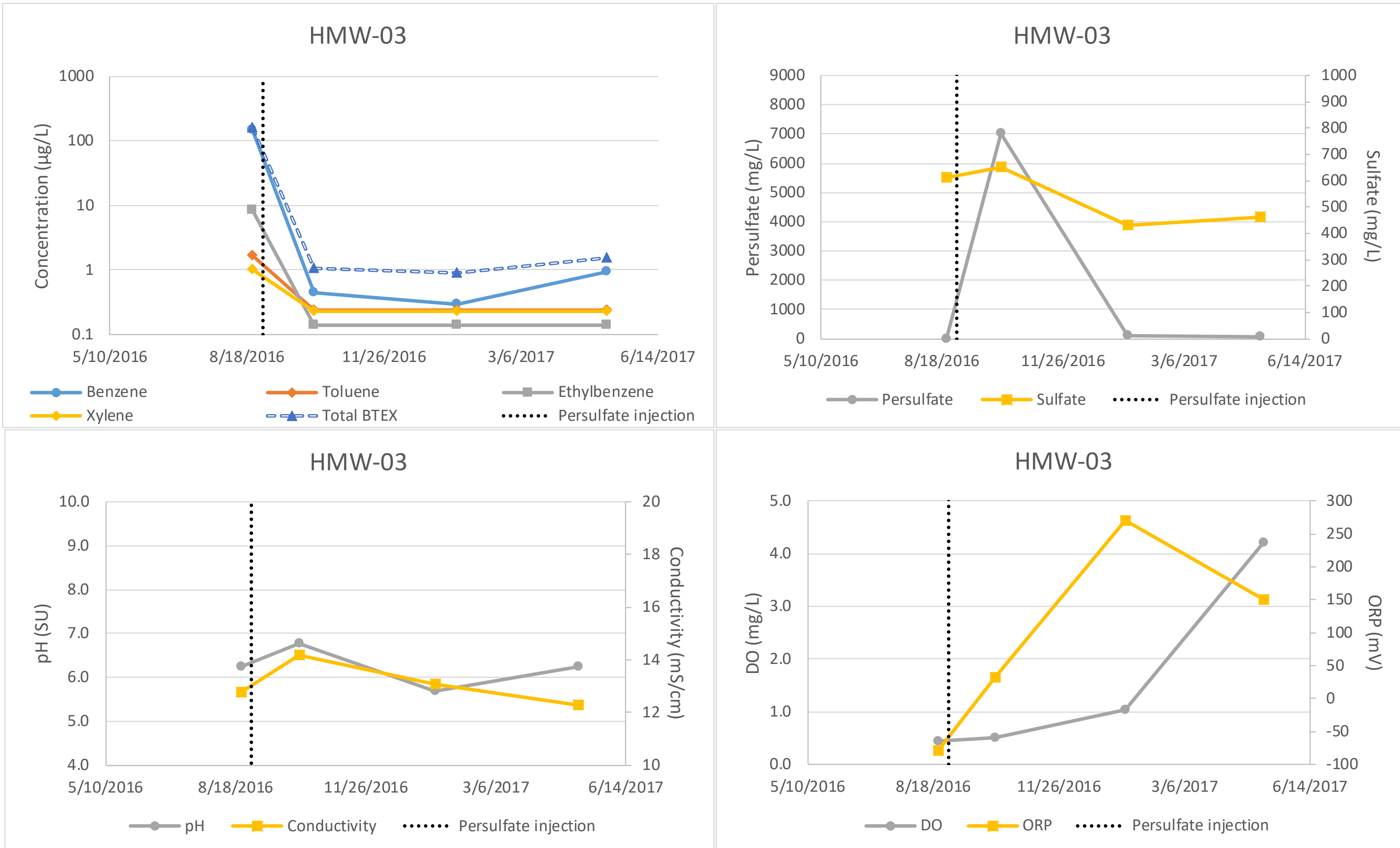

Figure 5.8. Trend Charts – 1115-HMW-03

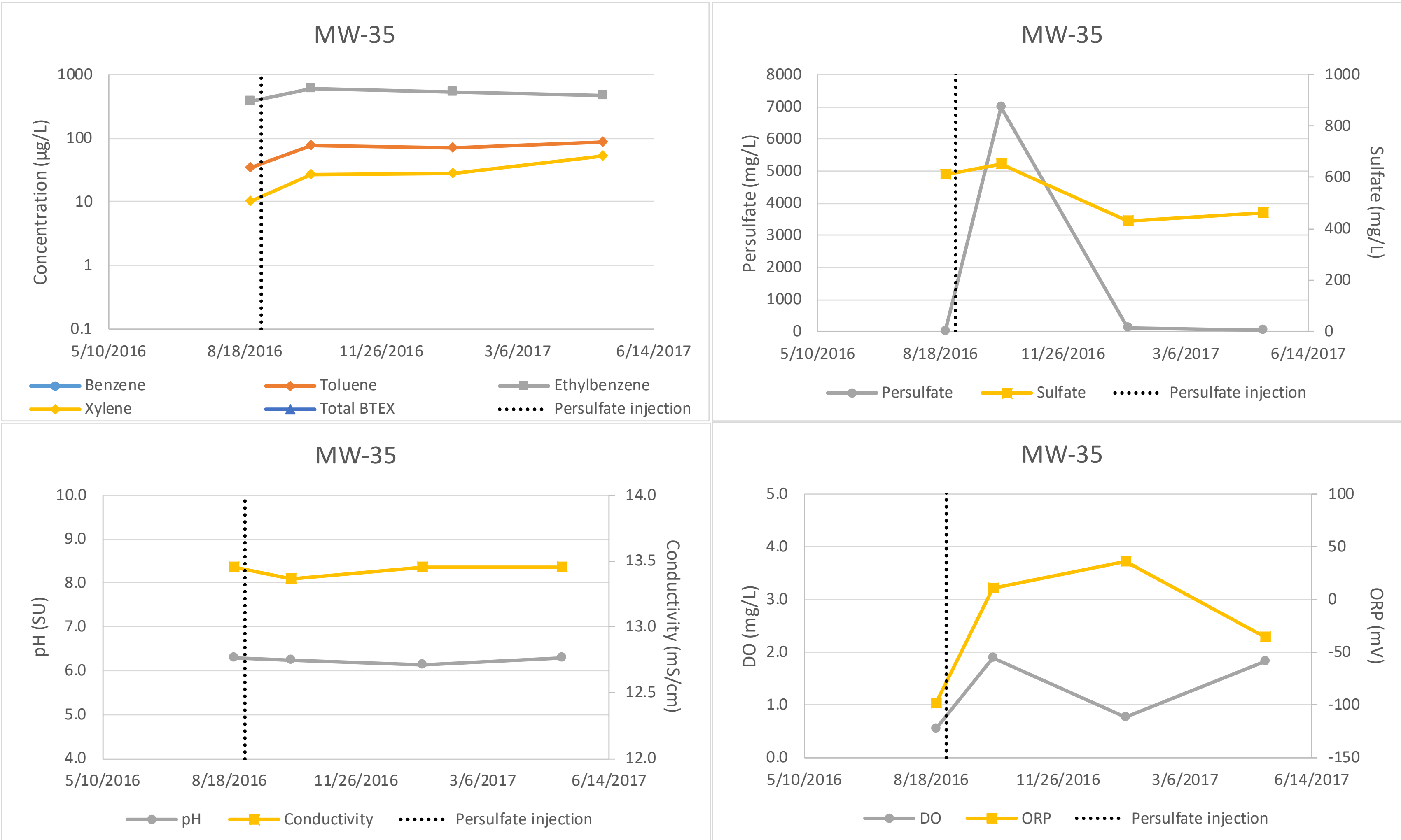

Figure 5.9. Trend Charts – 1115-MW-35

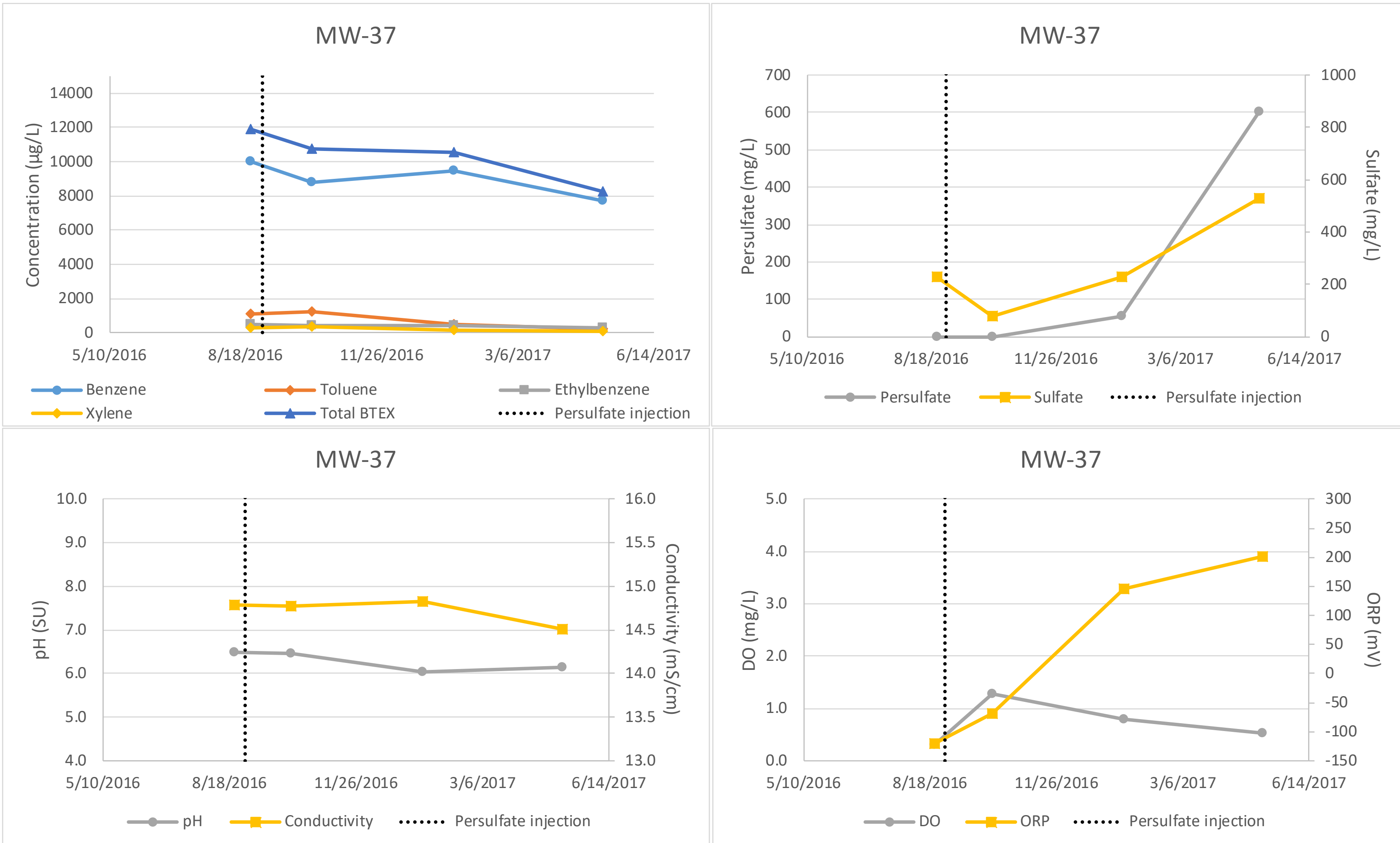

Figure 5.10. Trend Charts – 1115-MW-37

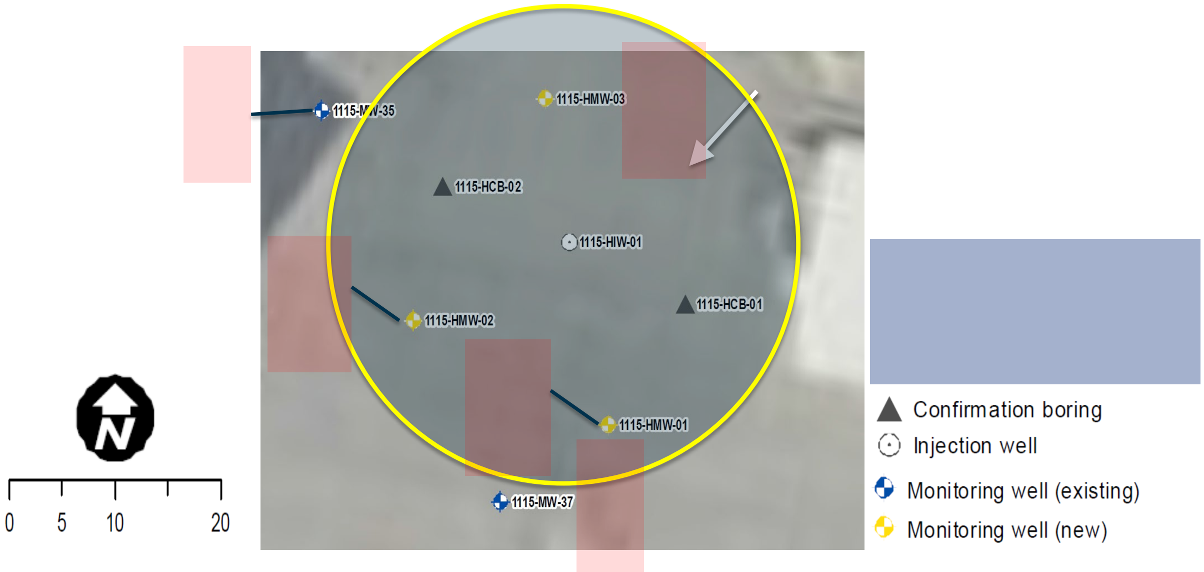

Figure 5.11. Changes in Persulfate Concentrations at MCB-CP (Plan View)

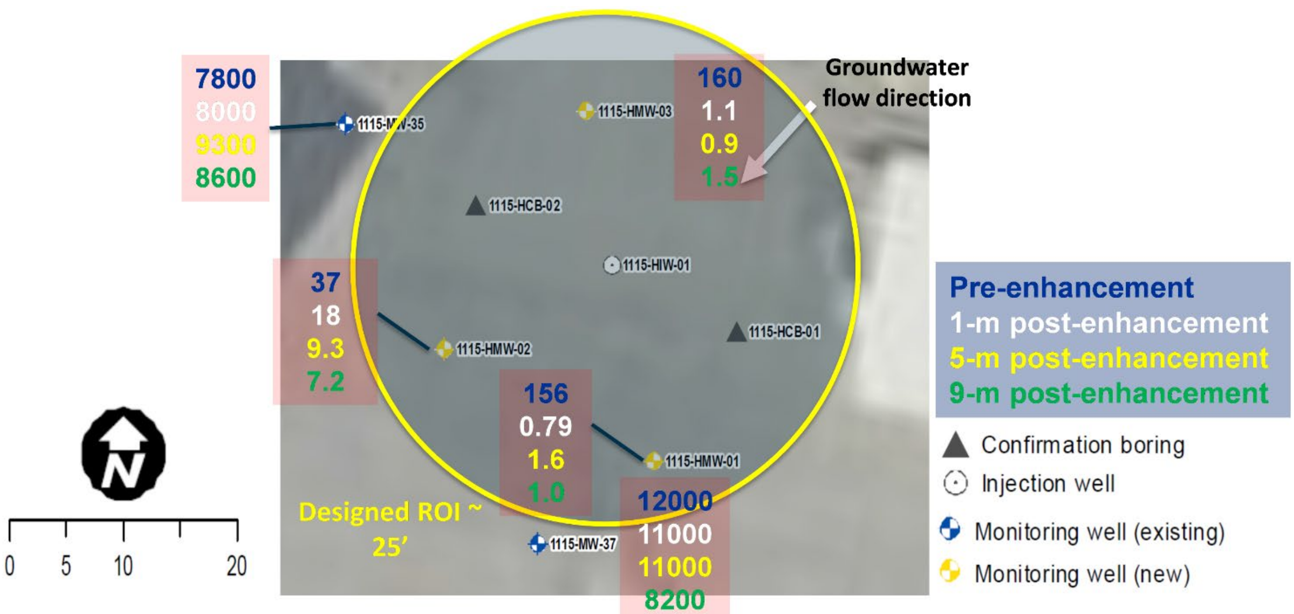

Figure 5.12. Changes in BTEX Concentrations at MCB-CP (Plan View)

5.3.5.4 Effectiveness of Geophysics and Other Monitoring Tools

Data obtained during tilt meter monitoring were used to generate 3D visualizations to graphically illustrate the vertical and horizontal extent of the fracture network initiated by the permeability enhancement at MCB-CP as shown in **Figure 5.13**.

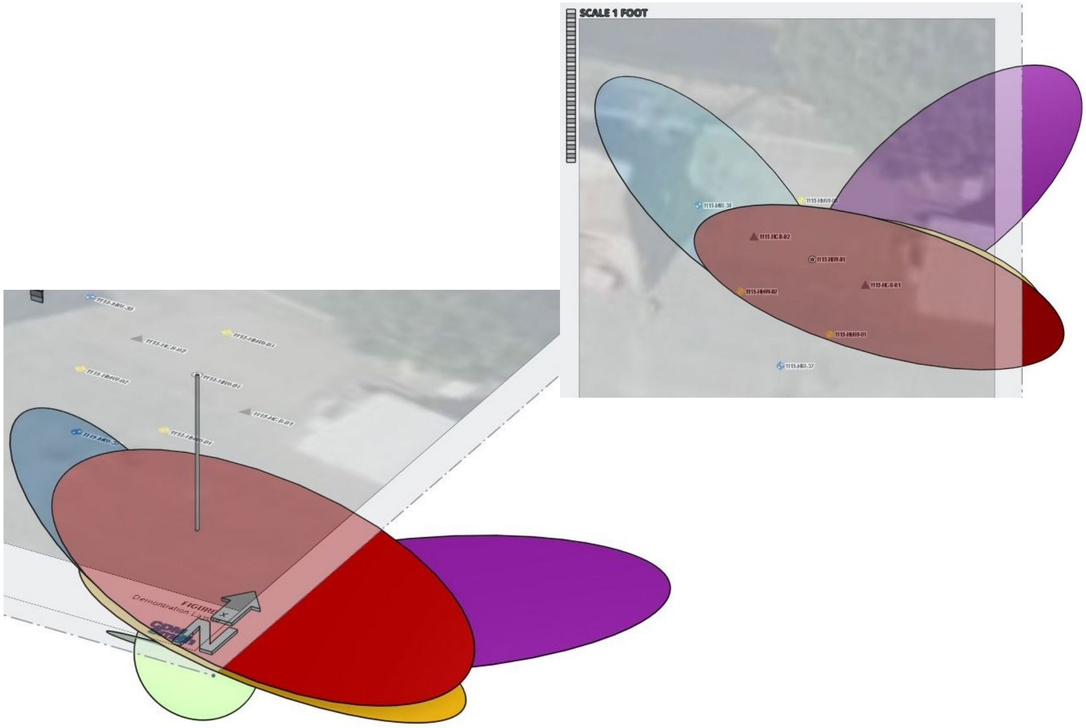

Figure 5.13. 3D Visualization of the Fracture Network at MCB-CP

The frequency distribution of fracture dip angles for the hydraulic permeability enhancement demonstration at MCB-CP is presented in **Figure 5.14**. All of the initiated fractures monitored using tilt meters were primarily horizontal with dip angles equal to or less than 50 degrees. Note that four of the six monitored fractures were very horizontal with dip angles equal to or less than 30 degrees.

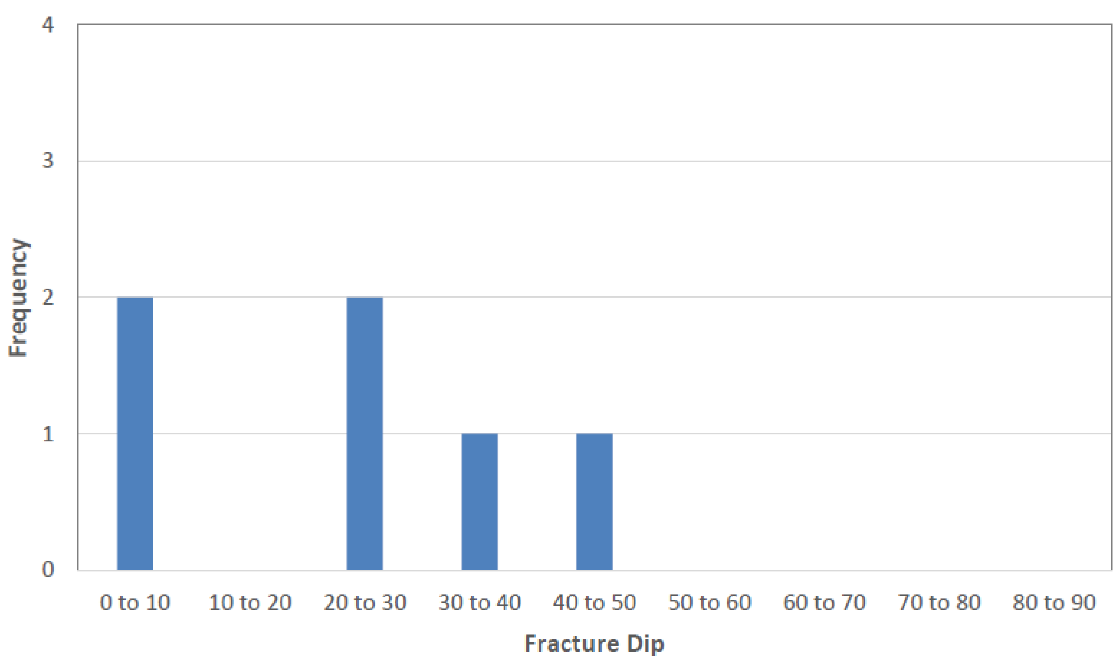

Figure 5.14. Distribution of Fracture Dip Angles at MCB-CP

In addition, tilt meter data were modeled to predict if and at which depth intervals the fracture network would intercept the nearby confirmation boreholes HCP-01 and HCP-02. Results of this modeling exercise, presented in **Table 5.7**, were subsequently correlated with the actual depth-discrete intervals where visual observations or analytical verification of emplaced materials were observed at the post-enhancement confirmation boreholes. The strong correlation between the predicted and the actual depths intervals influenced by permeability enhancement at CP indicated that tilt meter monitoring is an effective geophysical monitoring tool for visualization of the extent of the fracture network as well as to predict the impacted depth-discrete intervals at any given location.

Table 5.7. Predicted Fracture-Intercepting Depths at MCB-CP

Confirmation borehole	Predicted Intercept depth (ft bgs)	Originating enhancement location	Frac Rite's comments
1115-HCB-01	NI*	HIW-01-1	
	45.5	HIW-01-1 (conjugate)	Completely intercepts but near the edge of the fracture
	NI*	HIW-01-2b	
	40.5	HIW-01-4	Completely intercepts
	37.8	HIW-01-5	Completely intercepts
	28.5	HIW-01-6	Completely intercepts
1115-HCB-02	NI*	HIW-01-1	
	53.8	HIW-01-1 (conjugate)	Completely intercepts but near the edge of the fracture
	40.2	HIW-01-2b	Completely intercepts
	NI*	HIW-01-4	
	38	HIW-01-5	Completely intercepts
	26.8	HIW-01-6	Completely intercepts

* NI = not intercepting

5.4 LCAAP SITE 17D

This section discusses the overall objective of the technology demonstration at LCAAP. In addition, a summary of the technical approach, demonstration design and layout, details pertinent to field activities performed, and notable field observations and performance monitoring/ geophysics monitoring results is provided herein.

5.4.1 Overall Objective and Technical Approach

The overall objective for the technology demonstration at LCAAP was to directly compare the hydraulic and the pneumatic approach to permeability enhancement at a low-permeability site. A secondary objective was to compare these novel injection approaches to the conventional injection techniques previously implemented at the site – namely, using a series of permanent, 2-inch ID, Schedule 40, PVC injection wells for gravity-fed injection of a soluble amendment. Because this site has a low permeability, injectability using the conventional approach has been very limited.

A side-by-side comparison between the hydraulic and the pneumatic approach to permeability enhancement was performed at LCAAP. For pneumatic permeability enhancement, nitrogen gas was planned for fracture initiation as well as aerosolizing and subsequent delivery of the injection solution in three separate permeability enhancement boreholes. For hydraulic permeability, amendment injection was to be delivered via a single permanent injection well where 40/50 silica emplacement had previously been implemented, similar to MCB-CP. For both demonstrations, an injection solution consisting of approximately 3% LactOil® and 7,500 mg/l of potassium chloride (KCl) was used. The former was intended to promote bioremediation of chlorinated solvents present in site groundwater, whereas the latter was added to create the conductivity contrast between the injection solution and background conductivity for proper ERT monitoring. For both demonstrations, the same treatment depth interval of approximately 20 to 35 feet bgs was targeted and an injection volume of approximately 2,900 gallons was desired. The anticipated ROIs for the pneumatic and the hydraulic approach to permeability enhancement were 10 and 25 feet, respectively.

5.4.2 Technology Demonstration Design and Layout

The layout of the permeability enhancement technology demonstration at LCAAP is illustrated in **Figure 5.15**. For the pneumatic permeability enhancement demonstration, the layout was designed to include three initiation points, PIW-01 through -03, each with an anticipated ROI of 10 feet, and four monitoring wells located within or immediately outside of the anticipated ROI including PMW-01 through -04. The pneumatic demonstration cell was laid out such that existing monitoring wells, including 16MW76 and 16MW77, would be located immediately downgradient of the permeability enhancement to avoid damages to the structural integrity of these wells from the high-pressure injections. It should be noted that while 16MW76 is screened within the target treatment depth, 16MW77 is screened much deeper but was included in the monitoring network to assess potential downward contaminant migration due to permeability enhancement.

Originally, the hydraulic demonstration cell was to be located between existing monitoring wells 16MW76/77 and 16MW103; this original layout was based on a map that inaccurately depicted the location of a dirt road. This inaccuracy was not realized until utility location was performed at the site; therefore, the hydraulic demonstration cell had to be relocated to downgradient of the existing monitoring well 16MW103. Unlike the pneumatic demonstration cell, a larger ROI of 25 feet was planned for the hydraulic permeability enhancement demonstration at LCAAP. Three additional monitoring wells were installed at various distances from the original permeability enhancement initiation point HIW-01 to facilitate performance monitoring and evaluation.

It should be noted that all new monitoring wells were equipped with electrodes and wires throughout the well casings and wires for ERT monitoring. In addition, several of the new monitoring wells were also equipped with blank casings at the bottom of each well screen to accommodate ERT monitoring. Originally, each new monitoring well was to be equipped with 10 feet of blank casing. However, the amount of blank casing had to be reduced given the difficult drilling conditions encountered below approximately 30 feet bgs. The total well depth and screen placement for new monitoring wells within the hydraulic demonstration cell had to be similarly adjusted. Details pertinent to the well construction are provided in **Table 5.2**. The monitoring well networks for both the hydraulic and pneumatic demonstration cells were also configured to best facilitate ERT testing. Specifically, ERT measurement sequences are generally composed of a large number of four electrode measurements. For each single measurement, a current is injected into two electrodes and the change in potential between the two receiving electrodes is recorded.

As the distance between the current injection increases, the resolution of the monitoring method decreases. An aspect ratio, defined as the total depth of imaging divided by the horizontal distance between well, of 0.75 or less is often recommended. Therefore, if a monitoring well is equipped with ERT electrodes throughout its casings and screens to a depth of 30 ft bgs, the optimal horizontal distances among the monitoring wells where ERT is most effective is 22.5 ft or less.

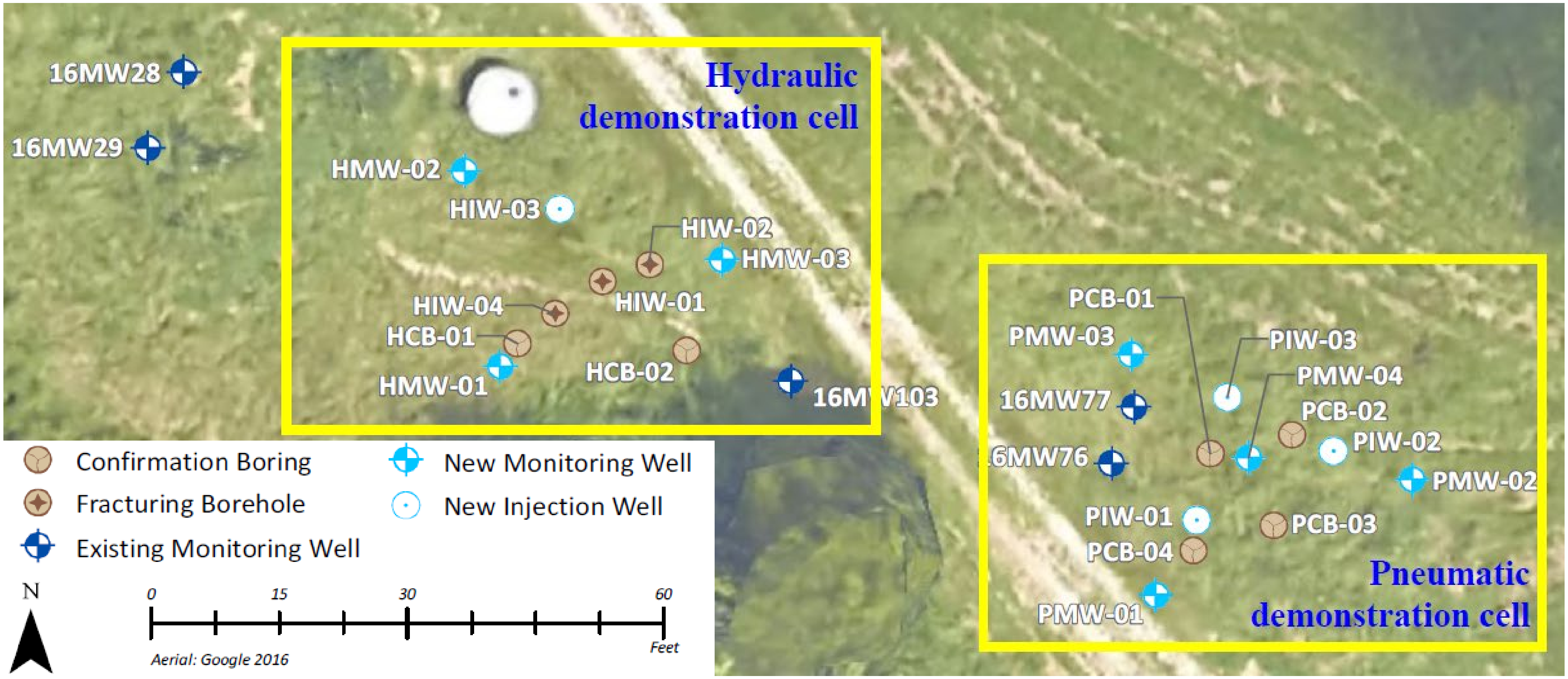

Figure 5.15. Demonstration Layout at LCAAP

5.4.3 Baseline sampling

Upon completion of all pre-enhancement soil sampling for total organic carbon (TOC), and installation and development activities, baseline groundwater sampling was performed at a number of existing monitoring wells located near the technology demonstration area and at the newly installed monitoring wells using HydraSleeves, which is a technique that has been used historically at the site. The existing monitoring wells were selected because they are located within, upgradient, or downgradient of the demonstration area; screened approximately within the target permeability enhancement intervals of between approximately 20 and 35 feet bgs; and in some cases, screened below the confining unit of the deepest permeability enhancement intervals to allow for monitoring of possible vertical migration. The HydraSleeves were deployed for approximately 24 hours prior to retrieval and sample collection in accordance with manufacturer-provided recommendations. A pre-calibrated YSI multi-parameter water quality indicator was used to obtain basic geochemical measurements whereas samples were submitted to an analytical laboratory for analyses of VOCs, methane, ethane, and ethene (MEE), TOC, and anions. The collected groundwater samples were also analyzed for ferrous iron using a HACH® spectrophotometer. The sampling and analysis plan for LCAAP is presented in **Table 5.8**.

5.4.4 Hydraulic Permeability Enhancement Activities

This section describes field activities that were performed as part of the hydraulic permeability enhancement technology demonstration at LCAAP. Specifically, details pertinent to the aboveground and underground setup, monitoring tools, post-enhancement confirmation sampling, and post-enhancement groundwater performance monitoring the hydraulic permeability enhancement demonstration at the site are provided below.

5.4.4.1 Aboveground Setup

The same EF9300 environmental hydraulic permeability enhancement unit used at MCB-CP was employed to facilitate hydraulic permeability enhancement at LCAAP. Unlike MCB-CP, a Geoprobe® 7822DT direct-push/hollow-stem auger rig was used to facilitate all drilling and permeability enhancement activities. Permeability enhancement was performed using both a top-down and a bottom-up emplacement methodology in the hydraulic demonstration cell. It should be noted that that the top down approach without packer-assisted depth isolation was planned originally. The bottom-up emplacement approach was utilized at one of the enhancement locations following repeated observations of amendment surfacing using the top down method. A wellhead assembly was installed at the top of the Geoprobe drill rod or drop pipe during top-down or bottom-up permeability enhancement, respectively, at the surface to allow for connection between the EF9300 injection skid and the downhole tooling/straddle packer system. The aboveground setup of the EF9300 permeability enhancement unit at LCAAP is illustrated in **Figure 5.16**.

Table 5.8. Sampling and Analysis Plan at LCAAP

Well ID	Area	Well type	Sampling event			Analyte	Analytical method	Sampling method
			Baseline	1 months post-enhancement	6 months post-enhancement			
PMW-01	Pneumatic	New monitoring well	✓	✓	✓	Field parameters VOCs TOC MEE Anions Ferrous iron	YSI EPA 8260B EPA 9060 RSK 175 EPA 300.1 HACH	HydraSleeves
PMW-02	Pneumatic	New monitoring well	✓	✓	✓			
PMW-03	Pneumatic	New monitoring well	✓	✓	✓			
PMW-04	Pneumatic	New monitoring well	✓	✓	✓			
16MW076	Pneumatic	Existing monitoring well	✓	✓	✓			
16MW077	Pneumatic	Existing monitoring well	✓	✓	✓			
16MW103	Hydraulic	Existing monitoring well	✓	✓	✓			
HMW-01	Hydraulic	New monitoring well	✓	✓	✓			
HMW-02	Hydraulic	New monitoring well	✓	✓	✓			
HMW-03	Hydraulic	New monitoring well	✓	✓	✓			
16MW028	Hydraulic	Existing monitoring well	✓	✓	✓			
16MW029	Hydraulic	Existing monitoring well	✓	✓	✓			

5.4.4.2 Underground Setup

During hydraulic permeability enhancement using the top-down emplacement methodology, direct-push drilling technology was used for the underground setup at LCAAP. Specifically, standard Geoprobe 2¼-inch ID drill rods were used to drive the proprietary permeability enhancement tooling to the desired fracture initiation depth interval. The downhole tooling is designed to isolate a small vertical zone within the borehole. Hydraulic permeability enhancement, using this emplacement methodology, was implemented from the shallowest to the deepest target interval. On the other hand, when the bottom-up emplacement methodology was used within the hydraulic permeability enhancement demonstration cell, auger drilling technology was used to create an open borehole. Subsequently, a straddle packer assembly was used to isolate the zones of interest for permeability enhancement. The drill rig's winch line was used to move the packer system in and out of the borehole. Once emplaced at the deepest depth interval targeted, the packer assembly was inflated to create an isolated zone within the borehole. Once permeability enhancement was initiated and the target permeability enhancement fluid volume was pumped into the zone of interest, the packer assembly was deflated and raised to the next depth, as appropriate.

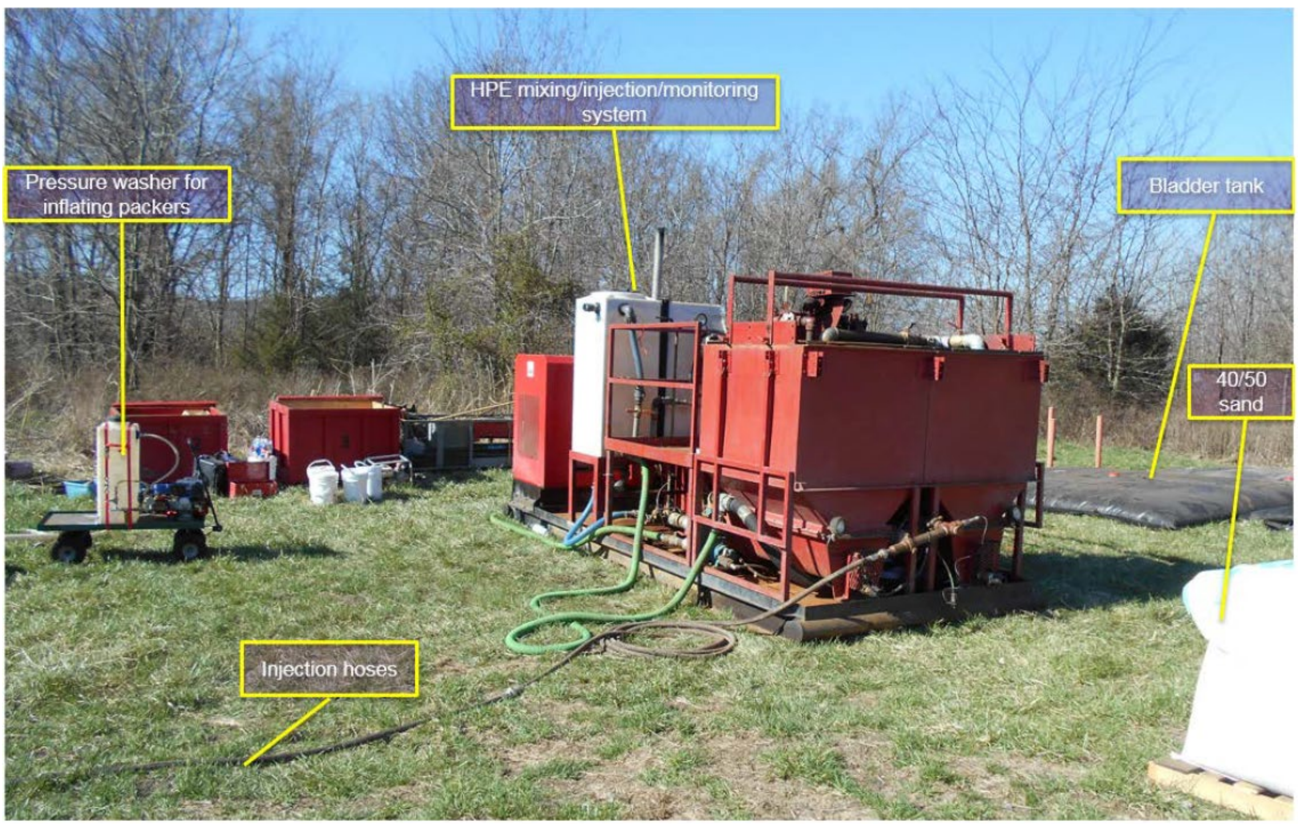

Figure 5.16. Aboveground Setup of Hydraulic Permeability Enhancement at LCAAP

5.4.4.3 Field Activities

Prior to commencement of any permeability enhancement activities, pre-enhancement ERT surveys were conducted to establish the baseline "image". DPT was first utilized to facilitate top-down emplacement of 40/50 silica sand suspended in a high-viscosity fluid system within the hydraulic demonstration cell. Top-down emplacement methodology was used to ensure a discrete fracture was initiated at each depth. Specifically, permeability enhancement was first initiated at the shallowest depth interval of interest of approximately 16 feet bgs at the permeability enhancement initiation point HIW-01 using a proprietary guar solution only. Following confirmation of fracture initiation via real-time monitoring of the injection vs. time curve, 40/50 silica sand was then mixed with the guar solution and a cross-linker added to ensure proper suspension of the solid material in solution throughout the injection process. Upon achieving the target injection volume of 580 gallons per enhancement interval, or following visual observations of significant amendment surfacing, the downhole pressure was allowed to dissipate. Subsequently, the wellhead assembly was removed and the downhole tooling advanced to the next depth interval of interest. Tilt meter monitoring was performed at each of the five depth-discrete intervals targeted for permeability enhancement at HIW-01.

It should be noted that significant amendment surfacing was observed at each depth interval targeted for permeability enhancement at HIW-01. Therefore, the target injection volume of 580 gallons was not achieved at any interval within this permeability enhancement initiation point as shown in **Table 5.9**. Because the DPT approach did not achieve the target volumes, the HSA based bottom-up method was used at a nearby borehole HIW-02. Similar to MCB-CP, hollow-stem auger drilling technology was utilized to create a 6-inch ID borehole to a total depth of 37 feet bgs. Following leak testing, the straddle packer assembly, with an injection port located between the two packers, was lowered to the deepest depth interval targeted for permeability enhancement at approximately 30 feet bgs. Two-inch ID galvanized drop pipes were used to connect to the top of the straddle packer system. It should be noted that the borehole was drilled 7 feet deeper than the deepest depth interval targeted for permeability enhancement to accommodate the bottom packer. Following setup at the deepest depth interval, the packers were inflated to approximately 200 psi with a pressure washer, a wellhead assembly connected to the top drop pipe at the surface, and 2-inch ID injection hoses used to connect between the wellhead assembly and the Frac Rite's EF9300 environmental hydraulic permeability enhancement unit.

Table 5.9. Emplacement Volume at LCAAP

Borehole ID	Depth interval (feet bgs)	Amount of sand injected (gallons)	Amount of guar added (gallons)	Total slurry volume added (gallons)
HIW-01	16	174	26	201
	21	21	34	55
	24	91	41	132
	26	291	62	353
	30	144	33	177
	32	26	26	53
HIW-02	18	132	13	145
	22	13	13	26
	26	53	13	66
	30	264	13	277
HIW-03	29.5	264	40	304
	20	26	13	40
HIW-04	25	159	26	185
Total injection volume (gallons)				**2014**
Target injection volume (gallons)				**2900**

Upon achieving the target injection volume or following visual observations of amendment surfacing, the downhole pressure was allowed to dissipate before the packers were deflated, straddle packer assembly raised to the next depth interval of interest, and the entire procedure repeated. It should be noted that, similar to the top-down emplacement approach, amendment surfacing was also observed during permeability enhancement using the bottom-up emplacement approach aided by the straddle packer assembly, and the target injection volume of 580 gallons per enhancement interval was not achieved in any of the intervals in HIW-02.

Because of this, two additional fracture initiation boreholes were installed in an effort to achieve emplacement of target volumes. Specifically, permeability enhancement was then performed at HIW-03 and HIW-04 at 29.5 and 25 feet bgs, respectively, using the top-down emplacement methodology. Similar to other enhancement initiation points, amendment surfacing was observed during implementation of the high-pressure injections at HIW-03 and HIW-04. Note that despite the difficulty experienced during hydraulic permeability enhancement, approximately 70% of the target emplacement volume was achieved at LCAAP, as shown in **Table 5.9**.

Following completion of all permeability enhancement activities, hollow-stem auger drilling technology was utilized to ream out the enhancement borehole HIW-03 and to install a 2-inch ID, Schedule 40, PVC injection well. Note that HIW-01 was intended to be converted into an injection well because the highest emplacement volume was achieved at this location, but metal objects were encountered during the borehole rimming process. HIW-02, the borehole with the second highest emplacement volume, was completely dry. HIW-03 was screened between 15 and 30 ft bgs to encompass all depth intervals subject to hydraulic permeability enhancement. Approximately 48 hours following installation, the injection well was developed using a combination of surging and pumping to remove as much of the added guar solution as possible.

The injection well was completed with a flush-mounted surface completion similar to other onsite wells. A slip-to-threaded adapter was installed at the top of the well casing to allow for installation of an injection wellhead assembly.

A Frac Rite EFI2000 injection unit was used to perform batch injections of LactOil® and KCl into the injection well. Approximately 2,900 gallons (representing a 25-foot injection ROI) of approximately 3% LactOil® and 7,500 mg/l of KCl were injected into the injection well HIW-03 in 15 separate batches. Potable water from a nearby water source was used to prepare the injection solution. The appropriate volume of potable water was first added to the poly tank. Subsequently, the propeller located on the bottom of the poly tank was turned on to mix the added amendments. The appropriate volume of LactOil® was then added to mixing tank using a plastic, battery-powered, submersible pump followed by addition of KCl through the top opening of the mixing tank. Following additions of all chemical reagents, the solution was mixed for approximately 10 minutes to allow for complete solubilization of the KCl and homogenization of all added amendments. The target injection volume was achieved within approximately 12 hours of injection. It should be noted that initially, relatively high injection rates were achieved with minimal pressure buildup. However, as the injection solution surfaced through the well seal following completion of the first five injection batches, the injection rate had to be reduced significantly.

Upon completion of all injection activities, post-enhancement ERT surveys and post-enhancement soil confirmation sampling were performed. Additionally, preliminary tilt meter analysis results were used to guide confirmation sampling locations. DPT was employed for the continuous collection of soil samples using dual tubes at two confirmation borings located within the anticipated ROI of the hydraulic permeability enhancement. Lithologic logging was performed, and soil samples were composited every foot between approximately 20 and 35 feet bgs and submitted to an analytical laboratory for total organic carbon (TOC) analysis. Post-enhancement hydraulic characterization was performed as described in **Section 5.2**

Performance monitoring was performed at select existing monitoring wells and at all newly installed monitoring wells approximately 1 and 9 months following the amendment injection into HIW-03. A pre-calibrated YSI multi-parameter water quality indicator was used to obtain basic geochemical measurements in the field, and collected samples were submitted to an analytical laboratory for analyses of VOCs, MEE, TOC, and anions. The collected groundwater samples were also field analyzed for ferrous iron using a HACH spectrophotometer.

5.4.5 Pneumatic Permeability Enhancement Activities

This section describes field activities that were performed as part of the pneumatic permeability enhancement technology demonstration at LCAAP. Specifically, details pertinent to the aboveground and underground setup, monitoring tools, post-enhancement confirmation sampling, and post-enhancement groundwater performance monitoring the pneumatic permeability enhancement demonstration at the site are provided herein.

5.4.5.1 Aboveground Setup

The aboveground setup for the pneumatic permeability enhancement demonstration at LCAAP consisted of a series of nitrogen gas cylinders connected in series to create a high-flow, high-velocity gas stream for fracture initiation. Similar to the hydraulic approach, injection rate and pressure are monitored continuously over time to aid determination of fracture initiation. The aboveground setup of the pneumatic permeability enhancement demonstration at LCAAP is illustrated in **Figure 5.17**.

5.4.5.2 Underground Setup

A Geoprobe 7822DT was used to create 4.25-inch ID open boreholes and facilitate bottom-up permeability enhancement in the pneumatic demonstration cell at LCAAP. A straddle packer assembly was used to isolate the target depth of interest during permeability enhancement. A top packer was also installed on top of the straddle packer assembly to minimize amendment surfacing. Once emplaced at the deepest depth interval targeted, the packer assembly was inflated to create an isolated zone within the borehole. Once permeability enhancement was initiated and the target permeability enhancement fluid volume was pumped into the zone of interest, the packer assembly was deflated and raised to the next depth, as appropriate.

5.4.5.3 Field Activities

Prior to commencement of any permeability enhancement activities, pre-enhancement ERT surveys were conducted to establish the baseline image within the pneumatic demonstration cell. The Geoprobe 7822DT rig was used to create three 4.25-inch ID open boreholes to a total depth of approximately 39 feet bgs to facilitate pneumatic permeability enhancement using HSA. Prior to commencement of permeability enhancement, an injection solution consisting of 3% LactOil® and 7,500 mg/l of KCl was prepared in a poly tank. Following packer deployment and inflation at the deepest depth of interest of between approximately 32 and 35 feet bgs, pneumatic permeability enhancement was initiated via high-pressure injection of a high-flow, high-velocity stream of nitrogen gas. Upon confirmation of fracture initiation via monitoring the injection pressure over time, the injection solution was hydraulically injected into the packer-isolated treatment depth interval. It should be noted that the injection solution was not atomized or aerosolized as originally planned because significant gas bypassing the packer assembly was observed during the fracture initiation using nitrogen gas alone. Had the injection solution been pneumatically delivered, immediately and complete amendment surfacing would have been observed. Therefore, a hybrid approach to pneumatic permeability enhancement was utilized where fractures were first initiated pneumatically with high-pressure injection of nitrogen gas then the pre-mixed amendment solution was introduced into the subsurface hydraulically (i.e., without being aerosolized). Upon achieving the target injection volume of approximately 200 gallons per enhancement interval, the downhole pressure was allowed to dissipate before the packers were deflated and straddle packer assembly raised to the next depth interval of interest. These procedures were repeated for each of the five depth-discrete intervals at each of the three pneumatic initiation boreholes. Tilt meter monitoring was performed at each depth interval of interest during pneumatic permeability enhancement at PIW-03.

Figure 5.17. Aboveground Setup of Pneumatic Permeability Enhancement at LCAAP

Following completion of all permeability enhancement activities, hollow-stem auger drilling technology was utilized to ream out the pneumatic enhancement boreholes PIW-01 through -03 and to install 2-inch ID, Schedule 40, PVC injection wells at these same locations, as requested by LCAAP for future injection applications. These injection wells were screened between 20 and 35 ft bgs. Note that aside from the amendment injections using the hybrid approach to pneumatic permeability enhancement, no additional injection work was performed in the injection wells as a part of this demonstration.

Upon completion of all permeability enhancement activities, post-enhancement ERT surveys were performed. Additionally, preliminary tilt meter analysis results were used to guide confirmation sampling locations. Direct-push drilling technology was used for continuous collection of soil samples using dual tubes at four confirmation borings located within the anticipated ROI of the pneumatic permeability enhancement including PCB-01 through -04. Lithologic logging was performed, and soil samples were composited every foot between approximately 20 and 35 feet bgs and submitted to an analytical laboratory for TOC analysis. Post-enhancement hydraulic characterization was performed as described in **Section 5.2**

Performance monitoring was conducted within the pneumatic demonstration cell in a similar manner to the hydraulic cell. Specifically, HydraSleeves were used to collect formation-representative samples at select existing monitoring wells and at all newly installed monitoring wells at approximately 1 and 9 months post-enhancement. A pre-calibrated YSI multi-parameter water quality indicator was used to obtain basic geochemical measurements in the field, and collected samples were submitted to an analytical laboratory for analyses of VOCs, MEE, TOC, and anions.

The collected groundwater samples were also field analyzed for ferrous iron using a HACH spectrophotometer.

5.4.6 Notable Results

Detailed analysis of all field observations, and analytical and geophysics monitoring results, especially with regard to the project-specific performance objectives, is provided in **Section 6**. A summary of notable field/laboratory observations with regard to amendment distribution and injection volume, changes in hydraulic conductivity and injectability, changes in geochemical conditions and contaminant profile, and effectiveness of geophysics and other monitoring tools employed at LCAAP for both the pneumatic and hydraulic permeability enhancement technologies are provided herein.

5.4.6.1 Amendment Distribution & Injection Volume

Following fracture initiation via the pneumatic mechanism, the target amendment injection volume was achieved in each enhancement interval within the pneumatic permeability demonstration cell. It should be noted that a hybrid approach to pneumatic permeability enhancement was used for amendment delivery following fracture initiation; the pneumatic subcontractor confirmed that had the injection solution been pneumatically delivered, immediately and complete amendment surfacing would have been observed given the significant amount of gas bypassing the packer assembly during fracture initiation.

Approximately 80% of the target solid amendment volume was achieved within the hydraulic demonstration cell; amendment surfacing observed was likely attributable to subsurface preferential pathways resulted from past site disturbances. Subsurface conditions within the pneumatic and the hydraulic demonstration cells were very different: as it turned out, an undocumented and previously unknown former TCE dump pit was present in the hydraulic demonstration cell. Because of this pit, this area as was highly disturbed and then backfilled, with a significant amount of NAPL present. In contrast, the pneumatic area has never been disturbed. Regardless, the target aqueous amendment injection volume was achieved in the hydraulic demonstration cell.

Significant increases in TOC were observed in both soil and groundwater following permeability enhancement, relative to baseline measurements, within the hydraulic demonstration cell despite amendment surfacing issues. On the other hand, despite achieving the target amendment injection volume, no significant increases in TOC in soil were observed within the pneumatic demonstration cell. Some increases in TOC concentrations in groundwater were observed within the pneumatic demonstration cell, albeit transient and at significantly lower than those observed in the hydraulic demonstration cell. These changes in TOC concentrations are depicted in **Figures 5.18** and **5.19**.

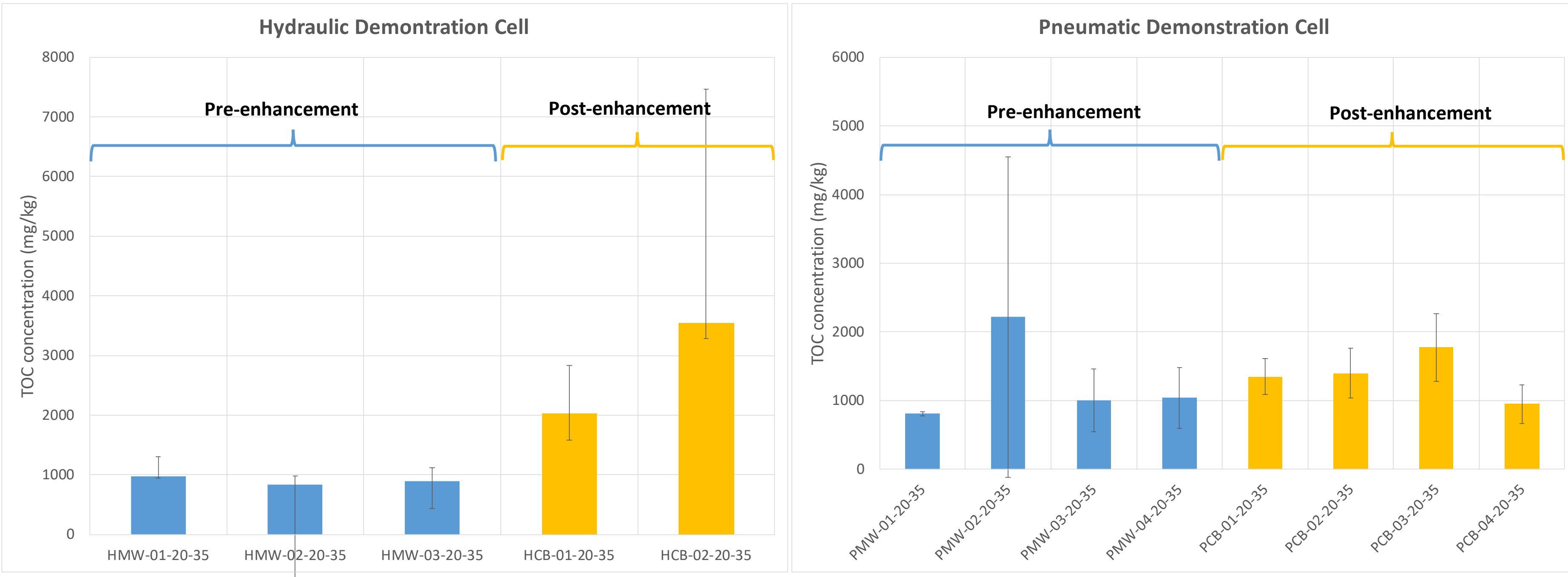

Figure 5.18. Pre- Versus Post-Enhancement TOC Concentration in Soil at LCAAP

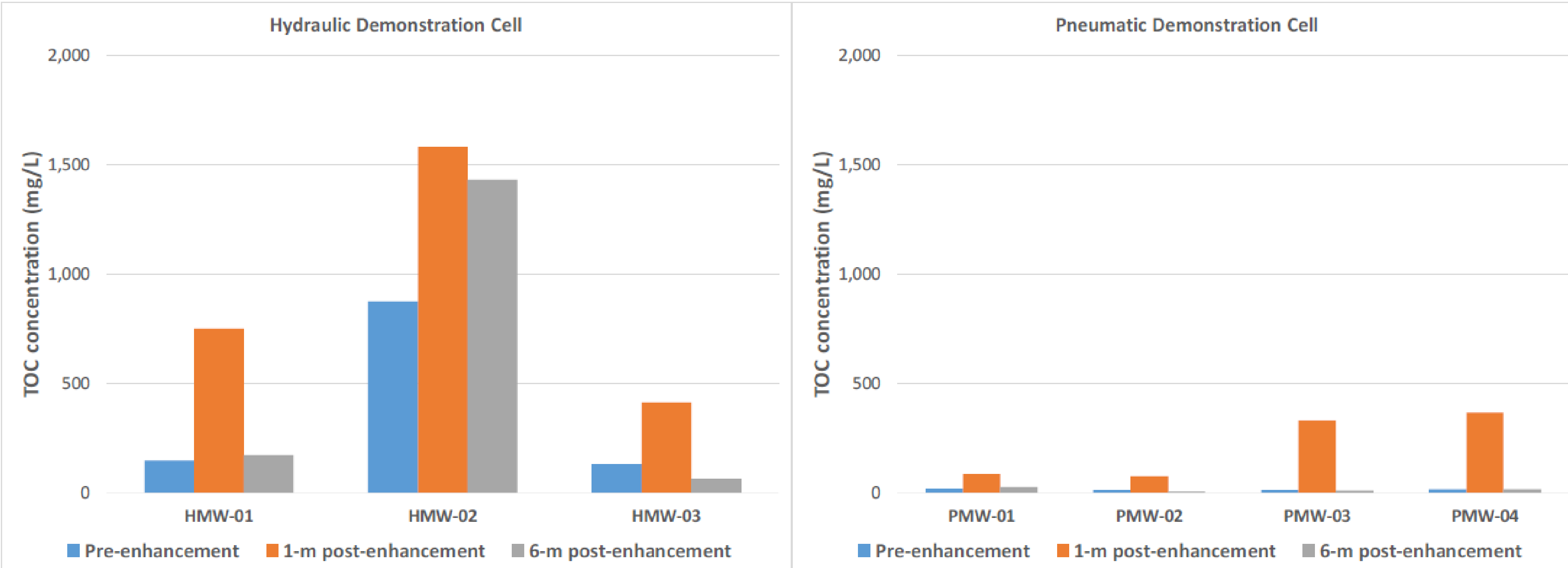

Figure 5.19. Pre- Versus Post-Enhancement TOC Concentration in Groundwater at LCAAP

5.4.6.2 Changes in Hydraulic Conductivities and Injectability

In general, no significant changes in hydraulic conductivities were observed following permeability enhancement in both the pneumatic and the hydraulic demonstration cells. In the case of pneumatic permeability enhancement, this was expected since no sand proppants were or could have been injected to create permanent high-permeability flow pathways within the target treatment zone. Unexpectedly, increased hydraulic conductivities were observed post-enhancement in several monitoring wells located within the pneumatic demonstration cell as shown in **Figure 5.20**. Somewhat surprisingly, minimal changes in hydraulic conductivities in the hydraulic demonstration cell were also observed. This was somewhat unexpected and was in contrast to other applications of hydraulic permeability enhancement (including the other sites in this demonstration). However, the unchanged conductivities and the observed amendment surfacing during permeability enhancement, were likely attributable to the subsurface disturbances, including the presence of NAPL, within this demonstration area. In addition, the occurrence of vertical and horizontal preferential pathways that were likely present in the distributed backfill also contributed to these results. Despite all of these factors, for both the pneumatic and hydraulic cells, the amendment injection rates observed during (in the open boreholes for pneumatic permeability enhancement) or following (through a permanent injection well co-located with an enhancement borehole for hydraulic permeability enhancement) enhancement were significantly higher than those previously obtained via gravity-feed amendment injections at the site (several hundreds of gallons over a six-month injection period).

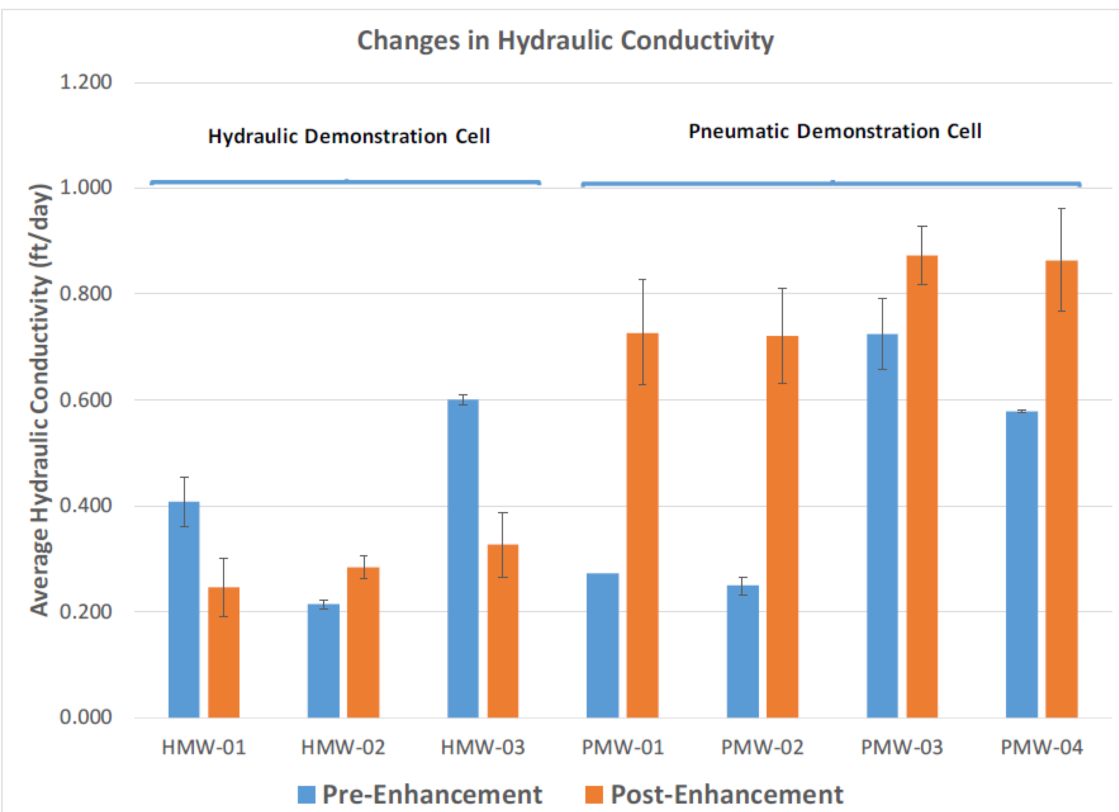

Figure 5.20. Pre- Versus Post-Enhancement Conductivities at LCAAP

5.4.6.3 Changes in Geochemical Conditions and Contaminant Profile & Estimated ROI

Highly reducing conditions were established in both the pneumatic and the hydraulic demonstration cells following enhancement. These geochemical changes were accompanied by significant changes in contaminant concentrations in several monitoring wells located within the ROI of permeability enhancement within both demonstration cells. The extent of contaminant reduction varied significantly as the baseline concentrations in groundwater within the two demonstration areas were vastly different; relatively low BTEX and chlorinated solvent concentrations were observed in the pneumatic monitoring wells, whereas NAPL was seen in all new hydraulic monitoring wells. These results are tabulated in **Table 5.10** and graphically depicted in **Figures 5.21** through **5.31**. The estimated ROIs of permeability enhancement for the pneumatic and the hydraulic demonstration are 10 and 25 feet, respectively, based on the overall evaluation of groundwater chemistry and contaminant profiles over time as well as results of the post-enhancement soil confirmation sampling.

Table 5.10. Summary of Performance Monitoring Results at LCAAP

Well ID	Sampling event	Sampling date	Contaminants and Breakdown Products							BTEX				TOC	Geochemical Parameters							
			PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	VC	Ethene	Ethane	B	T	E	X		pH	Cond	ORP	DO	NO_3	Fe^{2+}	SO_4	CH_4
			µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	mg/L	SU	mS/cm	mV	mg/L	mg/L	mg/L	mg/L	mg/L
PMW-01	Baseline	3/17/2016	< 2.2	290	650	5.7 J	190	< 76	160 J	13 J	12 J	7.6 J	7 J	18.9	6.29	1.599	130.1	4.03	0.0597 J	4.53	18.2	10.00
PMW-01	1-month post-enhancement	5/4/2016	< 3.75	8.3 J	2100	13 J	410	< 110	< 89	20 J	6.7 J	< 3.6	9.9 J	85.9	6.32	1.584	-23.1	1.44	< 0.0625	3.3	6.02	11.00
PMW-01	6-month post-enhancement	10/3/2016	< 3.75	12 J	1000	16 J	400	200 J	200 J	23 J	14 J	10 J	12 J	24.5	6.44	1.608	-85	1.73	0.128 J	3.5	2.37	7.00
PMW-02	Baseline	3/17/2016	0.23 J	33	34	0.48 J	5.8	30 J	< 32	0.2 J	1.5	< 0.05	0.1 J	12.5	6.54	1.05	132.7	4.29	0.0519 J	0.15	15.2	4.50
PMW-02	1-month post-enhancement	5/4/2016	< 0.75	0.88 J	220	1.1 J	25	< 30	< 32	0.5 J	0.82 J	< 0.5	< 0.5	77.3	6.09	1.225	35	2.41	0.0553 J	7.5	1.79	4.10
PMW-02	6-month post-enhancement	10/3/2016	< 0.075	0.13 J	6.2	0.76 J	7.2	< 30	< 32	0.3 J	0.45 J	< 0.05	< 0.05	7.68	6.51	1.197	-90.2	1.72	< 0.0125	6	2.72	4.50
PMW-03	Baseline	3/17/2016	5.7 J	250	200	1.4 J	35	< 15	46 J	1.3 J	4.1 J	0.5 J	0.5 J	11.9	6.55	0.981	149.2	3.94	0.0639 J	0.04	15.5	1.50
PMW-03	1-month post-enhancement	5/4/2016	0.95 J	110	180	1.8 J	12	3.75 J	21 J	0.52 J	4.8 J	0.5 J	0.5 J	331	5.4	1.365	38.2	1.56	< 0.0625	1.2	1.83 J	0.85
PMW-03	6-month post-enhancement	10/3/2016	< 0.075	0.11 J	1	2.1	< 0.06	30 J	100 J	2.3	1	0.8 J	0.78 J	9.66	1.87	1.358	-74	1.87	< 0.0125	1.8	0.612	3.60
PMW-04	Baseline	3/17/2016	4.1 J	260	590	3.7 J	44	30 J	< 32	1.4 J	3.5 J	0.5 J	0.5 J	15.7	6.79	0.82	130.9	4.62	0.0508 J	0.44	18.9	3.00
PMW-04	1-month post-enhancement	5/4/2016	< 3.75	< 3	1500	12 J	78	< 75	< 80	< 2.5	5.7 J	2.5 J	2.5 J	367	6.28	2.294	29.5	1.88	< 0.0625	2.72	4.56	11.00
PMW-04	6-month post-enhancement	10/3/2016	< 0.075	0.35 J	3	3.8	0.42 J	< 48	< 50	1.3	3.1	0.43 J	0.45 J	15.3	6.62	1.698	-84.1	1.97	< 0.0125	3.5	0.821	8.20
16MW076	Baseline	3/16/2016	< 0.75	7.8 J	60	1.9 J	31	< 60	< 65	6.7 J	390	7.6 J	6.1 J	42.1	6.64	1.739	86.8	3.86	0.068 J	3.17	1.42	12.00
16MW076	1-month post-enhancement	5/4/2016	0.16 J	22	88	1.6	12	75 J	< 80	3.6	67	2.1	1.9	1880	4.62	4.137	89	1.29	< 0.0625	0.51	3.55	13.00
16MW076	6-month post-enhancement	10/3/2016	< 0.075	0.26 J	3	1.1	< 0.06	75 J	< 80	4.7	8.5	5.3	4.2	58.3	6.43	1.708	-100.2	1.63	< 0.025	0.5	1.33	13.00
16MW077	Baseline	3/16/2016	< 0.075	< 0.05	< 0.05	< 0.05	< 0.06	< 1.5	< 1.6	< 0.05	< 0.05	< 0.05	< 0.05	0.699 J	6.91	1.576	113.3	4.64	0.11	0.01	12	0.17
16MW077	1-month post-enhancement	5/4/2016	< 0.075	< 0.05	< 0.05	< 0.05	< 0.06	< 3	< 3.2	< 0.05	< 0.05	< 0.05	< 0.05	0.523 J	5.84	1.456	31.6	8.26	0.376	0.47	13.4	0.29
16MW077	6-month post-enhancement	10/3/2016	< 0.075	0.11 J	0.24 J	< 0.05	< 0.06	< 3	< 3.2	< 0.05	< 0.05	< 0.05	< 0.05	4.9	7.22	1.532	-94.5	2.05	0.0623 J	0.5	10.7	0.34
16MW103	Baseline	3/16/2016	< 210	47000	53000	< 125	380 J	17 J	8.4 J	430 J	2900	410 J	740 J	55.4	6.64	1.111	92.2	5.4	0.0577 J	4.5	15	0.40
16MW103	1-month post-enhancement	5/4/2016	230 J	41000	83000	170 J	630 J	44	9.5 J	520 J	5500	790 J	1100 J	85.5	6.49	1.28	80.6	2.39	< 0.0625	3.3	8.9	0.50
16MW103	6-month post-enhancement	10/3/2016	330 J	55000	46000	120 J	600	110	16 J	500 J	3700	790 J	1100	33.4	6.54	0.962	-44.2	1.7	< 0.0125	3.5	15.2	0.63
HMW-01	Baseline	3/18/2016	1600 J	160000	150000	250 J	2800 J	5.3	1.6 J	700 J	40000	1200 J	1700 J	146	6.85	1.121	84.2	5.78	0.0651 J	0.11	4.46	0.03
HMW-01	1-month post-enhancement	5/4/2016	1400 J	89000	270000	920 J	3300	150	37 J	590 J	33000	1200 J	1900 J	751	7.28	2.328	64.6	1.89	< 0.0625	2.39	30.5	0.25
HMW-01	6-month post-enhancement	10/3/2016	185 J	810 J	140000	410 J	11000	430	40 J	340 J	27000	1400 J	2100 J	170	6.42	1.553	-66.9	2.1	< 0.0125	3.8	0.675	2.60
HMW-02	Baseline	3/18/2016	4500	200000	150000	< 125	14000	520	22 J	570 J	45000	930 J	1400 J	876	6.35	2.197	98.7	8.2	0.0764 J	0.83	14.9	0.65
HMW-02	1-month post-enhancement	5/4/2016	5700	240000	210000	< 250	19000	1100	< 13	720 J	59000	1300 J	2000 J	1580	6.91	3.263	77.9	2.05	< 0.0625	1.62	46.2	0.34
HMW-02	6-month post-enhancement	10/3/2016	6900	210000	320000	< 250	9300	380	10 J	810 J	65000	1800 J	2600 J	1430	6.15	2.677	-79.9	1.63	< 0.0125	4.5	51.9	0.26
HMW-03	Baseline	3/18/2016	1200 J	98000	200000	250 J	19000	240	69	570 J	42000	1100 J	1600 J	131	7.55	1.051	76.2	5.98	0.0553 J	0.24	15.7	0.79
HMW-03	1-month post-enhancement	5/4/2016	1500 J	160000	180000	250 J	5900	160	43	730 J	51000	1400 J	2100 J	413	7.36	1.794	41.6	1.97	< 0.0625	4.5	20.2	0.41
HMW-03	6-month post-enhancement	10/3/2016	1500 J	170000	110000	< 220	1700	34	16	630 J	53000	1600 J	2300 J	62.8	6.43	1.488	-81	1.5	0.0831 J	6.75	16.1	0.11
16MW028	Baseline	3/16/2016	< 1.9	5.6 J	550	2.9 J	620	< 41	< 32	3.3 J	16 J	6.4 J	5.3 J	3.27 J	9.6	0.67	35.5	5.38	< 0.0125	0.01	8.11	1.30
16MW028	1-month post-enhancement	5/4/2016	< 3.75	5.1 J	590	< 3	660	< 40	< 30	< 3	15 J	< 5.4	< 4.5	2.17	10.78	1.413	45.3	3.75	0.0495 J	0.18	8.53	1.10
16MW028	6-month post-enhancement	10/3/2016	< 3.75	6.2 J	770	< 3.8	1000	51 J	34 J	5.3 J	25 J	9.5 J	7.4 J	2.14	10.56	1.178	-52.2	3.02	0.0538 J	0.15	8.04	1.60
16MW029	Baseline	3/16/2016	< 0.075	0.51 J	0.39 J	< 0.05	0.38 J	30 J	32 J	0.1 J	< 0.05	< 0.05	< 0.05	1.41 J	8.53	0.97	101.4	5.81	0.343	0.13	8.12	2.40
16MW029	1-month post-enhancement	5/4/2016	< 0.075	0.7 J	3.6	< 0.05	0.67	30 J	32 J	< 0.05	< 0.05	< 0.05	< 0.05	0.873 J	7.44	1.032	69.4	2.44	0.156	0	7.34	2.70
16MW029	6-month post-enhancement	10/3/2016	< 0.075	0.65 J	2.7	< 0.05	0.8	15 J	16 J	< 0.05	< 0.05	< 0.05	< 0.05	0.67 J	7.69	0.904	-63.8	1.86	0.118	0.5	7.88	1.40

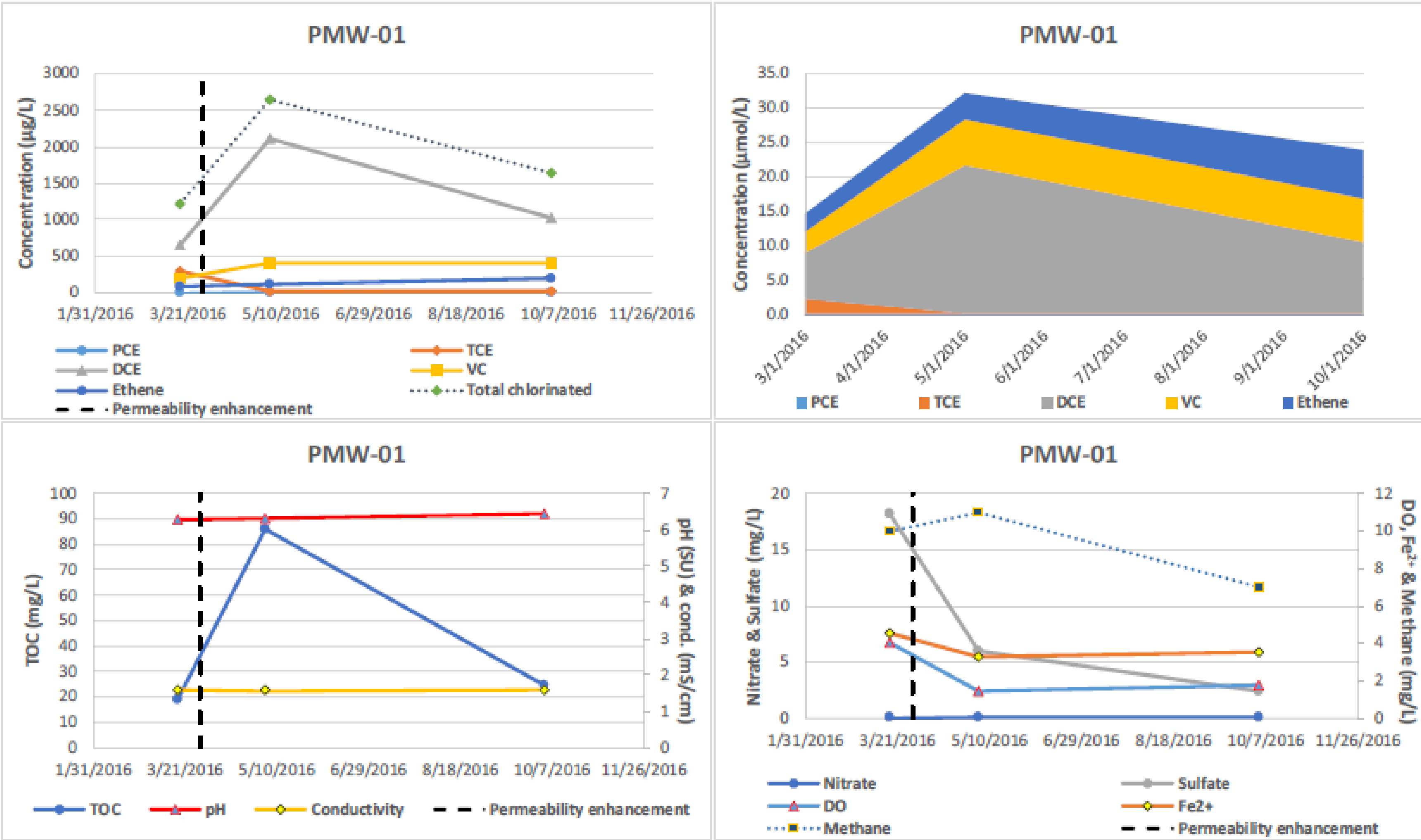

Figure 5.21. Trend Charts – PMW-01

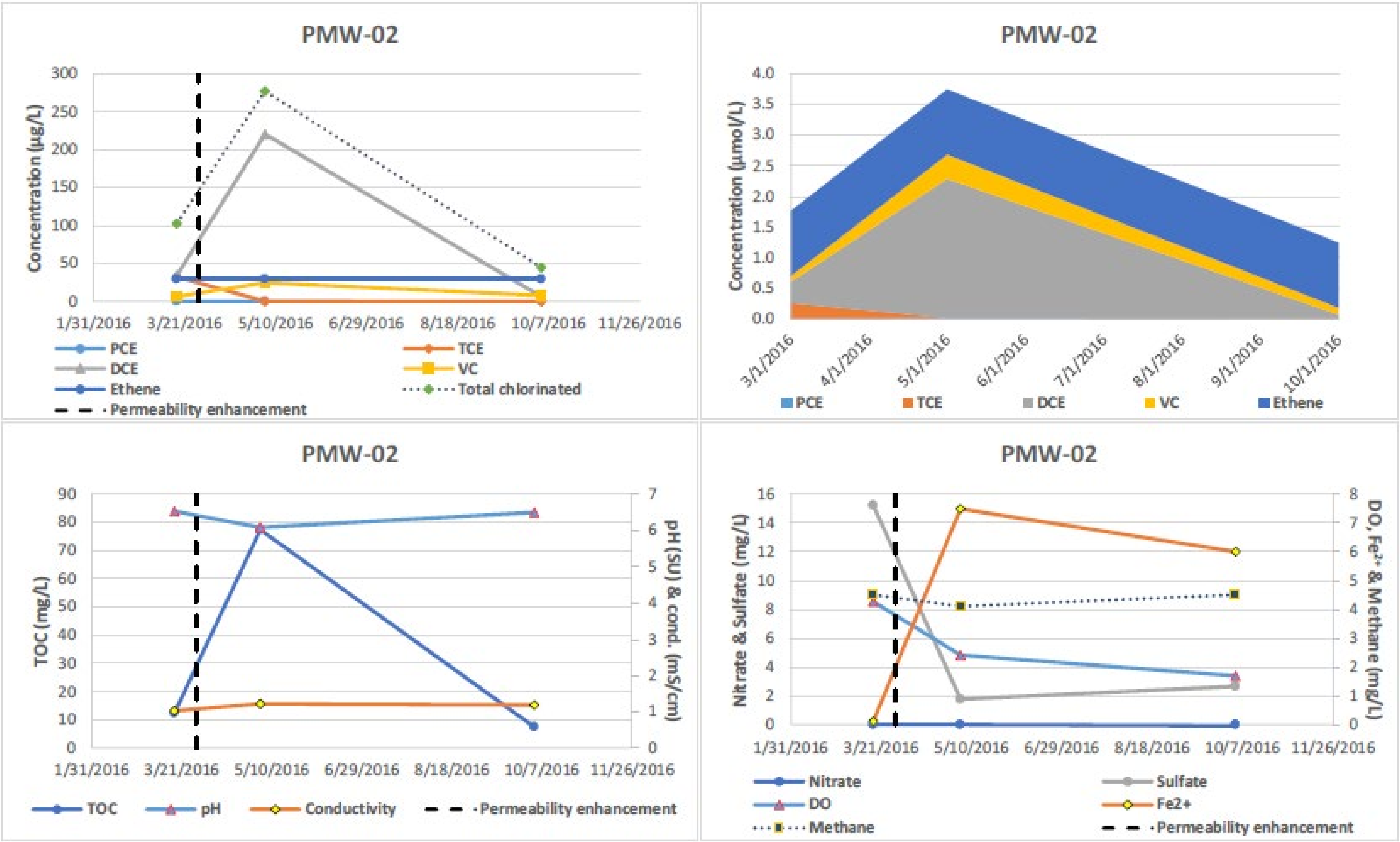

Figure 5.22. Trend Charts – PMW-02

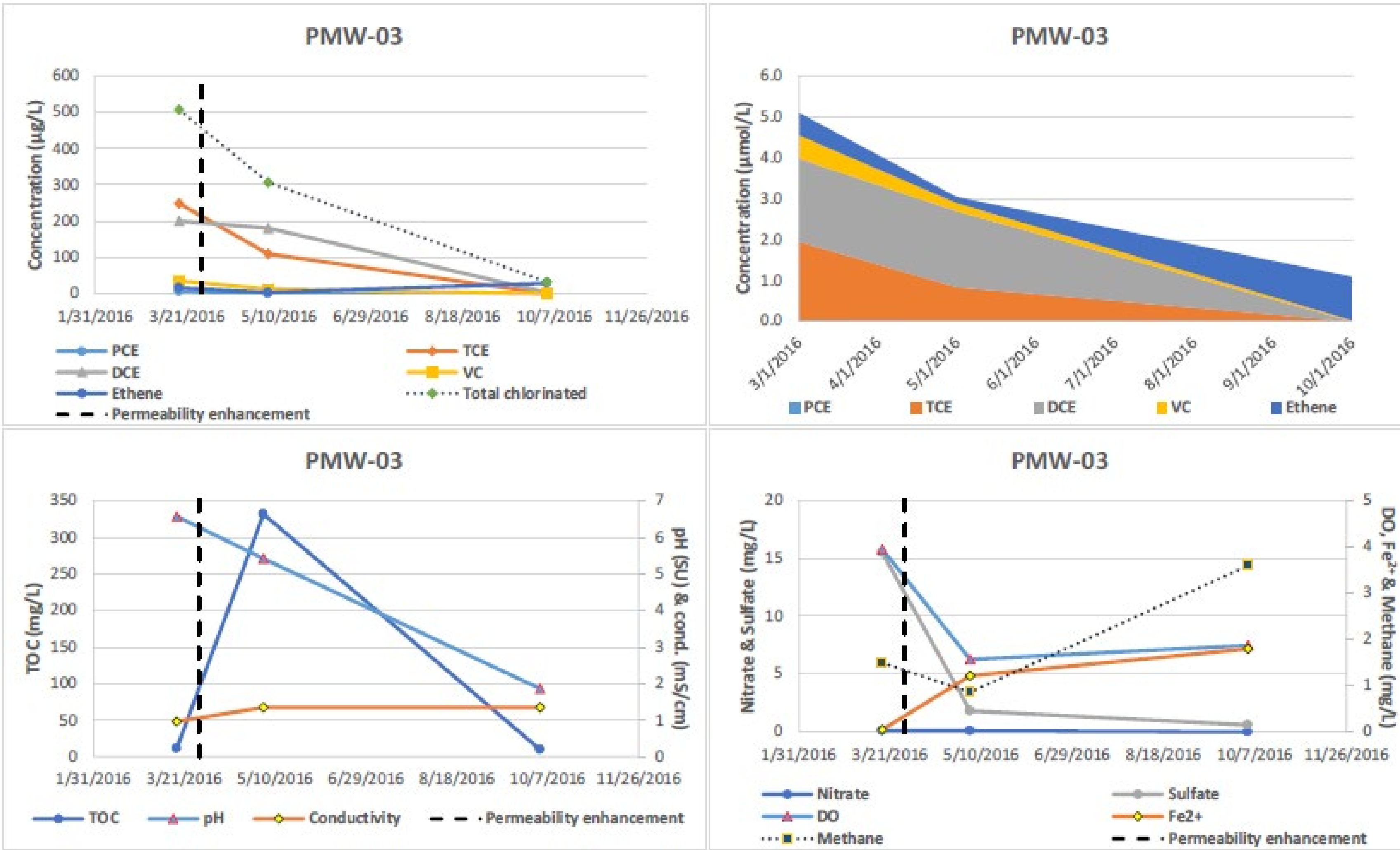

Figure 5.23. Trend Charts – PMW-03

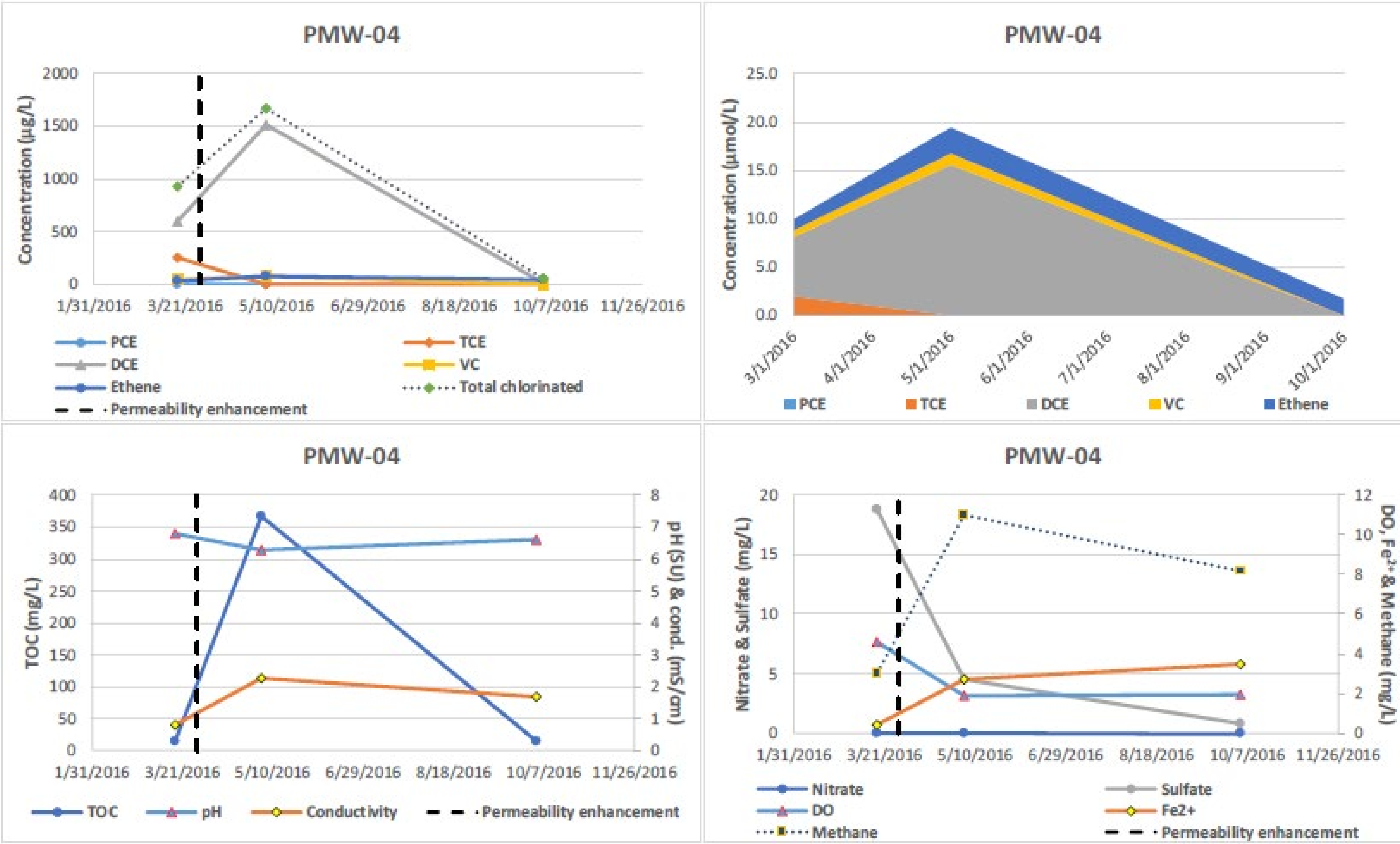

Figure 5.24. Trend Charts – PMW-04

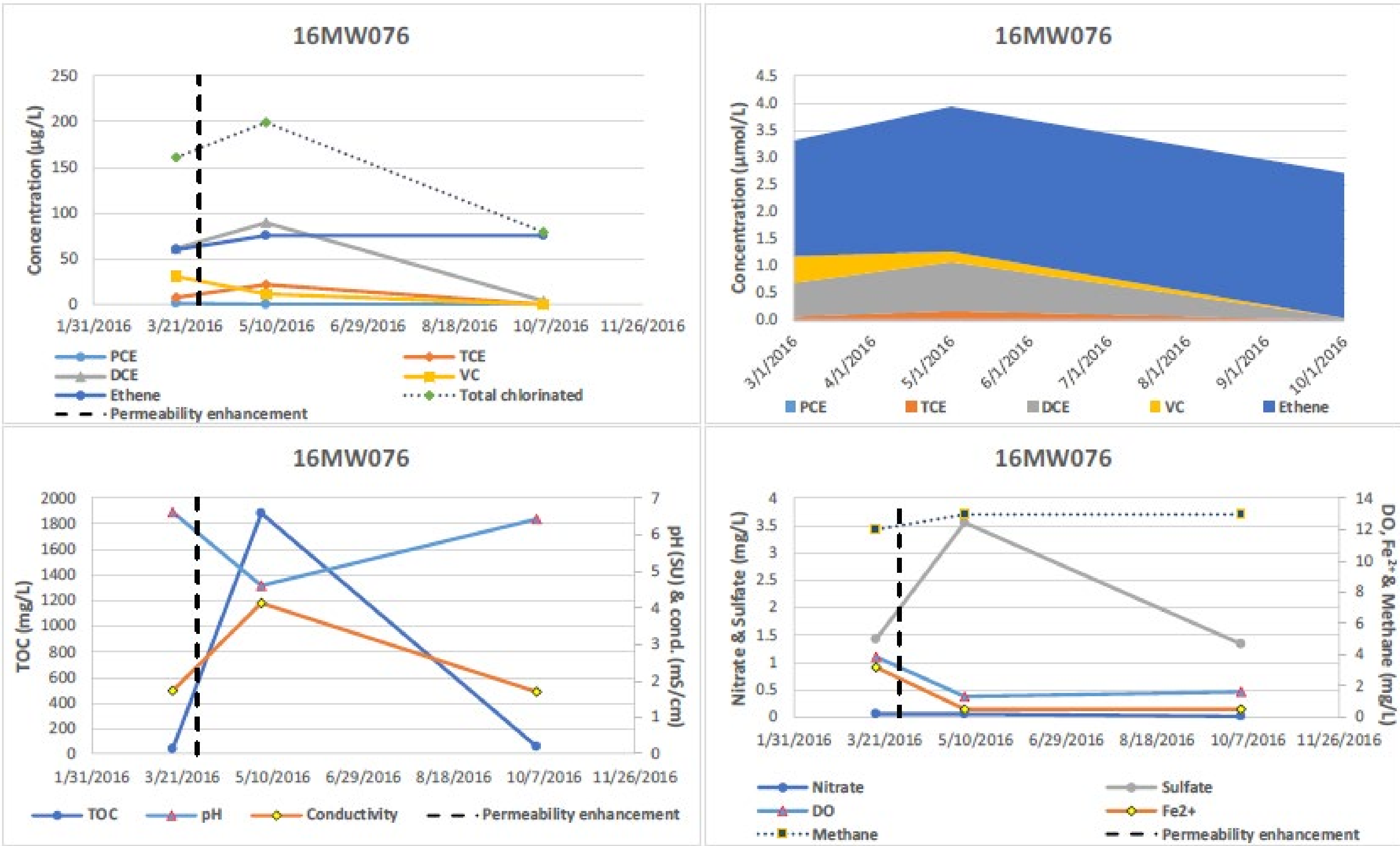

Figure 5.25. Trend Charts – 16MW076

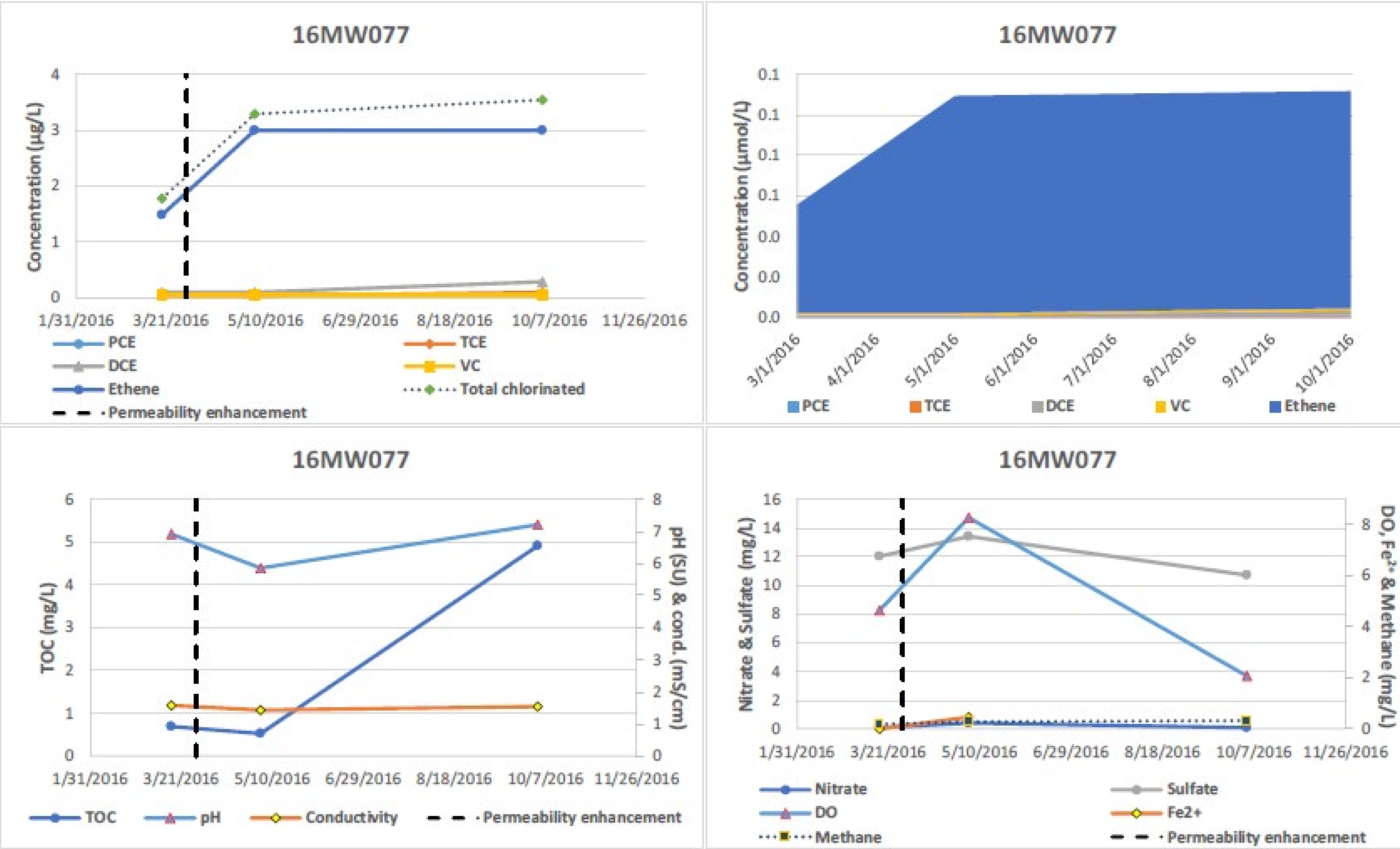

Figure 5.26. Trend Charts – 16MW077

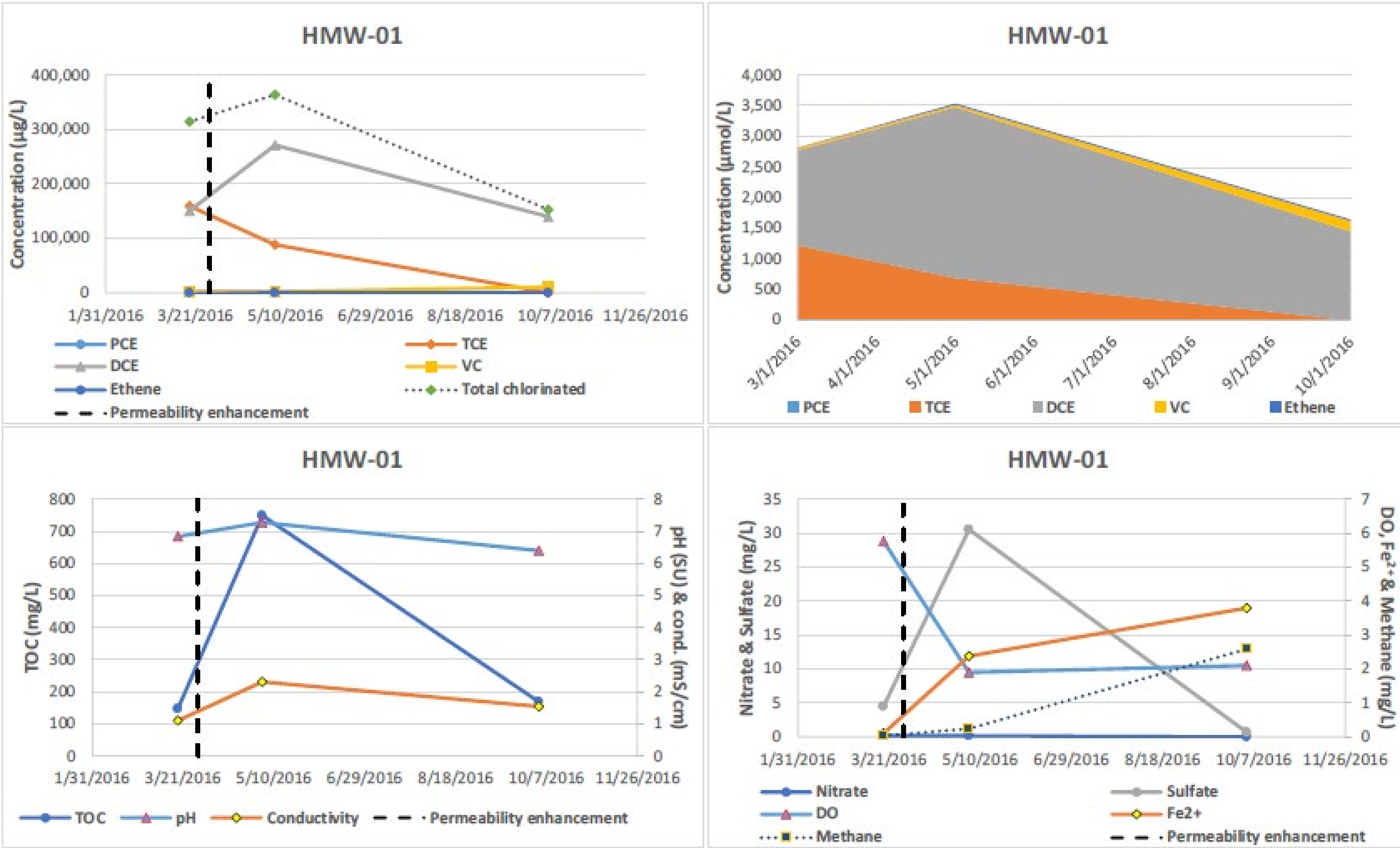

Figure 5.27. Trend Charts – HMW-01

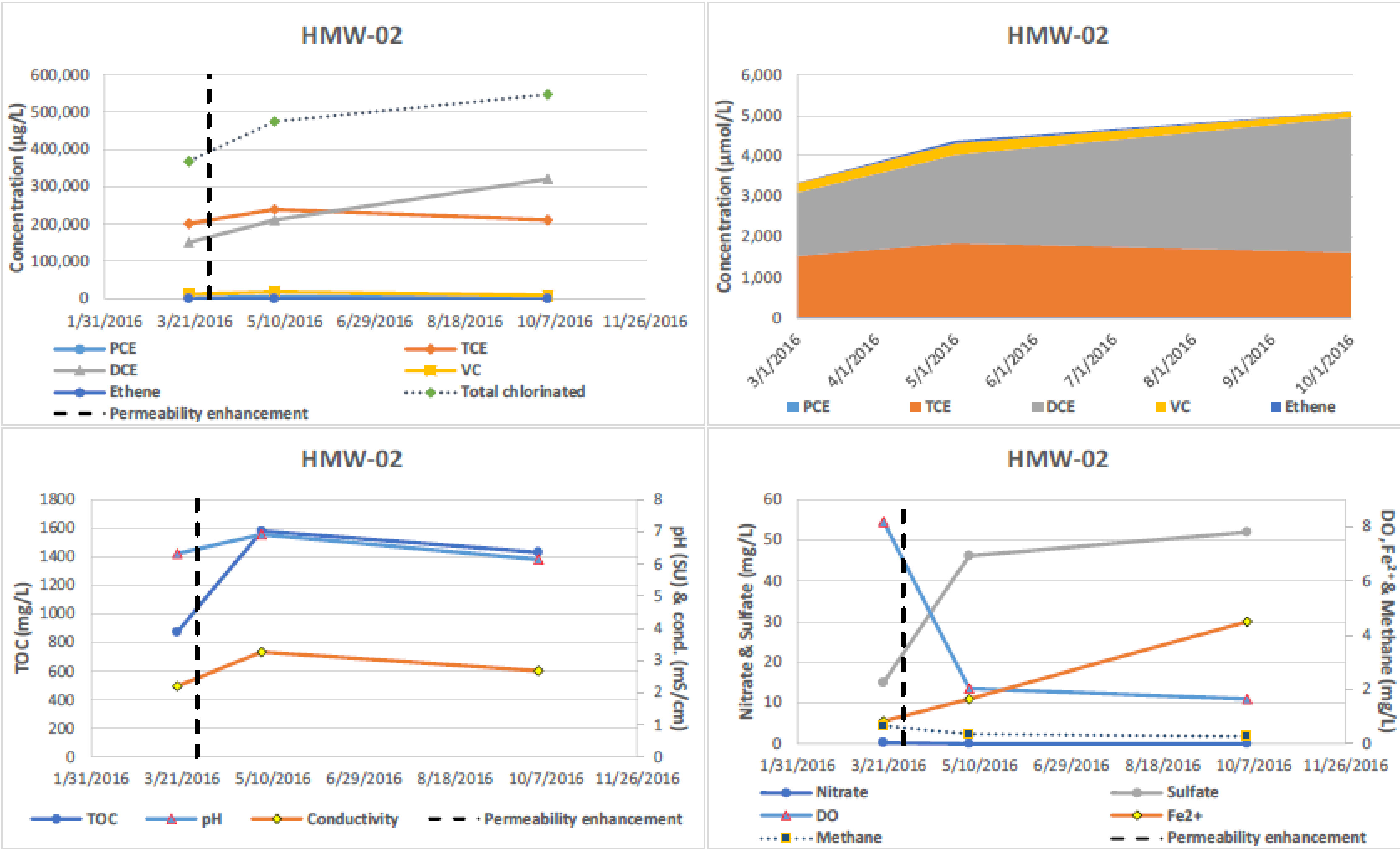

Figure 5.28. Trend Charts – HMW-02

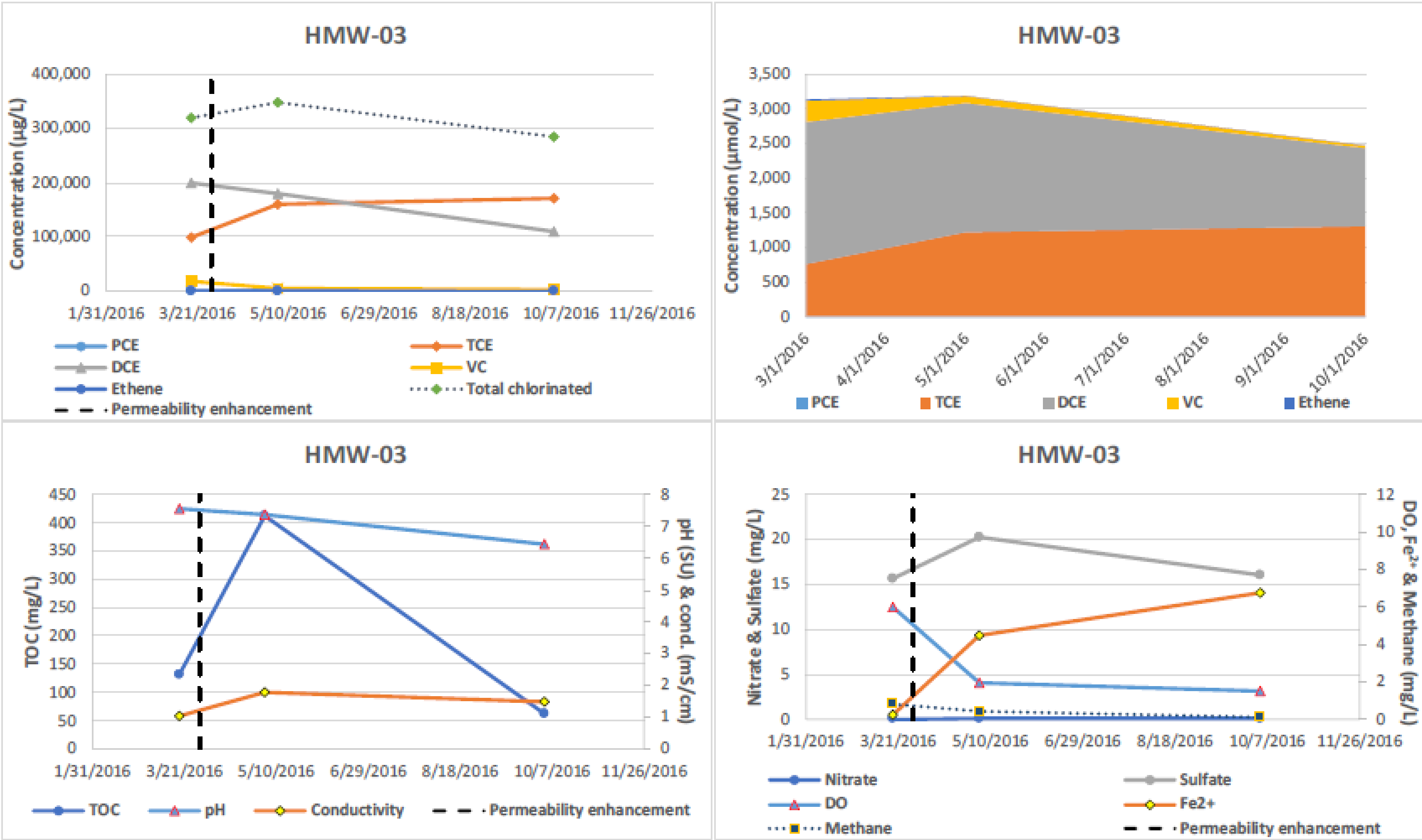

Figure 5.29. Trend Charts – HMW-03

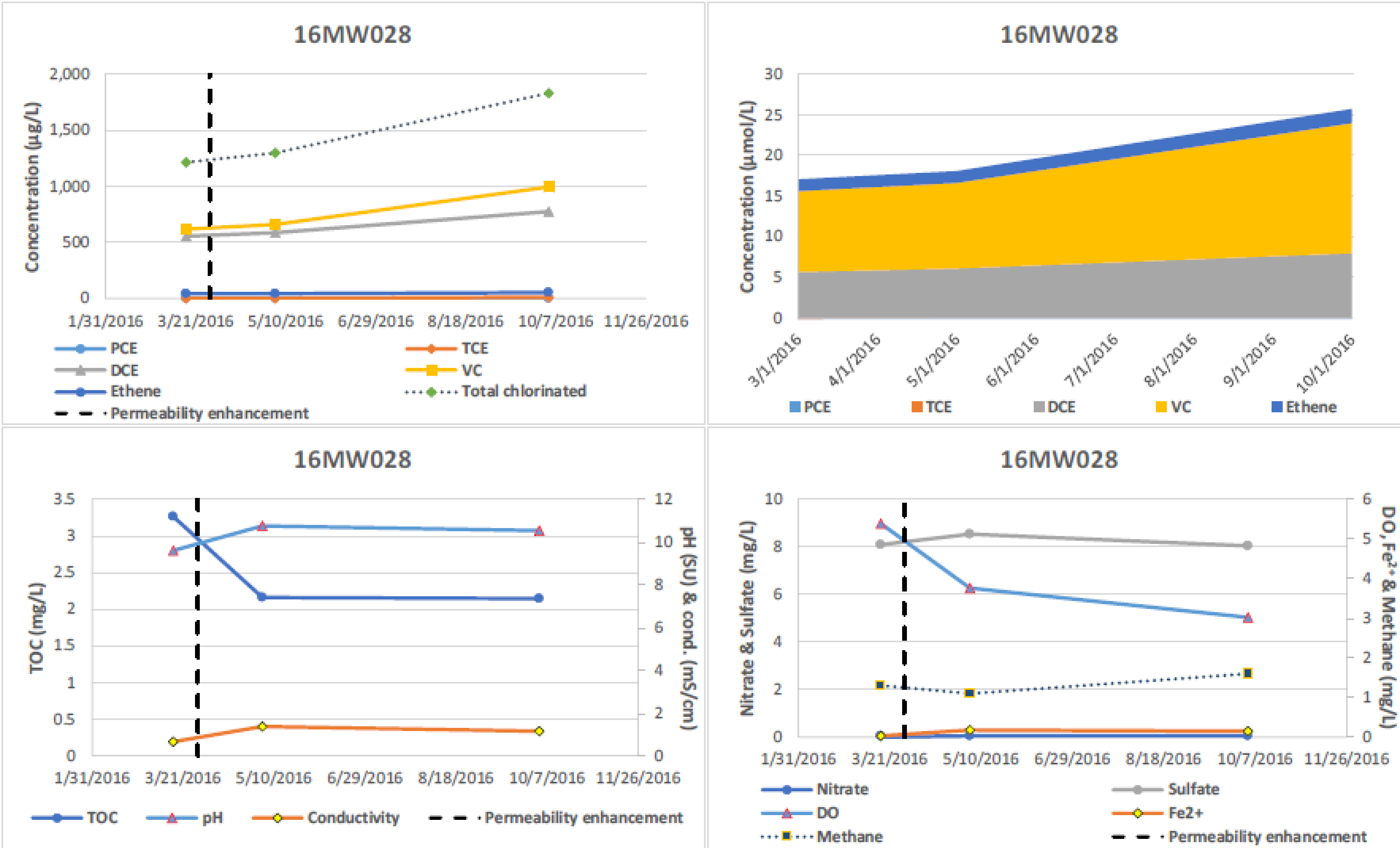

Figure 5.30. Trend Charts – 16MW028

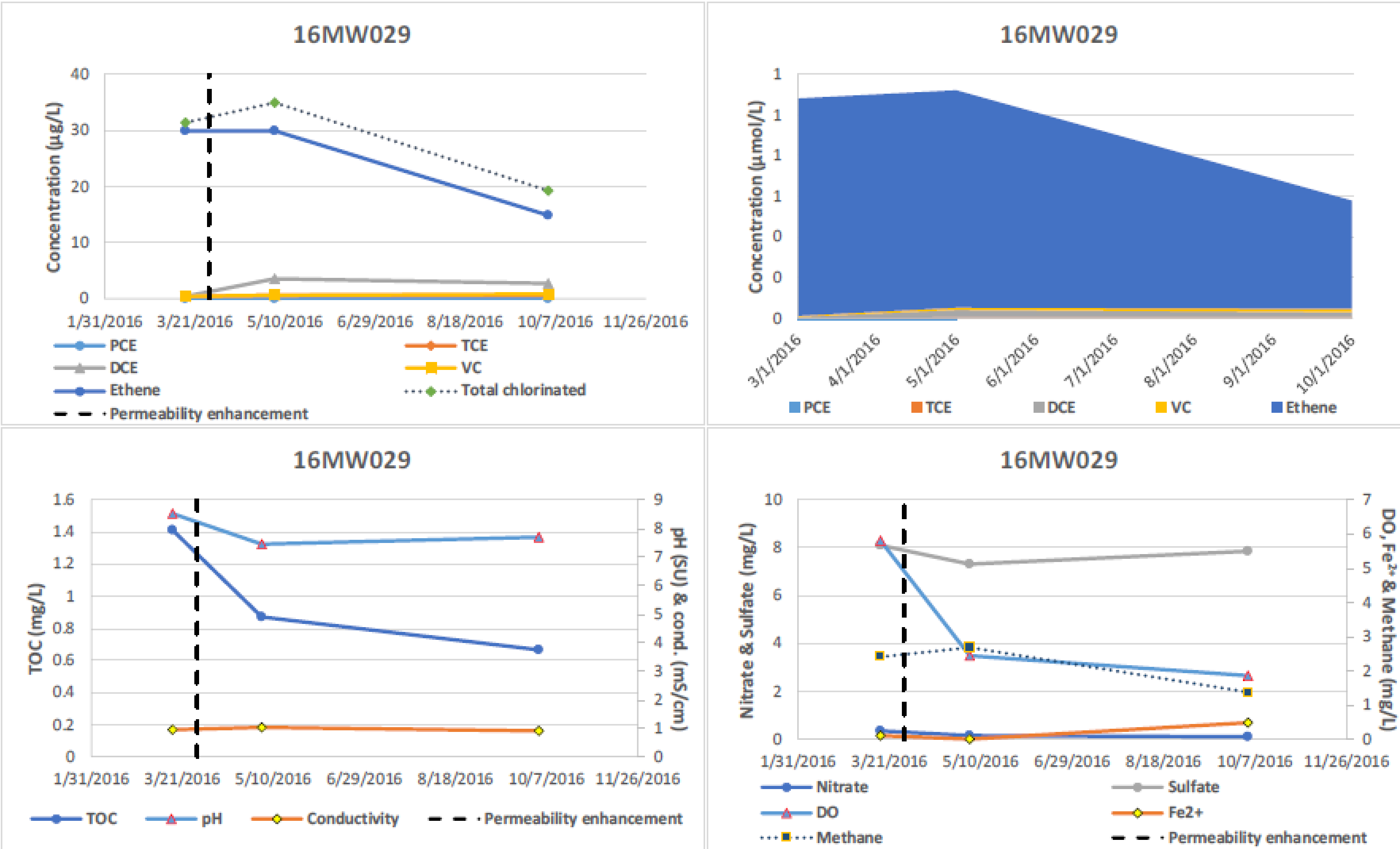

Figure 5.31. Trend Charts – 16MW029

Effectiveness of Geophysics and Other Monitoring Tools

Data obtained during tilt meter monitoring were used to generate 3D visualizations to graphically illustrate the vertical and horizontal extent of the fracture network initiated by both the hydraulic and the pneumatic permeability enhancement at LCAAP as shown in **Figure 5.32**. Note that the tilt meter monitoring was not performed at all permeability enhancement locations.

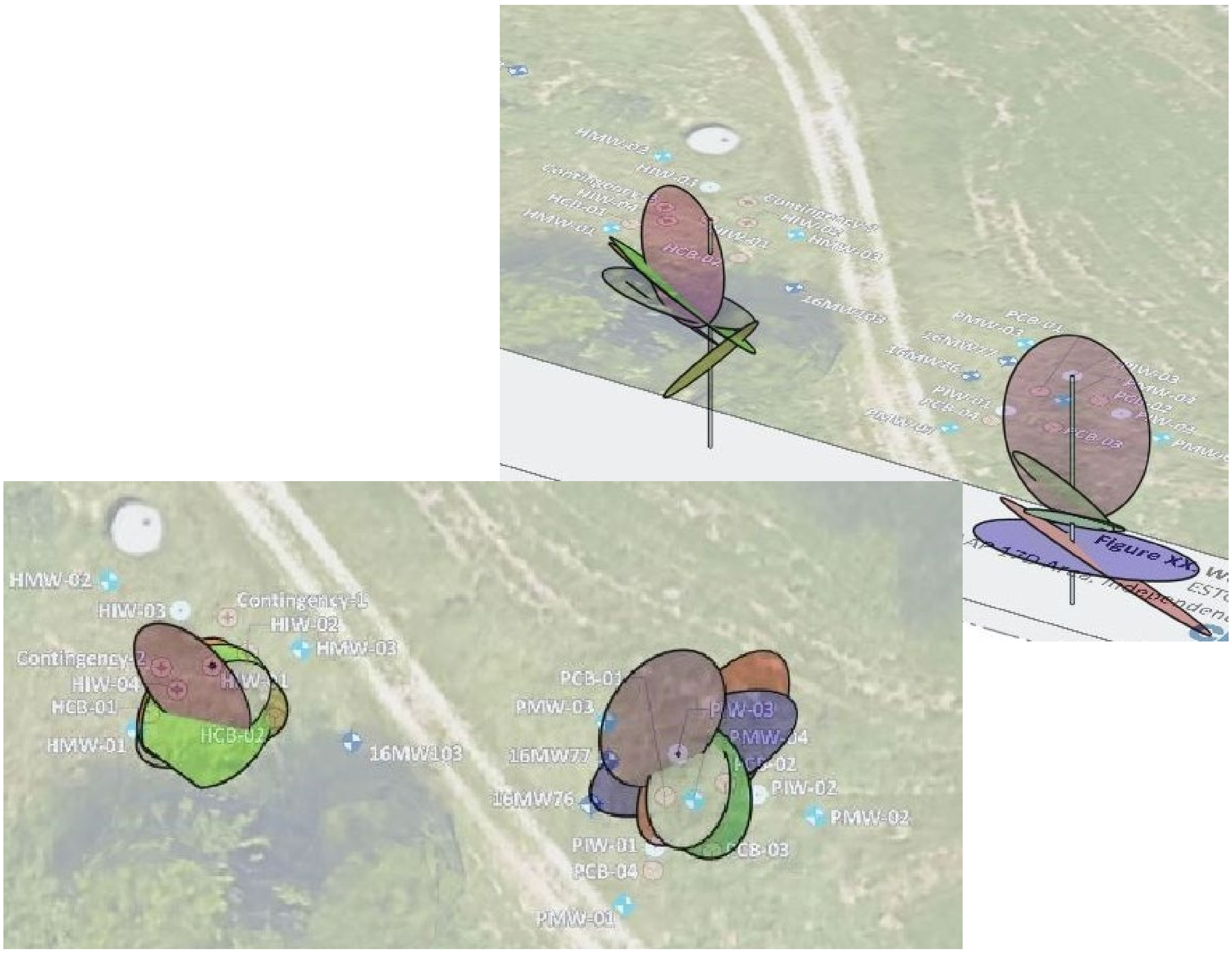

Figure 5.32. 3D Visualization of the Fracture Network at LCAAP

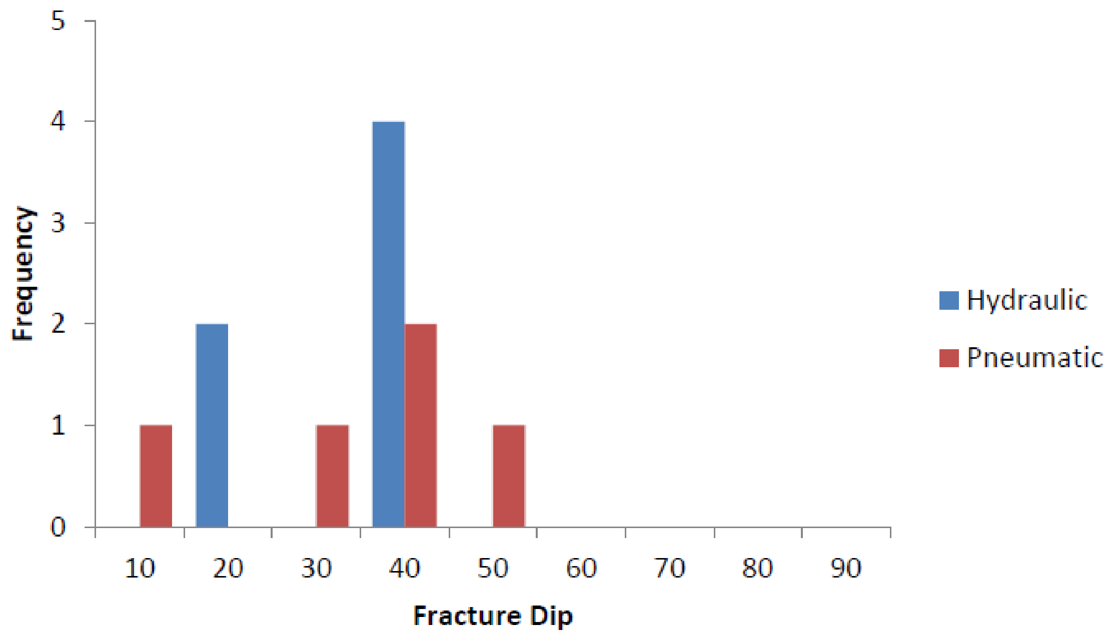

Figure 5.33. Distribution of Fracture Dip Angles at LCAAP

The frequency distribution of fracture dip angles for both the hydraulic and pneumatic demonstration cells is presented in **Figure 5.33**. The dip angle is defined as the degree of inclination from a horizontal plane. Therefore, the higher the dip angle, the less horizontal and the more vertical a fracture is predicted to be. At LCAAP, all of the fractures initiated by both the hydraulic and pneumatic permeability enhancement techniques were primarily horizontal with dip angles of less than 50 degrees. Note that relatively horizontal fractures were observed in the hydraulic demonstration area despite the subsurface anomalies resulted from past activities in the area.

Geophysics monitoring tools, including ERT and tilt meters, were implemented at LCAAP for both the hydraulic and pneumatic cell. The pneumatic cell ERT images showed very little change following permeability enhancement. For the hydraulic cell, ERT images delineated conductivity contrasts including the interpreted vadose zone boundary and a high conductivity layer within the screen interval representative of a high surface area lithology (i.e. clays) or high conductivity product. All of the changes that were observed in the pre-and post- ERT images appear to be local to the monitoring wells, and in the upper 10 ft; almost no change was seen between approximately 15-25 ft. This was reasonably consistent with changes in TOC observed in groundwater samples from the hydraulic cell.

Overall, while some changes in ERT images pre- and post-enhancement were observed primarily within the ERT boreholes, cross-borehole visualization of the fracture network and amendment delivery initiated by both hybrid pneumatic and hydraulic permeability enhancement was somewhat limited, in that increases were seen primarily in areas immediately surrounding the monitoring wells that were equipped with electrodes. Areas that were confirmed to be impacted by permeability enhancement via other monitoring tools did not always display increases in conductivity, possibly due to resolution issues or due to the fact that the emplaced solution did not contain a sufficient conductivity contrast compared to background. On the other hand, areas where conductivity did increase generally did also show evidence of being impacted by permeability enhancement.

It is notable that ERT did show more significant impacts in the hydraulic cell compared to the pneumatic cell. This is entirely consistent with other observations at the site, which suggest that amendment distribution was better in the hydraulic treatment cell.

On the other hand, similar to MCB-CP, tilt meter data obtained during permeability enhancement were used to generate 3D visualization and facilitate evaluation of the vertical and horizontal extent of the initiated fracture network. Additionally, the tilt meter-predicted fracture intercepted depth-intervals, presented in **Table 5.11**, correlate well with visual observations of the emplaced amendments as well as increases in TOC as a result of amendment injection in both the hydraulic and the pneumatic demonstration areas.

Table 5.11. Predicted Fracture-Intercepting Depths at LCAAP

Demonstration area	Confirmation borehole	Predicted Intercept depth (ft bgs)	Originating enhancement location	Frac Rite's comments
Hydraulic demonstration cell	HCB-01	12.25	HIW-01	
		17	HIW-02	Just outside edge of modelled fracture
		NI*	HIW-03	
		11.25	HIW-03b	
		10	HIW-04	At edge of modelled fracture
		NI*	HIW-05	
	HCB-02	NI*	HIW-01	
		NI*	HIW-02	
		18.75	HIW-03	
		22	HIW-03b	At edge of modelled fracture
		NI*	HIW-04	
		NI*	HIW-05	
Pneumatic demonstration cell	PCB-01	29	PIW-03-1	
		19.75	PIW-03-2	
		26	PIW-03-3	
		20.75	PIW-03-4	
		NI*	PIW-03-5	
	PCB-02	30.5	PIW-03-1	At edge of modelled fracture
		26.25	PIW-03-2	
		26	PIW-03-3	
		25.5	PIW-03-4	
		NI*	PIW-03-5	
	PCB-03	NI*	PIW-03-1	
		NI*	PIW-03-2	
		19.25	PIW-03-3	
		13	PIW-03-4	At edge of modelled fracture
		NI*	PIW-03-5	

* NI = not intercepting

5.5 GFAFB SITE TU504

This section discusses the overall objective of the technology demonstration at GFAFB. In addition, a summary of the technical approach, demonstration design and layout, details pertinent to field activities performed, and notable field observations and performance monitoring/ geophysics monitoring results is provided herein.

5.5.1 Overall Objective and Technical Approach

The overall objective for the technology demonstration at GFAFB was to evaluate the performance of the hydraulic approach to permeability enhancement at a low-permeability site with glacial till lithology in a direct comparison with conventional injection techniques previously implemented. Pre-packed 1-inch ID, Schedule 40, PVC injection wells had been previously installed for injections of LactOil® and bioremediation for treatment of chlorinated solvents at the site. Therefore, LactOil® was selected as the treatment amendment for the demonstration at the site to allow for a direct comparison with the previously implemented remedial activity. In this case, a sand proppant was not emplaced during hydraulic permeability enhancement. Also, it should be noted that CDM Smith's review of site-specific historical data suggested that a lack of *Dehalococcoides* at the site was likely preventing complete degradation to ethene. Because bioaugmentation was not part of the scope of this technology demonstration, it was not expected that complete dechlorination of TCE to ethene would be achieved within the hydraulic treatment cell.

During our demonstration, approximately 130 gallons of treatment solution consisting of approximately 3% LactOil®, 30,000 mg/L of KCl, and 200 µg/L of fluorescein were added to each of the three permeability enhancement intervals targeted between approximately 10 and 20 feet bgs. KCl was added to provide the conductivity contrast necessary for proper ERT monitoring and evaluation. It should be noted that the high KCl concentration was selected because of the elevated conductivity of site groundwater, and in fact an even higher concentration was initially desired. However, these higher KCl concentrations were not used because the resulting amendment solution would have been subject to preferential, density-driven flow. Fluorescein was also added to allow for visual observation of amendment surfacing and direct delivery into nearby monitoring wells. In addition, since silica sand was not emplaced as part of this technology demonstration at GFAFB, the fluorescein was used as a way to confirm amendment delivery in depth-discrete intervals during post-enhancement confirmation soil sampling.

5.5.2 Technology Demonstration Design and Layout

The layout of the permeability enhancement technology demonstration at GFAFB is illustrated in **Figure 5.34**. The layout was designed to include four permeability enhancement points, GFB539-HIP-01 through -HIP-04, with an anticipated ROI of 10 feet, and seven monitoring wells located within and just outside of the ROI for performance monitoring and evaluation. The permeability enhancement points were also positioned such that existing wells including GFB539-MW-05 and -MW-06 are located within the anticipated ROI of permeability enhancement. Because an aqueous amendment was employed for the technology demonstration at GFAFB (and not a sand proppant), injection pressures much lower than those utilized for emplacement of a solid amendment were anticipated and therefore, the potential for structural damages of existing monitoring wells located within the anticipated permeability enhancement ROI was believed to be minimal.

All new monitoring wells were screened within approximately 10 and 20 feet bgs to facilitate performance monitoring within this depth interval of interest. However, it should be noted that several new monitoring wells installed for this technology demonstrations, including GFB539-MW-15 through -MW-19, were equipped with ERT electrodes and wires throughout the entire well casing and screens. In addition, these monitoring wells were equipped with a 5-foot blank casing at the bottom of each well screen to accommodate ERT monitoring. The monitoring well network surrounding the two permeability enhancement points GFB539-HIP-01 and -HIP-02 was also configured to best facilitate ERT monitoring.

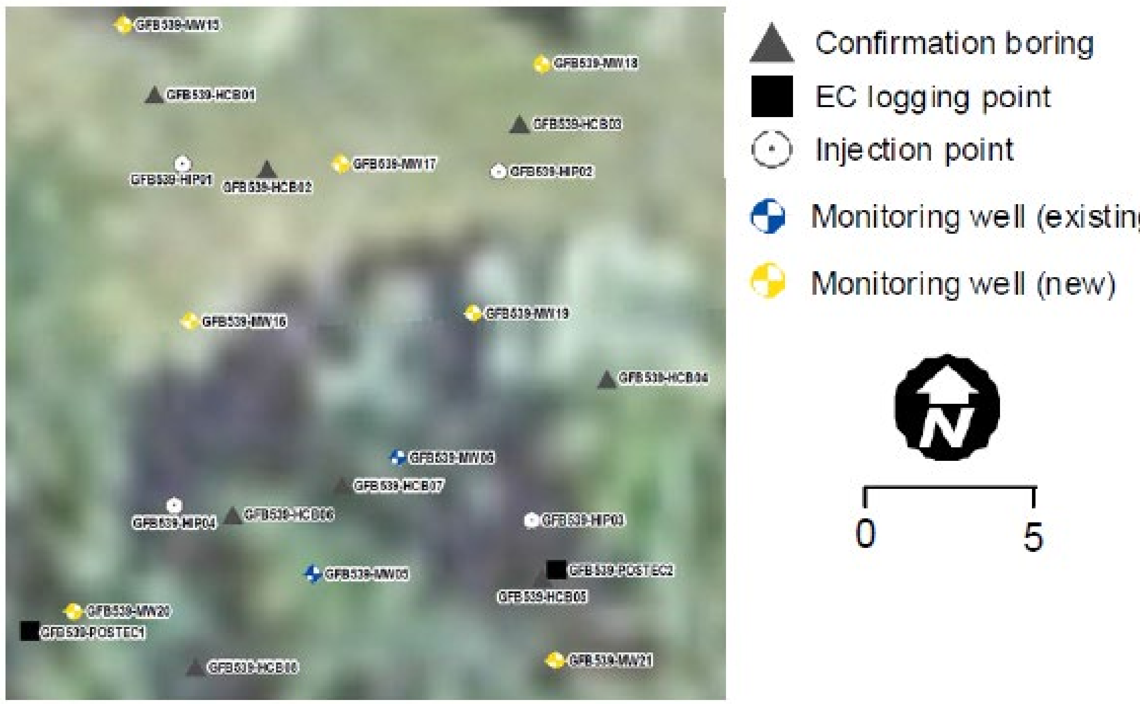

Figure 5.34. Demonstration Layout at GFAFB

5.5.3 Baseline sampling

Upon completion of all pre-enhancement soil sampling for TOC and fluorescein, EC logging, and well installation and development activities, baseline groundwater sampling was performed at a number of existing monitoring wells located near the technology demonstration area and at the newly installed monitoring wells using low-stress, low-flow sampling techniques (peristaltic pumps). The existing monitoring wells were selected because they are located within, upgradient, or downgradient of the demonstration area; screened approximately within the target permeability enhancement intervals of between approximately 10 and 20 feet bgs; and in some cases, screened below the confining unit of the deepest permeability enhancement intervals to allow for monitoring of vertical permeability enhancement. Following parameter stabilization using a pre-calibrated YSI multi-parameter water quality indicator, formation-representative samples were collected and submitted to an analytical laboratory for analyses of VOCs, MEE, TOC, and anions. The collected groundwater samples were also field analyzed for ferrous iron using a HACH spectrophotometer. The sampling and analysis plan for GFAFB is presented in **Table 5.12**.

Table 5.12. Sampling and Analysis Plan at GFAFB

Well ID	Well type	Sampling event			Analyte	Analytical method	Sampling method
		Baseline	1 months post-enhancement	9 months post-enhancement			
GFB539-MW01	Existing monitoring well	✓			Field parameters VOCs TOC MEE Anions Ferrous iron	YSI EPA 8260B EPA 9060 RSK 175 EPA 300.1 HACH	Low-flow with peristaltic pumps
GFB539-MW02	Existing monitoring well	✓					
GFB539-MW03	Existing monitoring well	✓	✓	✓			
GFB539-MW04	Existing monitoring well	✓	✓	✓			
GFB539-MW05	Existing monitoring well	✓	✓	✓			
GFB539-MW06	Existing monitoring well	✓	✓	✓			
GFB539-MW07	Existing monitoring well	✓					
GFB539-MW09	Existing monitoring well	✓	✓	✓			
GFB539-MW10	Existing monitoring well	✓	✓	✓			
GFB539-MW11	Existing monitoring well	✓	✓	✓			
GFB539-MW13	Existing monitoring well	✓					
GFB539-MW14	Existing monitoring well	✓					
GFB539-MW15	New monitoring well	✓	✓	✓			
GFB539-MW16	New monitoring well	✓	✓	✓			
GFB539-MW17	New monitoring well	✓	✓	✓			
GFB539-MW18	New monitoring well	✓	✓	✓			
GFB539-MW19	New monitoring well	✓	✓	✓			
GFB539-MW20	New monitoring well	✓	✓	✓			
GFB539-MW21	New monitoring well	✓	✓	✓			

5.5.4 Permeability Enhancement Activities

This section describes field activities that were performed as part of the permeability enhancement technology demonstration at GFAFB. Specifically, details pertinent to the aboveground and underground setup, monitoring tools, post-enhancement confirmation sampling, and post-enhancement groundwater performance monitoring are provided herein.

5.5.4.1 Aboveground Setup

Frac Rite's proprietary EFI2000 environmental hydraulic permeability enhancement unit was used for the technology demonstration at GFAFB. The unit is self-contained with power and pumps mounted on a single skid. In addition, this injection skid is equipped with a real-time data acquisition system capable of displaying and recording injection pressure and injection rate during permeability enhancement. A separate mixing tank skid was used to prepare the injection solution. A wellhead assembly was installed at the top of the Geoprobe drill rod at the surface to allow for connection between the EFI2000 injection skid and the downhole tooling via 2-inch ID injection hoses. The aboveground setup of the EFI2000 permeability enhancement unit at GFAFB is illustrated in **Figure 5.35**.

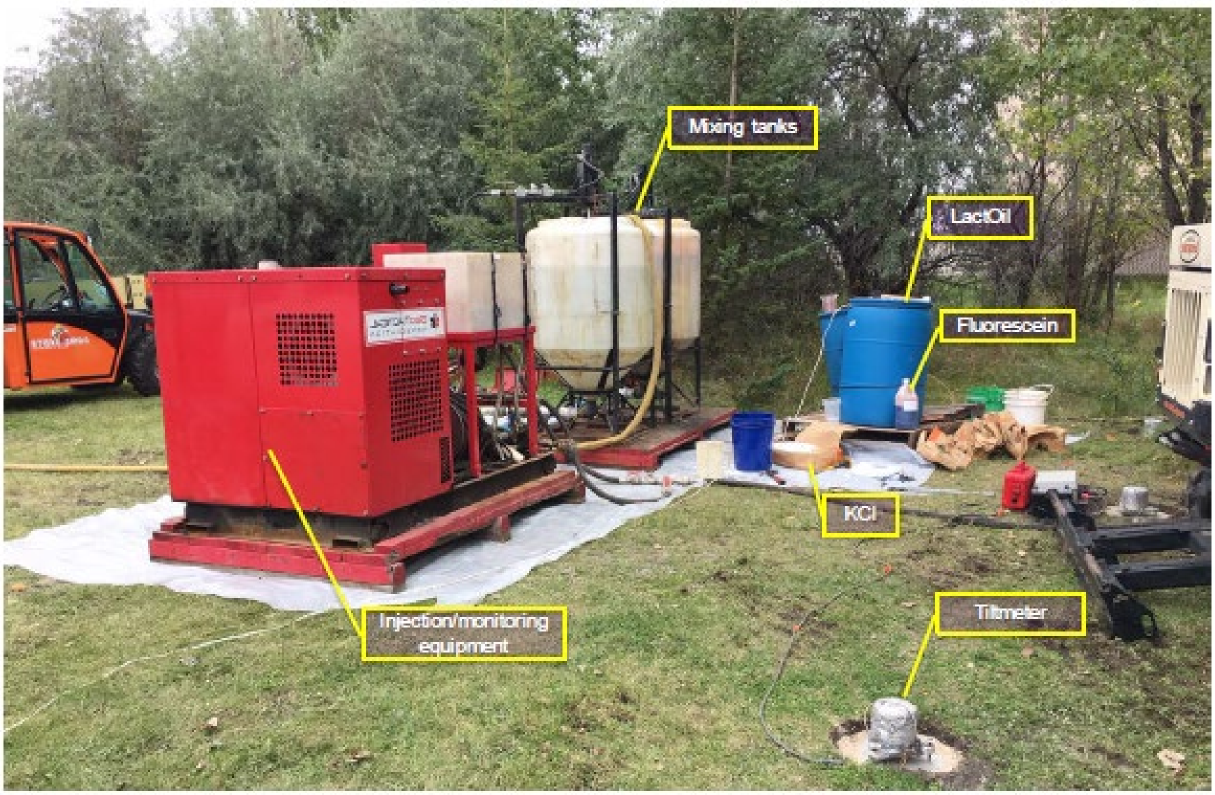

Figure 5.35. Aboveground Setup of Permeability Enhancement at GFAFB

5.5.4.2 Underground Setup

Direct-push drilling technology was employed to facilitate the underground setup of permeability enhancement at GFAFB. Standard Geoprobe 2¼-inch ID drill rods were used to drive the proprietary permeability enhancement tooling to the desired fracture initiation depth interval. The downhole tooling is designed to isolate a small vertical zone within the borehole.

5.5.4.3 Field Activities

Prior to commencement of permeability enhancement, the injection solution was prepared by diluting stock chemicals with potable water from a nearby hydrant water source in a 150-gallon poly tank. Specifically, the appropriate volume of potable water was first added to the poly tank. Subsequently, the propeller located on the bottom of the poly tank was turned on to create a vortex and allow for homogenization of the added chemicals. The appropriate volume of LactOil® was then added to mixing tank using a plastic, battery-powered, submersible pump followed by addition of KCl and fluorescein through the top opening of the mixing tank. Following additions of all chemical reagents, the solution was mixed for approximately 10 minutes to allow for complete solubilization of the KCl and homogenization of all chemical reagents.

Top-down emplacement methodology was used to ensure a discrete fracture was initiated at each depth. Specifically, permeability enhancement was first initiated at the shallowest depth interval of interest of approximately 12 feet bgs within each enhancement borehole. Upon confirmation of fracture initiation and injection of the target volume of the amendment/tracer mixture into a permeability enhancement interval, the downhole pressure was allowed to dissipate. Subsequently, the wellhead assembly was removed and the downhole tooling advanced to the next depth interval of interest of approximately 15 feet bgs. These procedures were repeated until permeability enhancement was completed at three depth-discrete intervals of 12, 15, and 18 feet bgs at each of the four permeability enhancement initiation points. Tilt meter monitoring was performed at each depth-discrete interval of three of the four permeability enhancement initiation points including GFB539-HIP-01 through -HIP-03.

Upon completion of all permeability enhancement activities, preliminary tilt meter analysis results were used to guide confirmation sampling locations. Direct-push drilling technology was used for continuous collection of soil samples using dual tubes at eight confirmation borings located within and outside of the anticipated ROI of permeability enhancement from 0 to 25 feet bgs (GFB539-HCB01 through -HCB08). Note that the soil confirmation sampling was performed immediately following permeability enhancement. Lithologic logging was performed and soil samples were composited every 8 feet and submitted to an analytical laboratory for TOC analysis. A subset of the composited samples was also collected for field analysis of fluorescein using a handheld fluorometer. Specifically, approximately 5 grams of soil from each composited sample were added to 25 ml of deionized water, vortexed, centrifuged, and filtered through a 0.45-micron syringe filter, diluted as necessary, and analyzed for fluorescein.

Performance monitoring was performed by the U.S. Air Force subcontractor, LRS, and CDM Smith at select existing monitoring wells and at all newly installed monitoring wells at approximately 1 and 9 months following permeability enhancement. Similar to baseline groundwater sampling, low-stress, low-flow sampling techniques using peristaltic pumps were employed to facilitate collection of formation-representative samples. Following parameter stabilization monitored using a pre-calibrated multi-parameter water quality meter, the collected groundwater samples were submitted to an analytical laboratory for analyses of VOC, MEE, TOC, and anions. In addition, a subset of the collected samples was field analyzed for ferrous iron using a handheld HACH spectrophotometer.

5.5.5 Notable Results

Detailed analysis of all field observations as well as analytical and geophysics monitoring results, especially with regard to the project-specific performance objectives, is provided in **Section 6**. A summary of notable field/laboratory observations with regard to amendment distribution and injection volume, changes in hydraulic conductivity and injectability, changes in geochemical conditions and contaminant profile, and effectiveness of geophysics and other monitoring tools employed at GFAFB are provided herein.

5.5.5.1 Amendment Distribution & Injection Volume

The target injection volume of approximately 130 gallons per enhancement intervals was achieved at all three depth-discrete intervals of 12-, 15-, and 18-feet bgs at all four permeability enhancement initiation points as detailed in **Table 5.13**.

Table 5.13. Emplacement Volume at GFAFB

Enhancement initiation point	Enhancement depth (ft bgs)	# of enhancement intervals	Volume of solution emplaced (gal)
HIP-01	12-18	3	367
HIP-02	12-20	4	380
HIP-03	12-18	3	390
HIP-04	12-18	3	405
Total injection volume (gal)			**1542**
Target injection volume (gal)			**1560**

Very minimal surfacing (less than 5 gallons) was observed. Amendment delivery into nearby monitoring wells were visually observed. Uniform vertical amendment distribution was also observed as indicated by elevated fluorescein concentrations in soil in depth-discrete intervals at several post-enhancement confirmation borings. Unlike fluorescein, no significant differences in TOC concentrations in pre- and post-enhancement soil samples were observed due to the elevated background TOC (likely attributable to the presence of TPH and GRO), as shown in **Figure 5.36**.

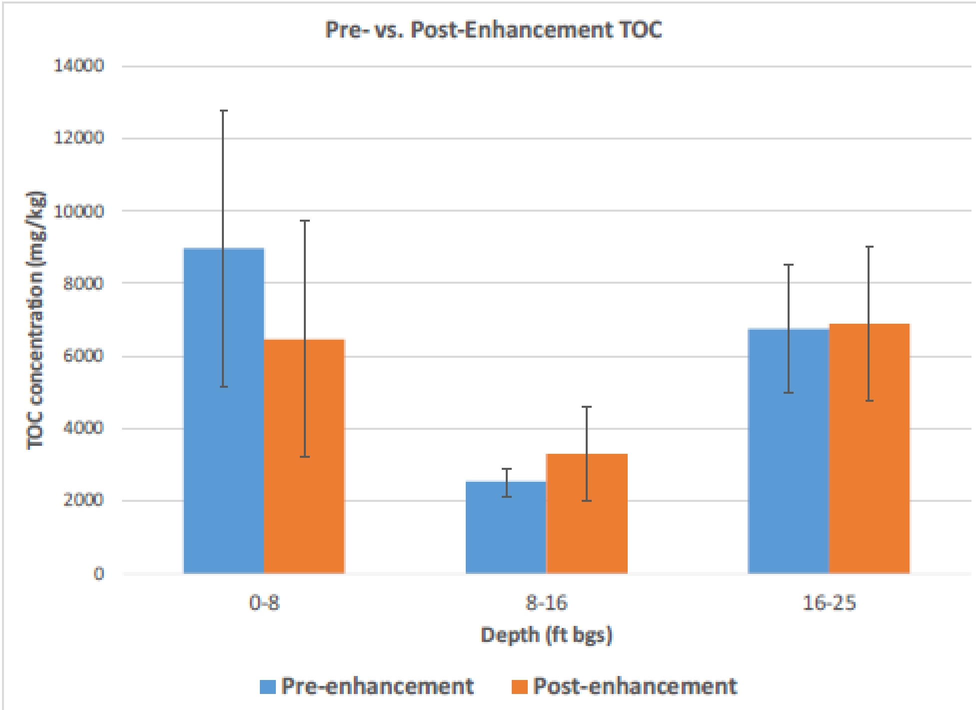

Figure 5.36. Pre- Versus Post-Enhancement TOC at GFAFB

5.5.5.2 Changes in Hydraulic Conductivities and Injectability

No significant changes in hydraulic conductivities were observed following permeability enhancement at GFAFB as shown in **Figure 5.37**; this was expected since no sand proppants were injected to create permanent high-permeability flow pathways within the target treatment zone. It should be noted that an injection rate of approximately 10 gpm was achieved during permeability enhancement, which is orders of magnitude higher than that was previously achieved at the site using conventional injection techniques (between 0.1 and 0.35 gpm).

5.5.5.3 Changes in Geochemical Conditions and Contaminant Profile & Estimated ROI

Highly reducing conditions characteristic of sulfate-reduction were observed following permeability enhancement at GFAFB. Compared to baseline conditions, orders-of-magnitude increases in TOC concentrations, coupled with depleted DO, very low ORP, elevated ferrous iron, and complete or near complete sulfate reduction, were observed at many of the nearby monitoring wells. Significant reduction in contaminant concentrations were observed. However, complete dechlorination of the chlorinated solvents were not achieved, which was anticipated, due to the lack of the appropriate microbial communities. These results are tabulated in **Table 5.14** and graphically depicted in **Figures 5.38** through **5.51**. Changes in TOC, conductivity, ORP, DO, and sulfate are also presented in plan views in **Figures 5.52** through **5.56**. The effective ROI of the hydraulic permeability enhancement at GFAFB was estimated to be at least 10 feet.

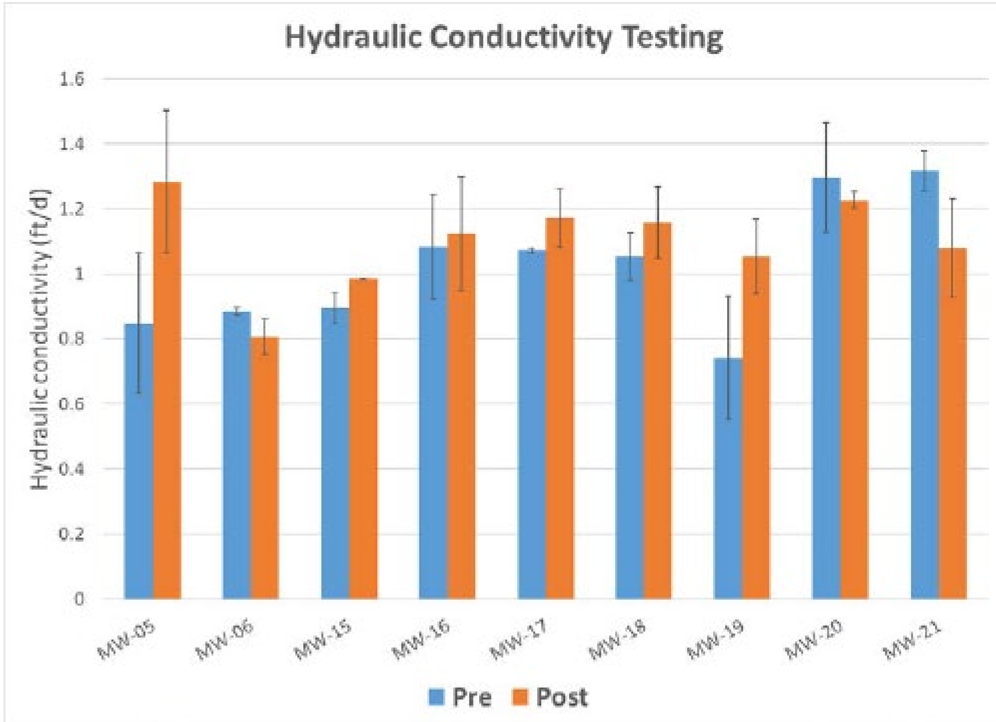

Figure 5.37. Pre- Versus Post-Enhancement Hydraulic Conductivity at GFAFB

Table 5.14. Summary of Performance Monitoring Results at GFAFB

Well ID	Sampling event	Sampling date	Chlorinated ethenes					BTEX				MEE		
			PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	VC	Benzene	Toluene	Ethylbenzene	Xylene	Methane	Ethene	Ethane
			µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
GFB539-MW01	1-m post-enhancement	10/11/2016	< 0.5	< 0.5	< 0.5	< 1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW02	1-m post-enhancement	10/12/2016	< 0.5	14200	12800	913	< 50	1700	< 50	1400	< 25	7.2 J	< 5	< 5
GFB539-MW03	Pre-enhancement	9/12/2016	< 0.15	< 0.1	< 0.1	< 0.1	< 0.12	< 0.1	< 0.1	< 0.1	< 0.1	0.64 J	< 0.3	< 0.32
GFB539-MW03	1-m post-enhancement	10/12/2016	< 0.5	< 0.5	< 0.5	< 1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW03	9-m post-enhancement	6/12/2017	< 0.15	< 0.1	< 0.1	< 0.1	< 0.12	< 0.1	< 0.1	< 0.1	< 0.1	0.52 J	< 0.3	< 0.32
GFB539-MW04	Pre-enhancement	9/11/2016	< 25	< 0.1	< 0.1	< 0.1	< 0.12	< 0.1	< 0.1	< 0.1	< 0.1	0.17 J	< 0.3	< 0.32
GFB539-MW04	1-m post-enhancement	10/12/2016	< 0.5	< 0.5	< 0.5	< 1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW04	9-m post-enhancement	6/12/2017	< 25	0.2 J	0.3 J	< 0.1	< 0.12	< 0.1	< 0.1	< 0.1	< 0.1	0.41 J	< 0.3	< 0.32
GFB539-MW05	Pre-enhancement	9/11/2016	< 37	15000 E	20000 E	3200 E	< 30	1500 E	25 J	390 E	< 25	73 E	3.4 J	1.3 J
GFB539-MW05	1-m post-enhancement	10/12/2016	< 0.5	14900	12300	846	< 50	1600	< 50	1490	< 25	7.6 J	< 5	< 5
GFB539-MW05	9-m post-enhancement	6/12/2017	< 37	13000 E	7800 E	290	< 30	820 E	25 J	730 E	25 J	180 E	3 J	3.2 J
GFB539-MW06	Pre-enhancement	9/11/2016	< 0.5	23	14	1.1	< 0.12	0.86 J	< 0.1	< 0.1	< 0.1	2.3	< 0.3	< 0.32
GFB539-MW06	1-m post-enhancement	10/12/2016	< 2.5	54.9	49.6	5 J	< 5	3.1	< 5	< 5	< 2.5	< 5	< 5	< 5
GFB539-MW06	9-m post-enhancement	6/13/2017	< 0.5	15	17	0.74 J	< 0.12	0.63 J	< 0.1	< 0.1	< 0.1	28	< 0.3	< 0.32
GFB539-MW07	1-m post-enhancement	10/11/2016	< 0.5	< 0.5	< 0.5	< 1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW09	Pre-enhancement	9/11/2016	< 25	5.6	6.1	0.27 J	< 0.12	< 0.1	< 0.1	< 0.1	< 0.1	2.2	< 0.3	< 0.32
GFB539-MW09	1-m post-enhancement	10/12/2016	< 0.5	1.8	68.8	2.6	< 1	< 0.5	< 1	< 1	< 0.5	5.3 J	< 5	< 5
GFB539-MW09	9-m post-enhancement	6/12/2017	< 25	1.7	51	1.9	< 0.12	< 0.1	< 0.1	< 0.1	< 0.1	140 E	< 1.5	< 1.6
GFB539-MW10	Pre-enhancement	9/11/2016	< 1.5	120 E	99	1.5 J	< 1.2	< 1	< 1	< 1	< 1	1.5 J	< 0.3	< 0.32
GFB539-MW10	1-m post-enhancement	10/12/2016	< 25	129	153	2.1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW10	9-m post-enhancement	6/12/2017	< 1.5	15	140 E	< 1.3	< 1.2	< 1	< 1	< 1	< 1	110 E	< 1.5	< 1.6
GFB539-MW11	Pre-enhancement	9/12/2016	< 25	75	200 E	5.3 J	1.2 J	1 J	< 1	< 1	< 1	13	< 0.3	< 0.32
GFB539-MW11	1-m post-enhancement	10/12/2016	< 0.5	50	236	6	< 1	< 0.5	< 1	< 1	< 0.5	78.2	< 5	< 5
GFB539-MW11	9-m post-enhancement	6/12/2017	< 25	42	190 E	4.9 J	1.2 J	1 J	< 1	< 1	< 1	2200 E	< 30	< 32
GFB539-MW13	1-m post-enhancement	10/11/2016	< 0.5	< 0.5	< 0.5	< 1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW14	1-m post-enhancement	10/11/2016	< 0.5	< 0.5	< 0.5	< 1	< 1	< 0.5	< 1	< 1	< 0.5	< 5	< 5	< 5
GFB539-MW15	Pre-enhancement	9/12/2016	< 37	18000 E	12000 E	2300 E	< 30	350	87 J	180 J	< 25	5.5	0.73 J	4.3
GFB539-MW15	1-m post-enhancement	10/13/2016	< 25	6400	4820	923	< 50	131	104	124	< 25	< 5	< 5	< 5
GFB539-MW15	9-m post-enhancement	6/12/2017	< 7.5	2100 E	2000 E	280	< 6	52 J	27 J	15 J	< 5	22	1.6 J	2.1
GFB539-MW16	Pre-enhancement	9/12/2016	< 37	4700 E	22000 E	5100 E	32 J	530	54 J	460 E	25 J	3.8	0.83 J	4.2
GFB539-MW16	1-m post-enhancement	10/13/2016	< 25	3090	11400	2740	< 50	362	110	573	< 25	7 J	< 5	< 5
GFB539-MW16	9-m post-enhancement	6/12/2017	< 7.5	650 E	3700 E	570 E	< 6	79	28 J	45 J	5 J	17	2	2.8
GFB539-MW17	Pre-enhancement	9/12/2016	< 15	5600 E	8700 E	990 E	16 J	98 J	230 E	62 E	10 J	3	< 0.3	< 0.32
GFB539-MW17	1-m post-enhancement	10/13/2016	< 25	3840	4560	583	< 50	84.1	143	151	< 25	7.1 J	< 5	< 5
GFB539-MW17	9-m post-enhancement	6/13/2017	< 7.5	1700 E	2000 E	170	13 J	40 J	35 J	36 J	< 5	39 E	0.67 J	0.64 J
GFB539-MW18	Pre-enhancement	9/12/2016	< 7.5	220 E	250 E	22 J	< 6	< 5	97	< 5	5 J	1.1 J	< 0.3	< 0.32
GFB539-MW18	1-m post-enhancement	10/13/2016	< 25	393	247	< 50	< 50	< 25	< 50	< 50	< 25	7.2 J	< 5	< 5
GFB539-MW18	9-m post-enhancement	6/13/2017	< 0.75	190	150	7.6	0.93 J	0.71 J	12	< 0.5	< 0.5	38 E	0.6 J	0.64 J
GFB539-MW19	Pre-enhancement	9/12/2016	< 15	2300 E	7000 E	660 E	15 J	48 J	20 J	< 10	10 J	8.1	< 0.3	< 0.32
GFB539-MW19	1-m post-enhancement	10/13/2016	< 25	1470	3250	334	< 50	28	< 50	< 50	< 25	12.1	< 5	< 5
GFB539-MW19	9-m post-enhancement	6/13/2017	< 7.5	700 E	2300 E	170	6.8 J	14 J	8.3 J	5.3 J	< 5	40 E	2.3 J	0.99 J
GFB539-MW20	Pre-enhancement	9/11/2016	< 15	1800 E	9600 E	1000 E	19 J	120	14 J	64 E	< 10	12	1.2 J	4.3
GFB539-MW20	1-m post-enhancement	10/12/2016	< 0.5	1480	7840	1140	8.8	121	12.6	78.7	7	10.3	< 5	< 5
GFB539-MW20	9-m post-enhancement	6/12/2017	< 37	730 E	14000 E	1600 E	< 30	150 J	25 J	78 E	25 J	30	4.2	16
GFB539-MW21	Pre-enhancement	9/11/2016	< 37	99 J	16000 E	600 E	32 J	130 J	25 J	< 25	< 25	30	0.69 J	0.41 J
GFB539-MW21	1-m post-enhancement	10/13/2016	< 5	117	9920	477	20.6	95	< 10	16.5	< 5	28.9	< 5	< 5
GFB539-MW21	9-m post-enhancement	6/13/2017	< 7.5	51 J	3800 E	160 E	8.1 J	22 J	5 J	5 J	< 5	74 E	1.9 J	1.3 J

Table 5.14. Summary of Performance Monitoring Results at GFAFB (cont'd)

Well ID	Sampling event	Sampling date	Geochemical parameters							
			TOC	pH	Conductivity	DO	ORP	Nitrate	Ferrous iron	Sulfate
			mg/L	SU	mS/cm	mg/L	mV	mg/L	mg/L	mg/L
GFB539-MW01	1-m post-enhancement	10/11/2016	#N/A	#N/A	#N/A	#N/A	#N/A	1.7	#N/A	3020
GFB539-MW02	1-m post-enhancement	10/12/2016	4560	#N/A	#N/A	#N/A	#N/A	1.3 J	#N/A	1350
GFB539-MW03	Pre-enhancement	9/12/2016	25.7	6.97	7.65	4.14	22.5	0.198	0.1	4680
GFB539-MW03	1-m post-enhancement	10/12/2016	33.2	6.68	12.61	1.01	-135.2	0.3	0.47	3910
GFB539-MW03	9-m post-enhancement	6/12/2017	20.2	6.76	9.714	2.62	165.8	0.212	0	6050
GFB539-MW04	Pre-enhancement	9/11/2016	19.8	6.97	13.77	0.5	5.3	1.12	0.2	6330
GFB539-MW04	1-m post-enhancement	10/12/2016	23.1	6.84	8.515	3.05	-0.9	0.44	0	7880
GFB539-MW04	9-m post-enhancement	6/12/2017	19.5	6.87	12.5	1.11	-25.9	0.109	0	8810
GFB539-MW05	Pre-enhancement	9/11/2016	74.7	6.97	2.919	0.4	-101.5	0.219	4	1030
GFB539-MW05	1-m post-enhancement	10/12/2016	4490	5.56	15.66	0.19	-239.6	1.2 J	#N/A	1600
GFB539-MW05	9-m post-enhancement	6/12/2017	867	6.25	7.15	0.85	-170.6	< 0.125	3.03	60.7
GFB539-MW06	Pre-enhancement	9/11/2016	3.25	6.95	3.808	0.54	-32.6	< 0.025	0.1	2050
GFB539-MW06	1-m post-enhancement	10/12/2016	25.8	6.88	3.441	0.24	-169	< 0.019	3.45	2100
GFB539-MW06	9-m post-enhancement	6/13/2017	6.43	6.88	3.686	0.81	-297.5	< 0.025	2.58	1250
GFB539-MW07	1-m post-enhancement	10/11/2016	#N/A	#N/A	#N/A	#N/A	#N/A	< 0.019	#N/A	6460
GFB539-MW09	Pre-enhancement	9/11/2016	19.5	7.19	2.006	0.45	-65	0.0534 J	0.4	926
GFB539-MW09	1-m post-enhancement	10/12/2016	24.6	7.06	2.864	3.63	-61.8	< 0.057	4.2	1640
GFB539-MW09	9-m post-enhancement	6/12/2017	11.3	6.63	3.623	1.23	11.8	< 0.025	3.95	1570
GFB539-MW10	Pre-enhancement	9/11/2016	13	7.12	5.187	0.35	-41.3	< 0.025	1.2	3280
GFB539-MW10	1-m post-enhancement	10/12/2016	12.5	6.19	4.085	0.6	-150.2	< 0.057	2.47	3390
GFB539-MW10	9-m post-enhancement	6/12/2017	7.17	6.83	3.673	1.09	-41.6	< 0.025	1.65	1920
GFB539-MW11	Pre-enhancement	9/12/2016	23.6	7.11	6.642	0.39	-105	< 0.025	0.5	4080
GFB539-MW11	1-m post-enhancement	10/12/2016	28.9	6.41	5.11	0.4	-207.7	< 0.057	2.79	3750
GFB539-MW11	9-m post-enhancement	6/12/2017	26.5	6.61	5.701	1.09	-45.6	< 0.025	3.28	3270
GFB539-MW13	1-m post-enhancement	10/11/2016	#N/A	#N/A	#N/A	#N/A	#N/A	0.18	#N/A	6830
GFB539-MW14	1-m post-enhancement	10/11/2016	#N/A	#N/A	#N/A	#N/A	#N/A	< 0.057	#N/A	6130
GFB539-MW15	Pre-enhancement	9/12/2016	24.8	6.93	6.4	11.4	78.3	0.0686 J	0.2	4580
GFB539-MW15	1-m post-enhancement	10/13/2016	4910	6.34	18.4	1.42	29.4	0.75 J	#N/A	2110
GFB539-MW15	9-m post-enhancement	6/12/2017	872	6.39	12.9	0.84	-229.8	< 0.125	0.23	737

Table 5.14. Summary of Performance Monitoring Results at GFAFB (cont'd)

Well ID	Sampling event	Sampling date	Geochemical parameters							
			TOC	pH	Conductivity	DO	ORP	Nitrate	Ferrous iron	Sulfate
			mg/L	SU	mS/cm	mg/L	mV	mg/L	mg/L	mg/L
GFB539-MW16	Pre-enhancement	9/12/2016	31	7.14	4.015	10.99	115.3	0.0578 J	0.1	2240
GFB539-MW16	1-m post-enhancement	10/13/2016	4020	6.16	17.09	2.32	13	0.76 J	#N/A	1370
GFB539-MW16	9-m post-enhancement	6/12/2017	1080	6.18	12.88	0.88	-230.5	< 0.125	2.03	309
GFB539-MW17	Pre-enhancement	9/12/2016	31.2	7.01	6.678	9.73	145.5	0.104	0.1	4700
GFB539-MW17	1-m post-enhancement	10/13/2016	2550	6.12	16.01	0.22	-250.3	< 0.56	3	2790
GFB539-MW17	9-m post-enhancement	6/13/2017	207	6.86	8.835	0.83	-312.5	< 0.125	0	208
GFB539-MW18	Pre-enhancement	9/12/2016	17.1	6.95	7.555	9.8	137.6	0.155	0.1	5950
GFB539-MW18	1-m post-enhancement	10/13/2016	2740	6.17	16.28	0.18	-203.3	0.66 J	#N/A	3120
GFB539-MW18	9-m post-enhancement	6/13/2017	312	6.71	11.53	0.81	-329	< 0.125	0.19	961
GFB539-MW19	Pre-enhancement	9/12/2016	28.4	7.21	6.6	10.92	132.7	0.0613 J	0.1	4630
GFB539-MW19	1-m post-enhancement	10/13/2016	7170	6	22.9	0.39	-67.1	0.8 J	3	1670
GFB539-MW19	9-m post-enhancement	6/13/2017	1230	6.11	12.7	0.81	-267.8	< 0.125	23	1060
GFB539-MW20	Pre-enhancement	9/11/2016	11.8	6.96	4.154	6.22	72.6	< 0.025	0.1	2550
GFB539-MW20	1-m post-enhancement	10/12/2016	28.4	7.07	3.032	3.31	-97	< 0.019	5	2500
GFB539-MW20	9-m post-enhancement	6/12/2017	15.3	6.74	3.51	0.98	-62.1	< 0.025	2.96	1860
GFB539-MW21	Pre-enhancement	9/11/2016	26.3	7.15	3.436	8.6	122.7	< 0.025	0.1	1780
GFB539-MW21	1-m post-enhancement	10/13/2016	40	6.86	2.689	3.37	-4.3	< 0.057	0.34	1840
GFB539-MW21	9-m post-enhancement	6/13/2017	16	6.97	4.145	0.9	-199.4	< 0.025	2.43	2750

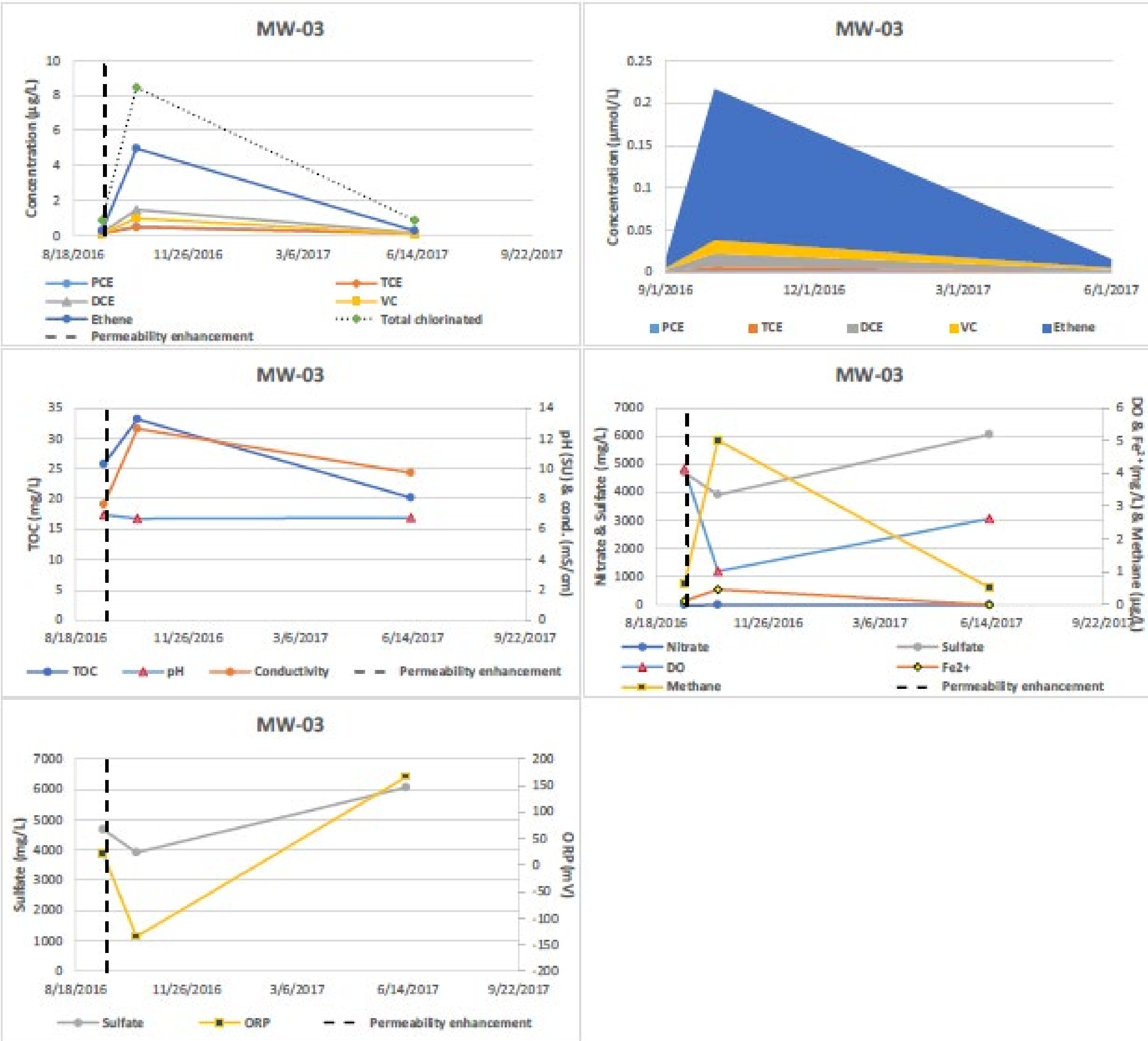

Figure 5.38. Trend Charts – GFB539-MW03

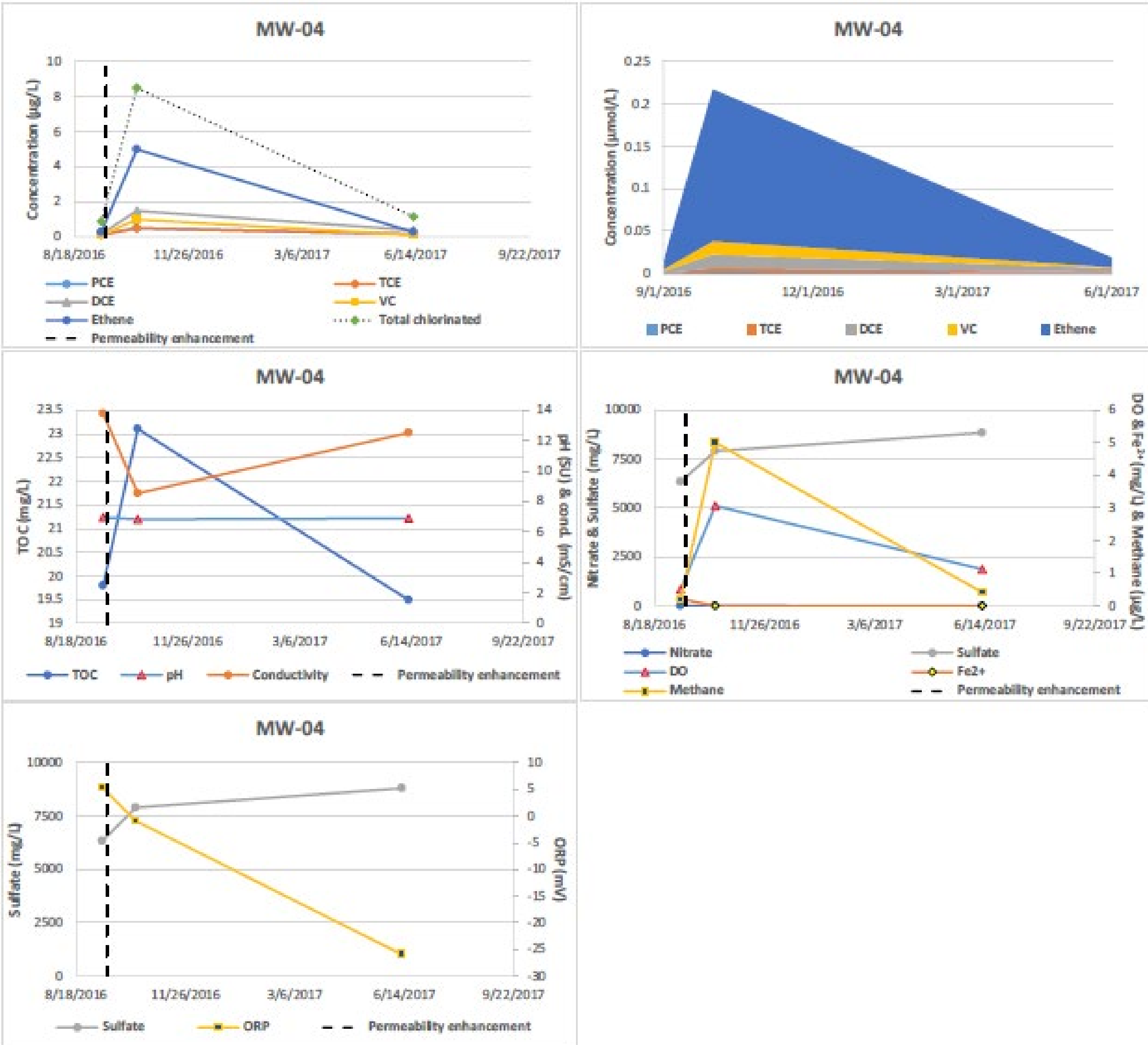

Figure 5.39. Trend Charts – GFB539-MW04

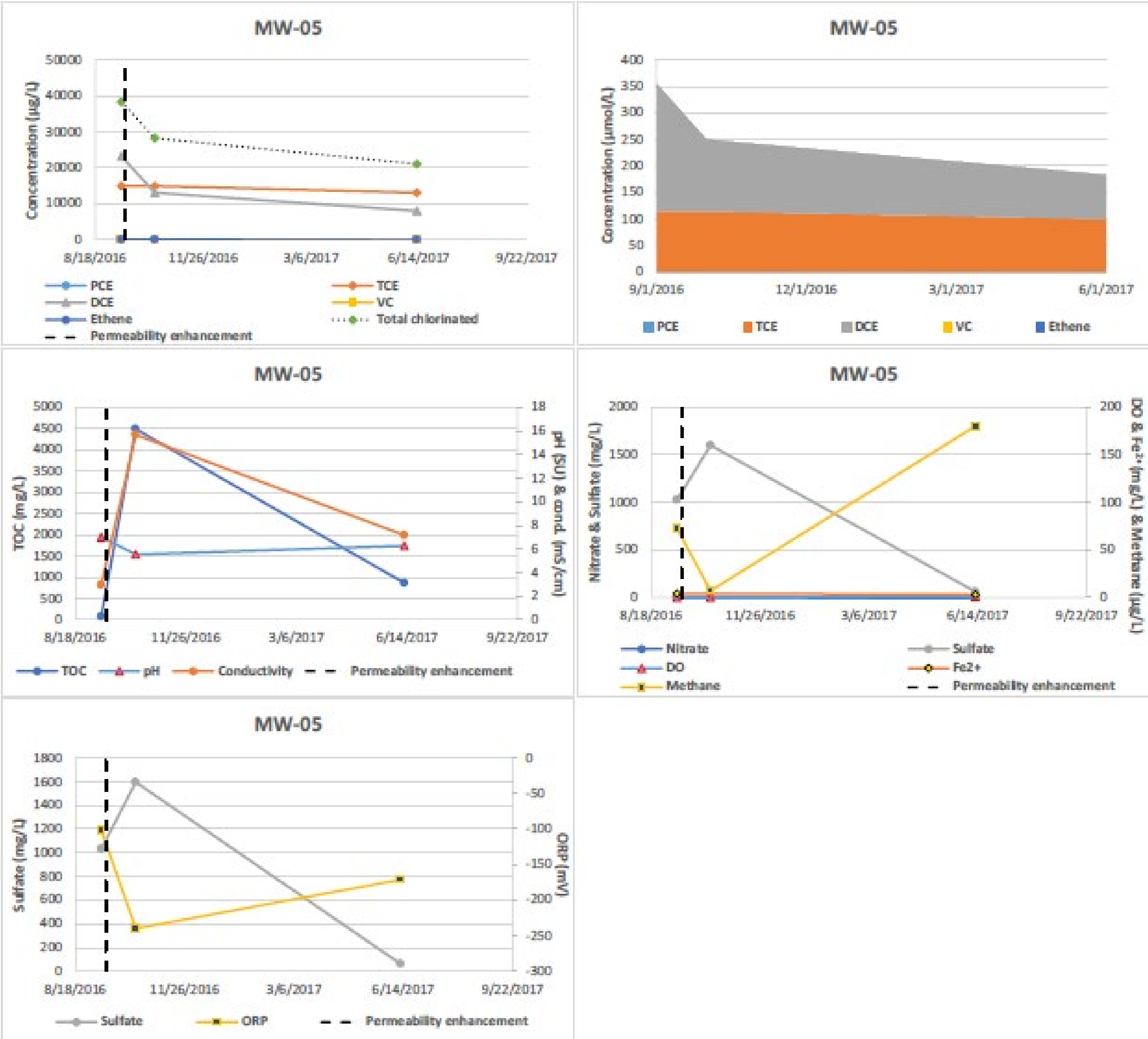

Figure 5.40. Trend Charts – GFB539-MW05

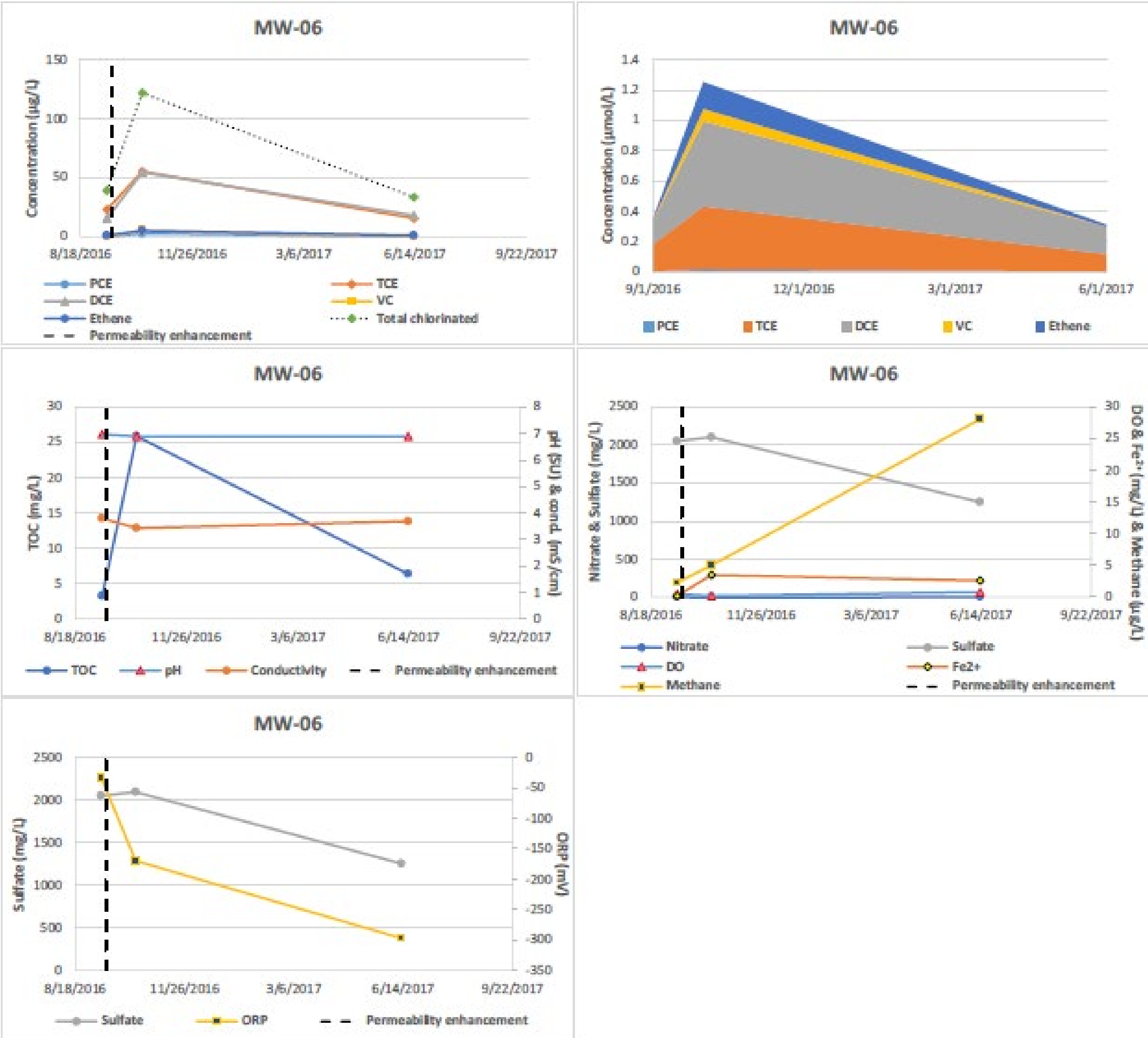

Figure 5.41. Trend Charts – GFB539-MW06

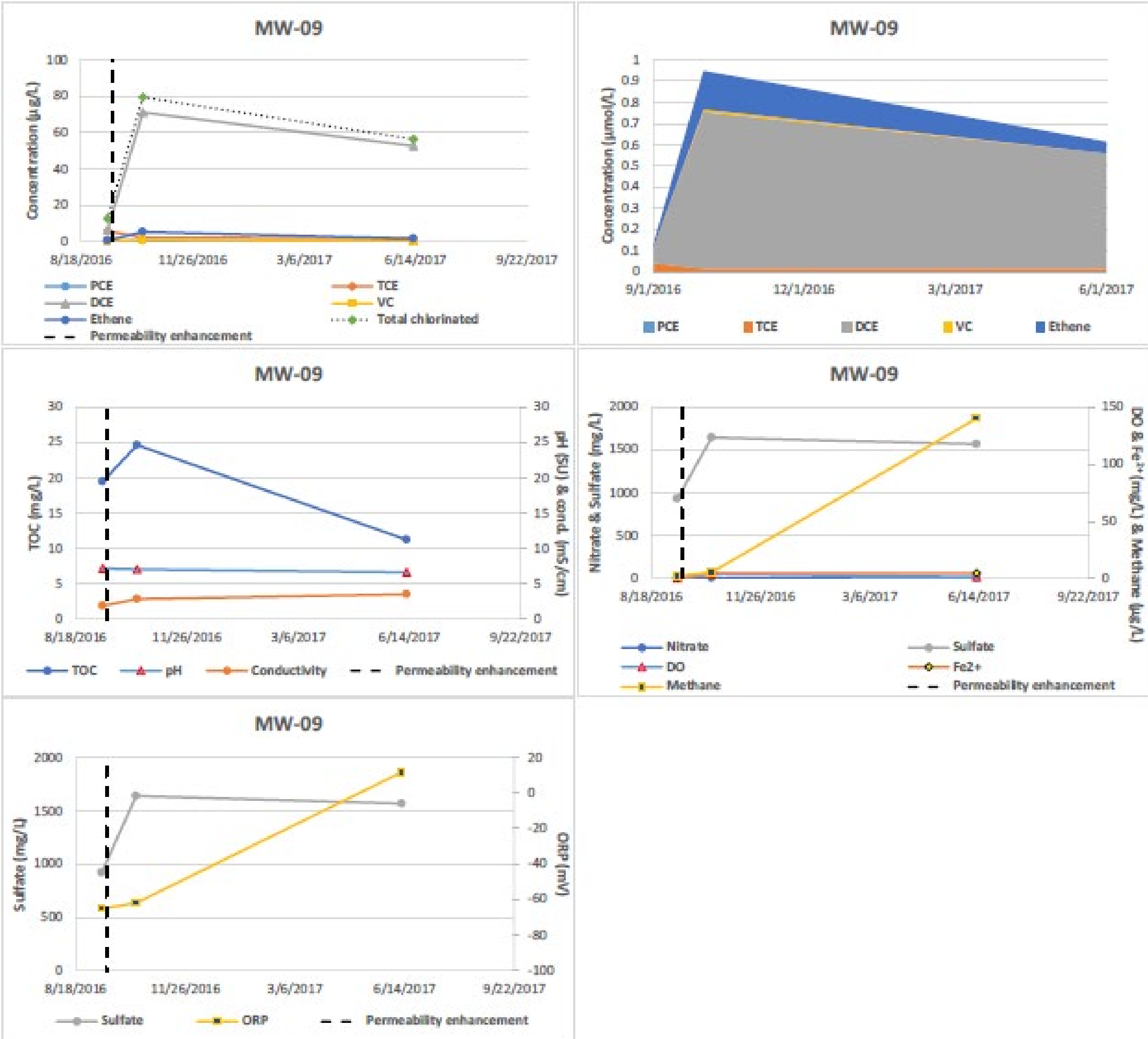

Figure 5.42. Trend Charts – GFB539-MW09

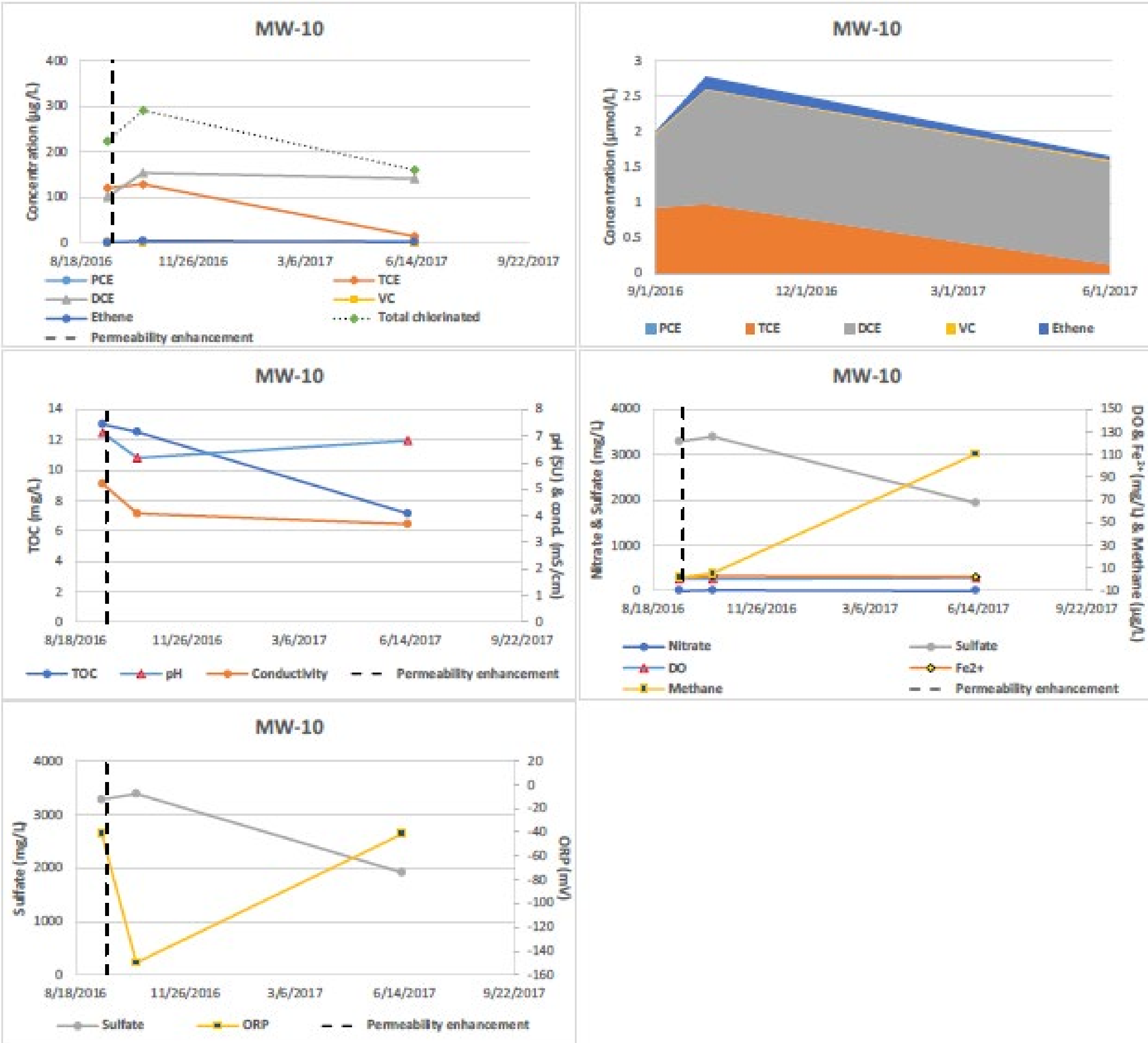

Figure 5.43. Trend Charts – GFB539-MW10

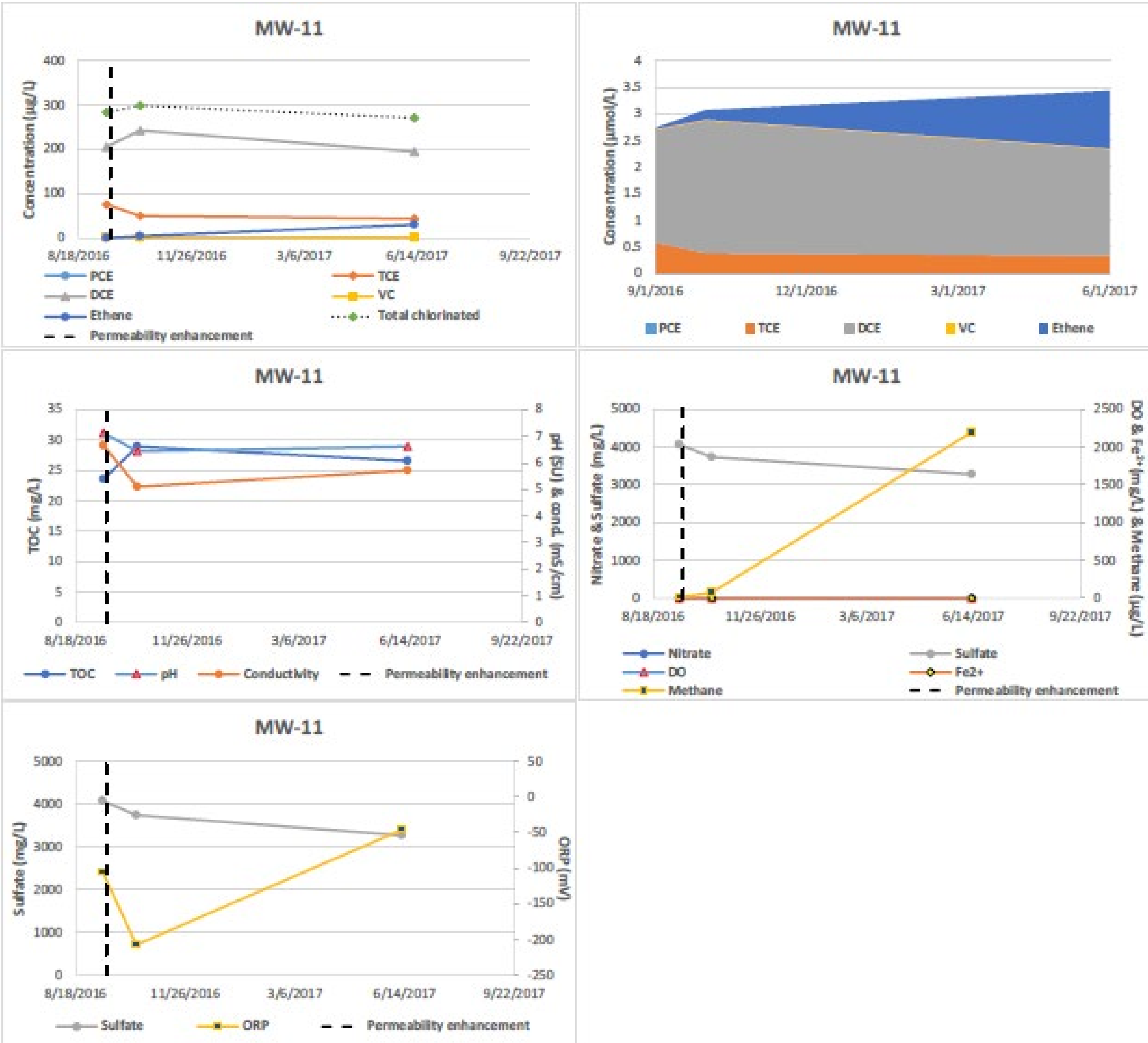

Figure 5.44. Trend Charts – GFB539-MW11

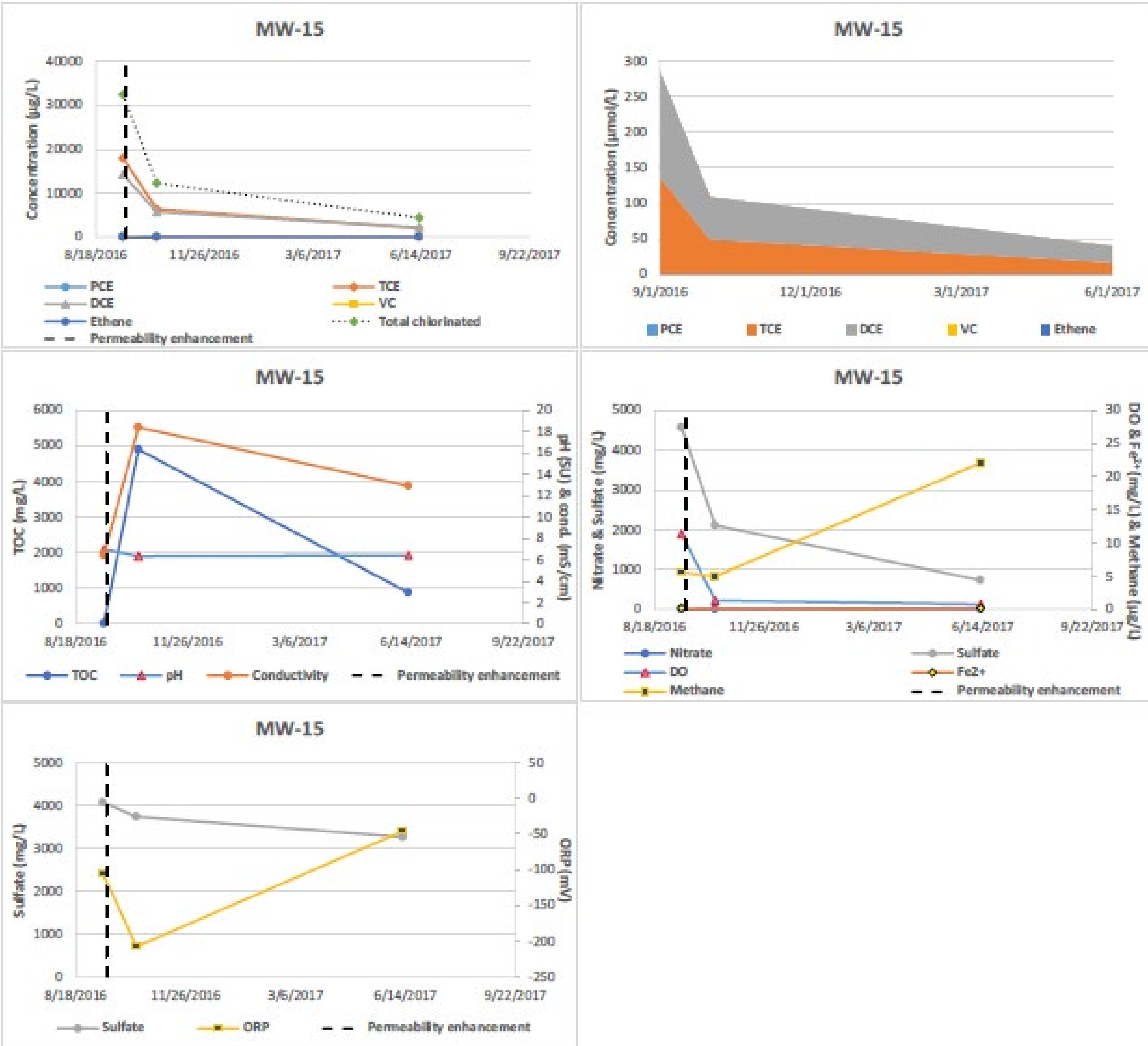

Figure 5.45. Trend Charts – GFB539-MW15

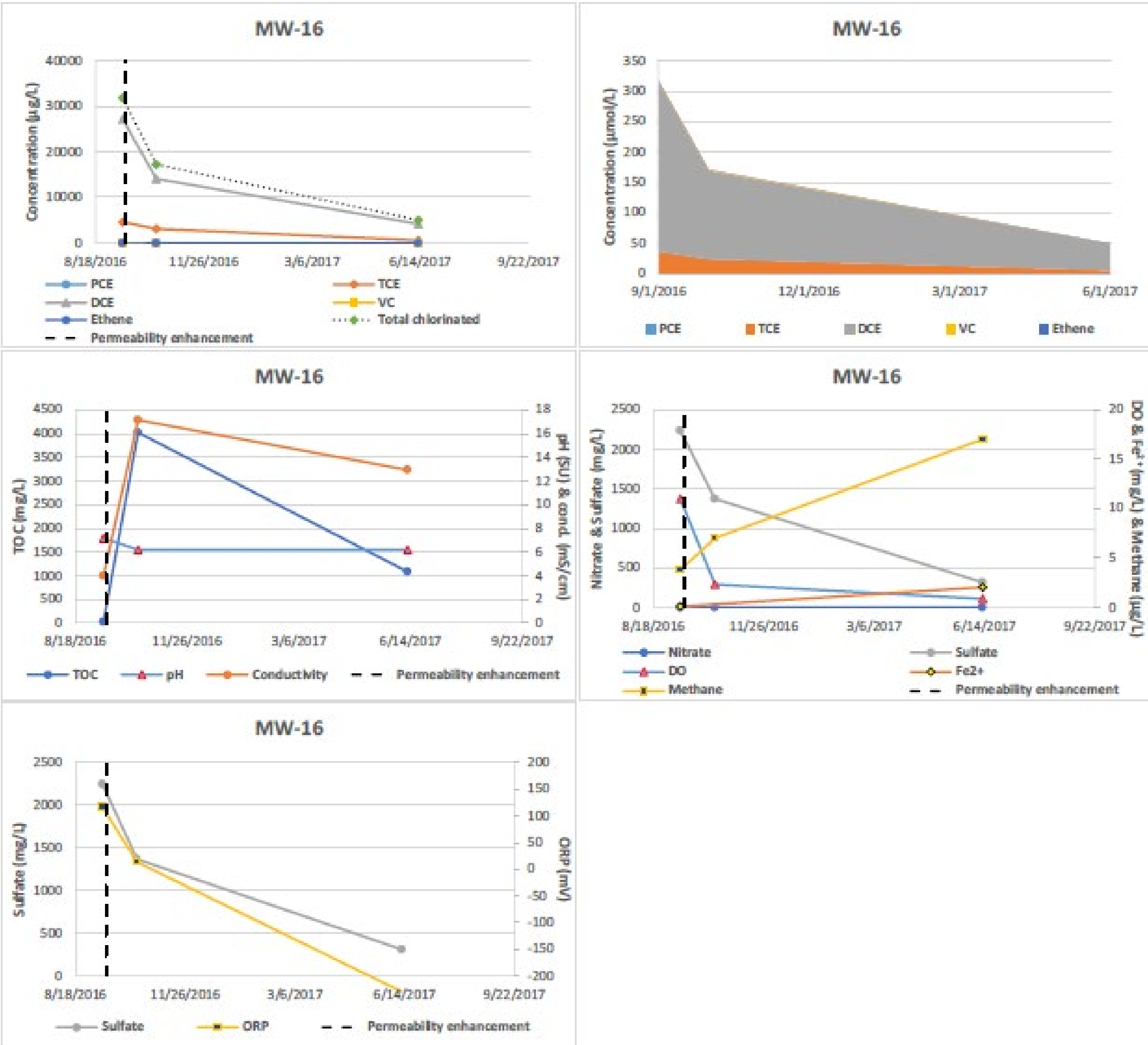

Figure 5.46. Trend Charts – GFB539-MW16

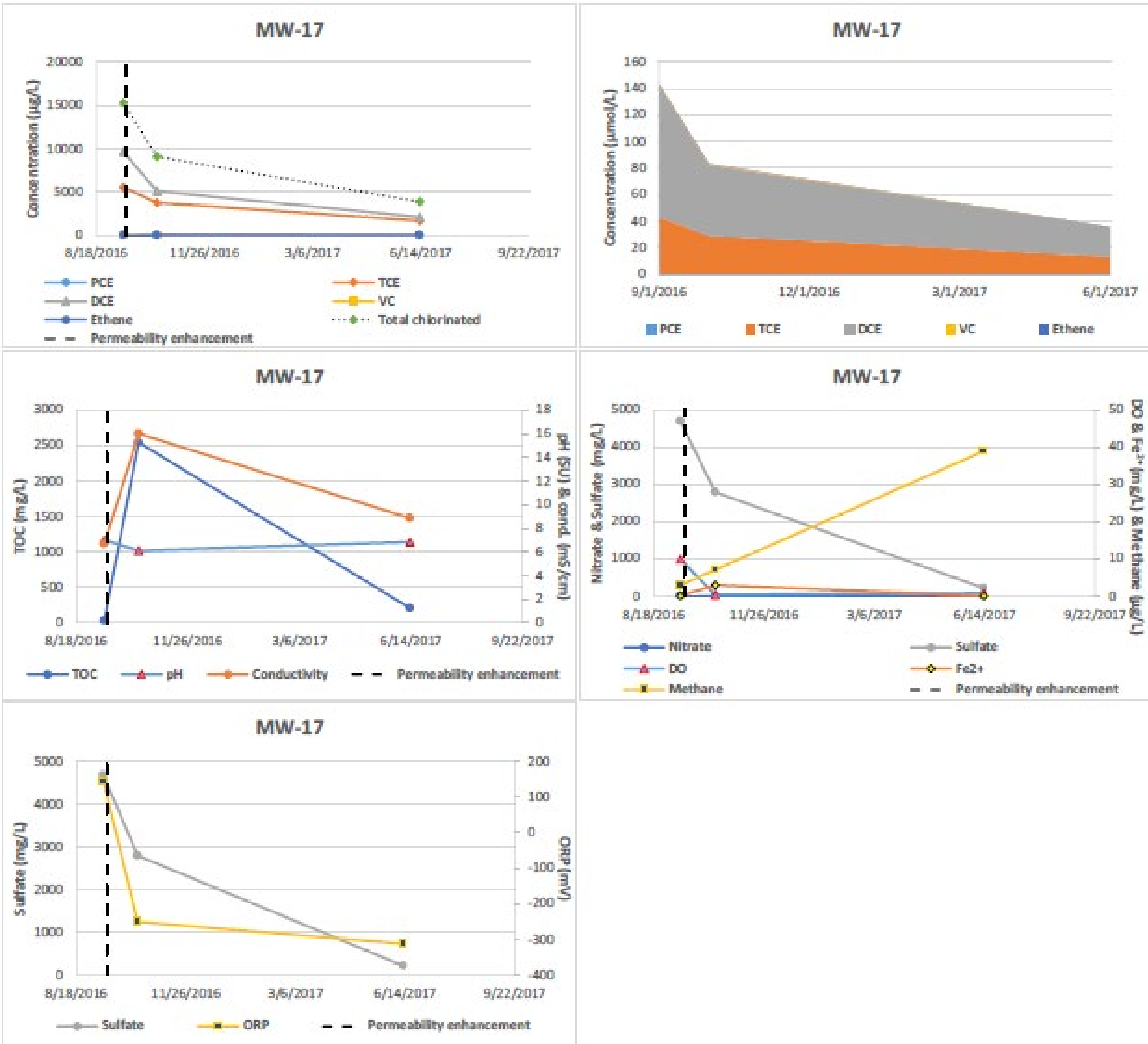

Figure 5.47. Trend Charts – GFB539-MW17

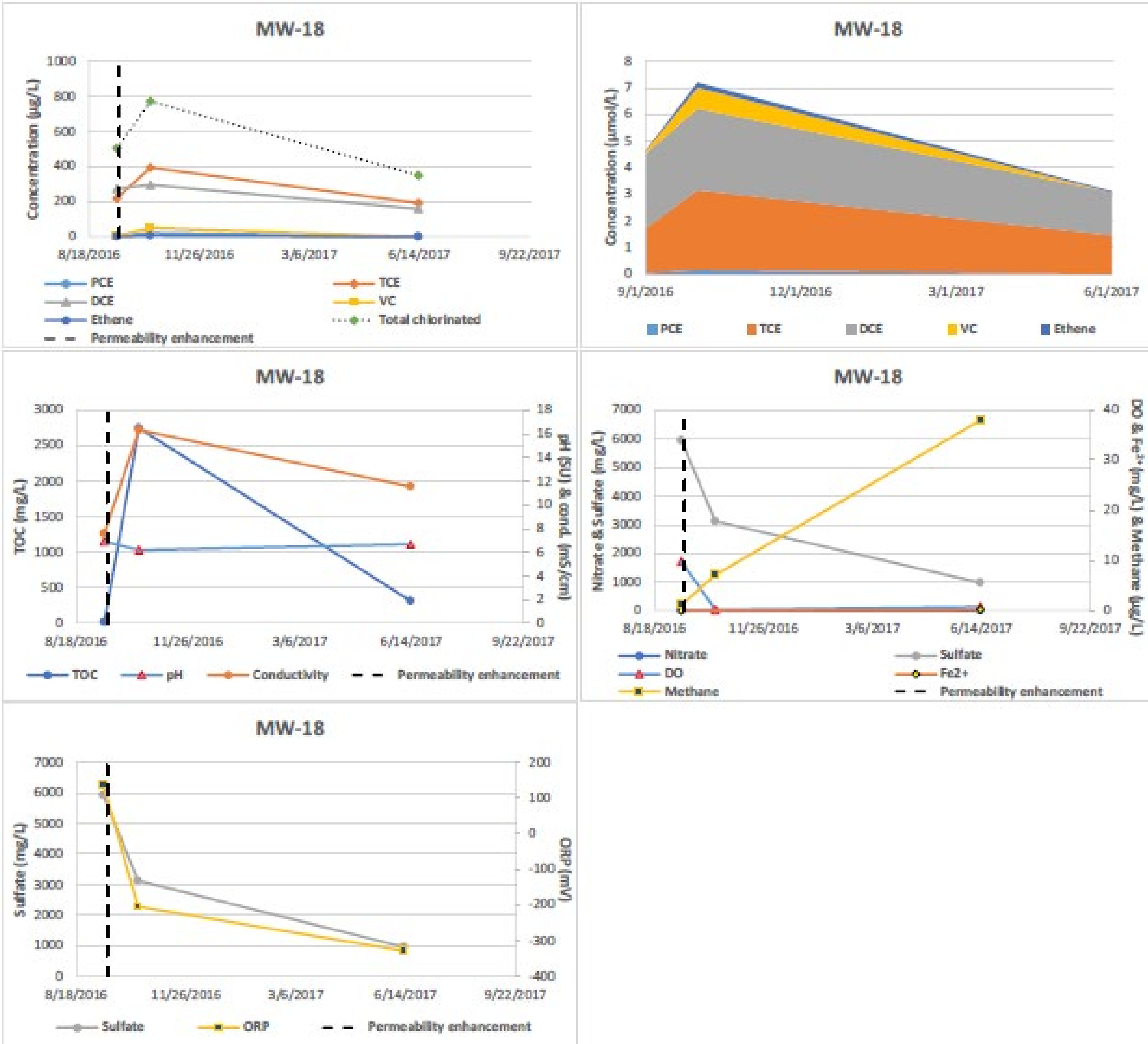

Figure 5.48. Trend Charts – GFB539-MW18

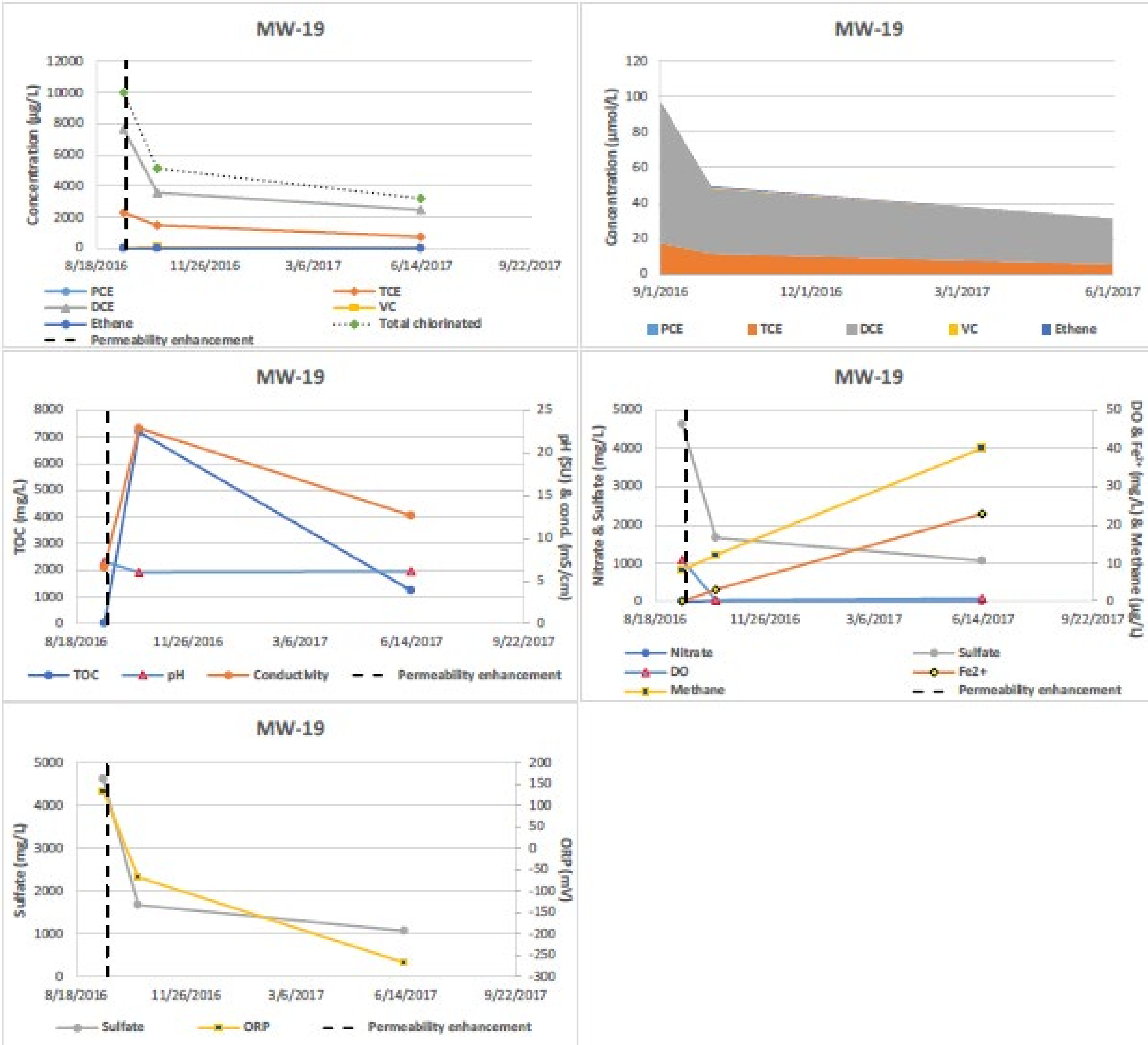

Figure 5.49. Trend Charts – GFB539-MW19

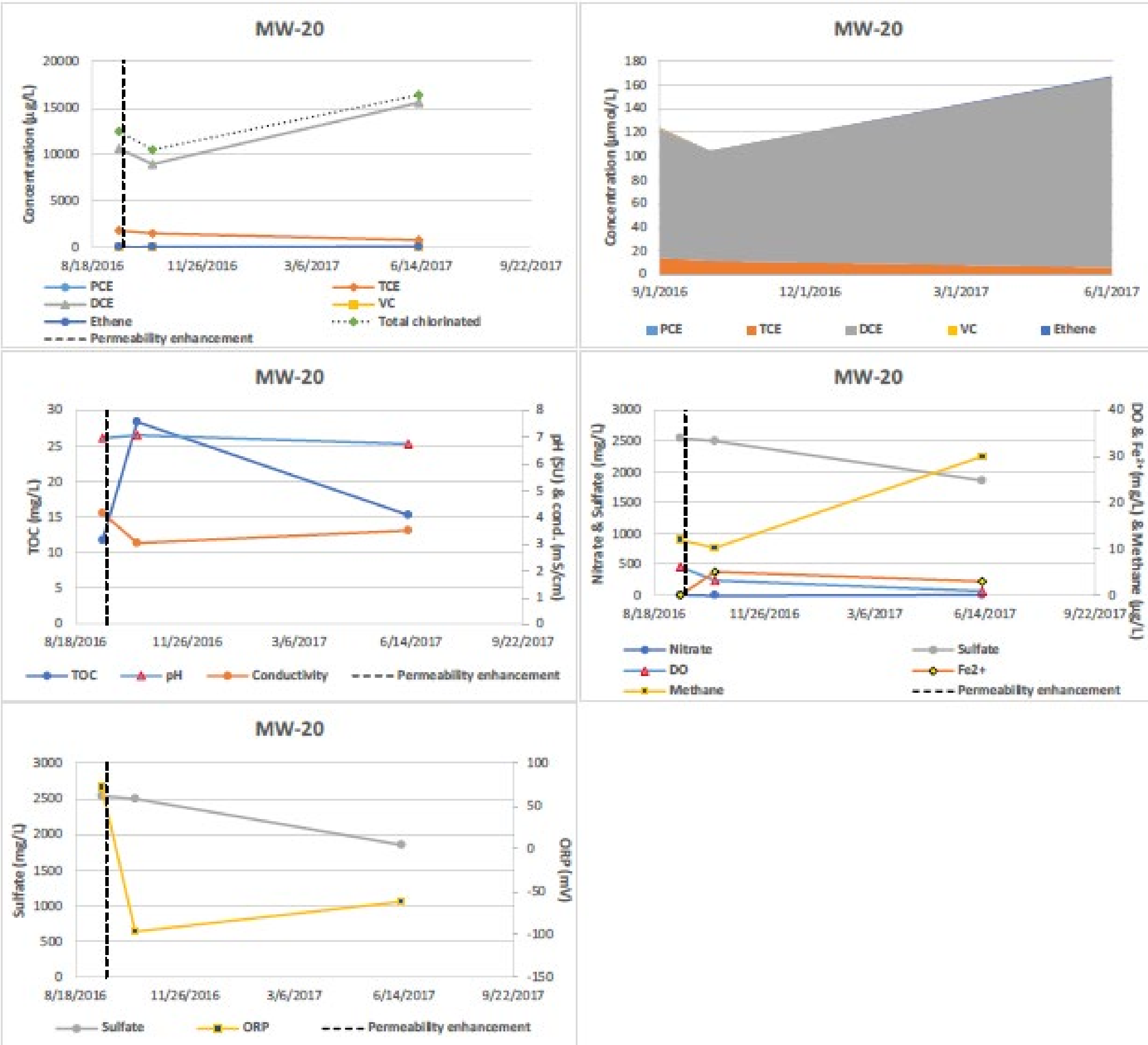

Figure 5.50. Trend Charts – GFB539-MW20

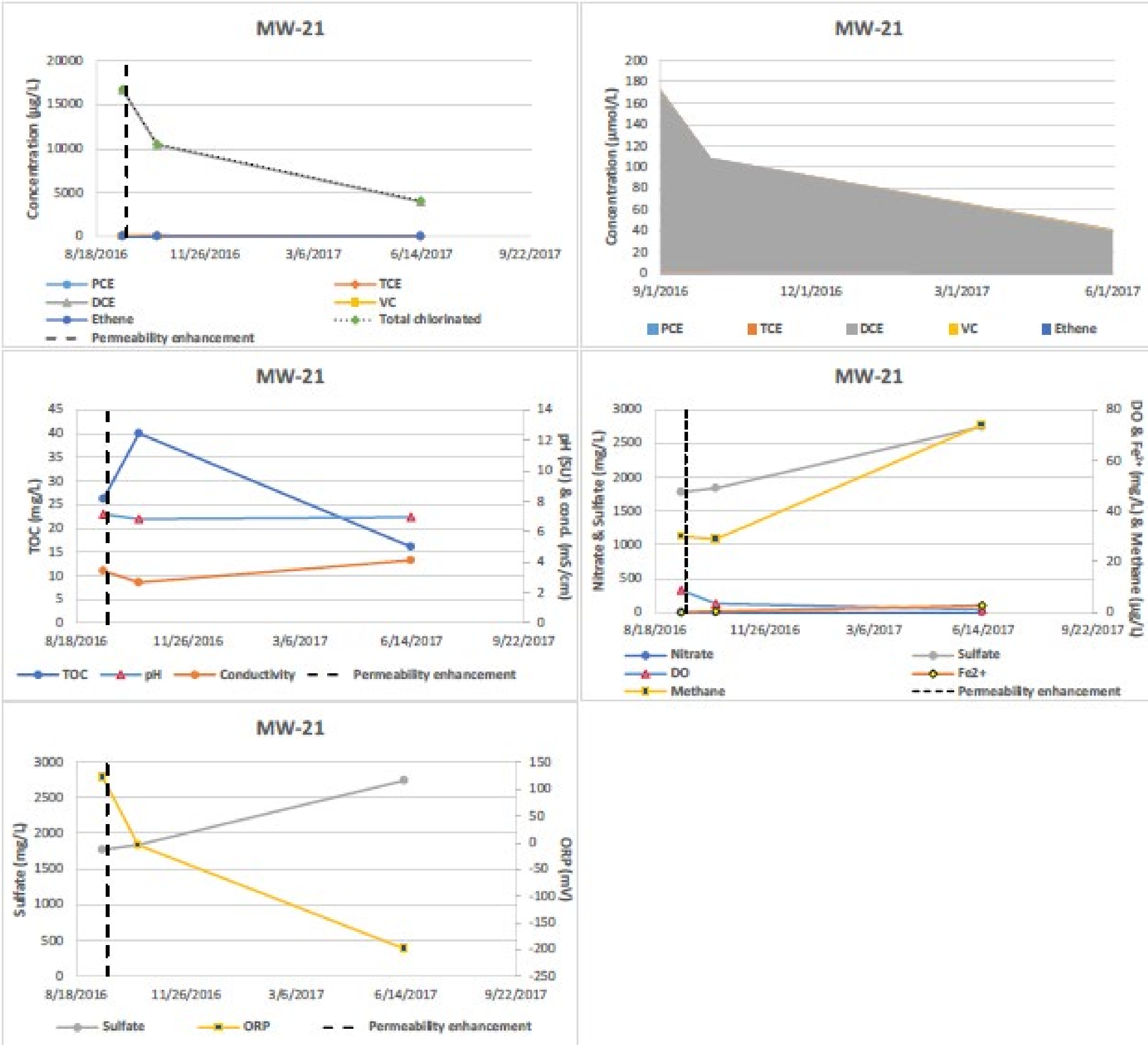

Figure 5.51. Trend Charts – GFB539-MW21

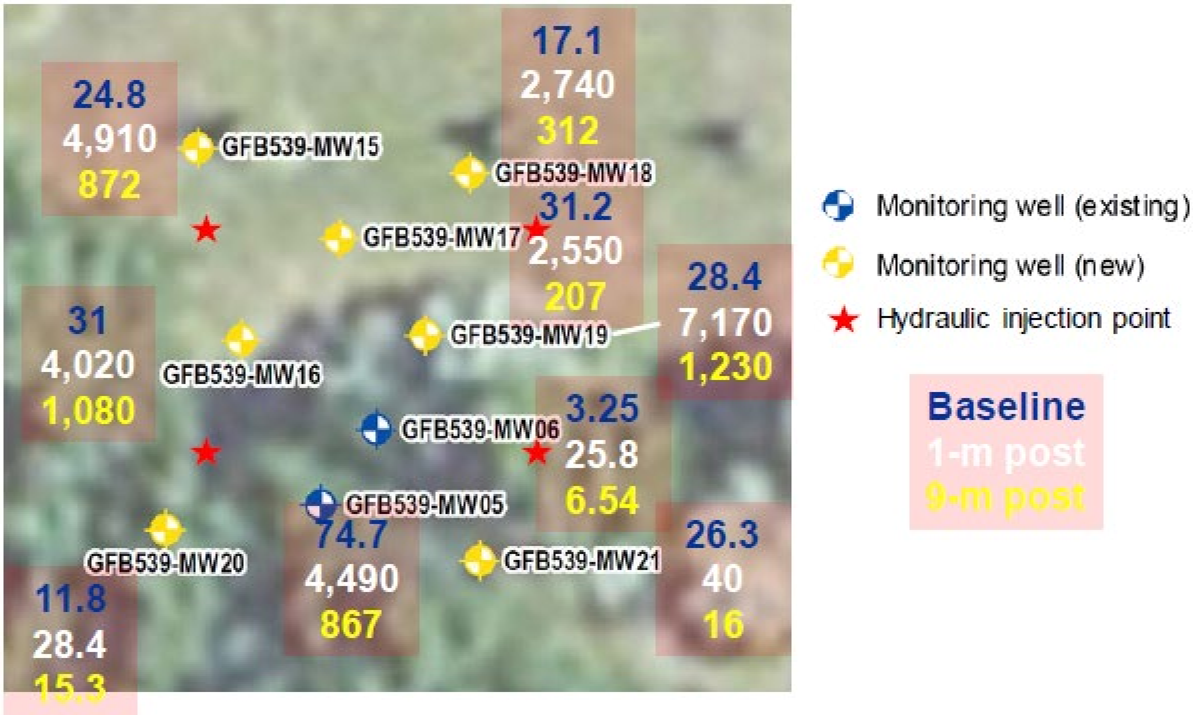

Figure 5.52. Changes in TOC (mg/L) at GFAFB (Plan View)

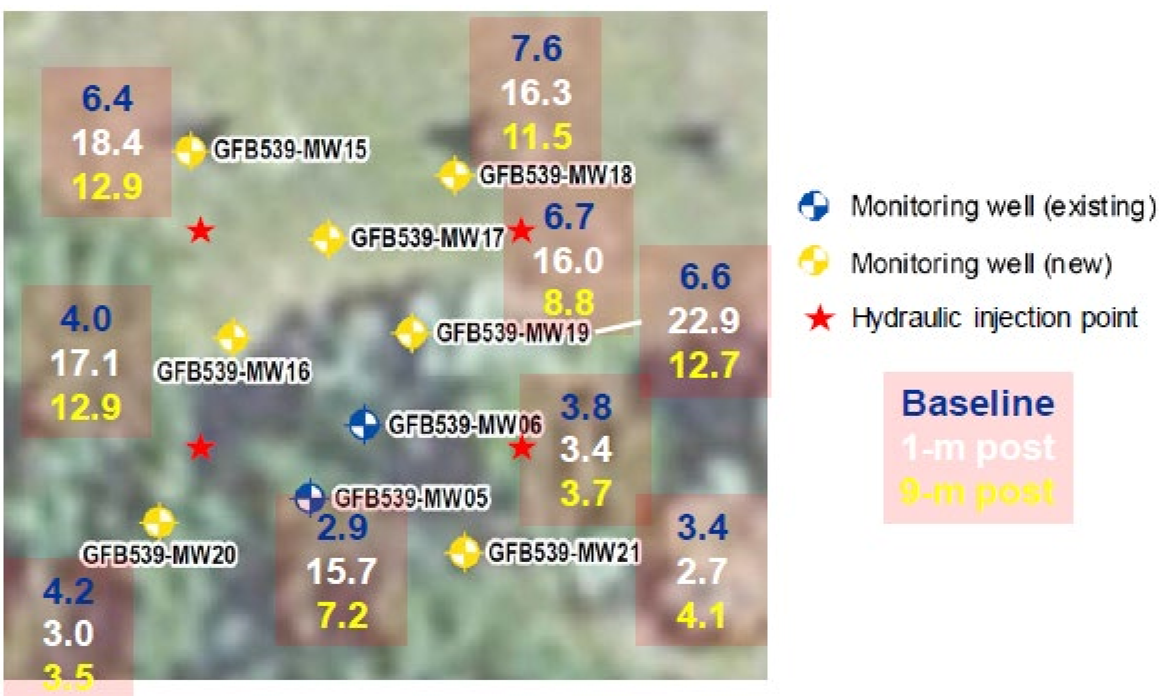

Figure 5.53. Changes in Conductivity (mS/cm) at GFAFB (Plan View)

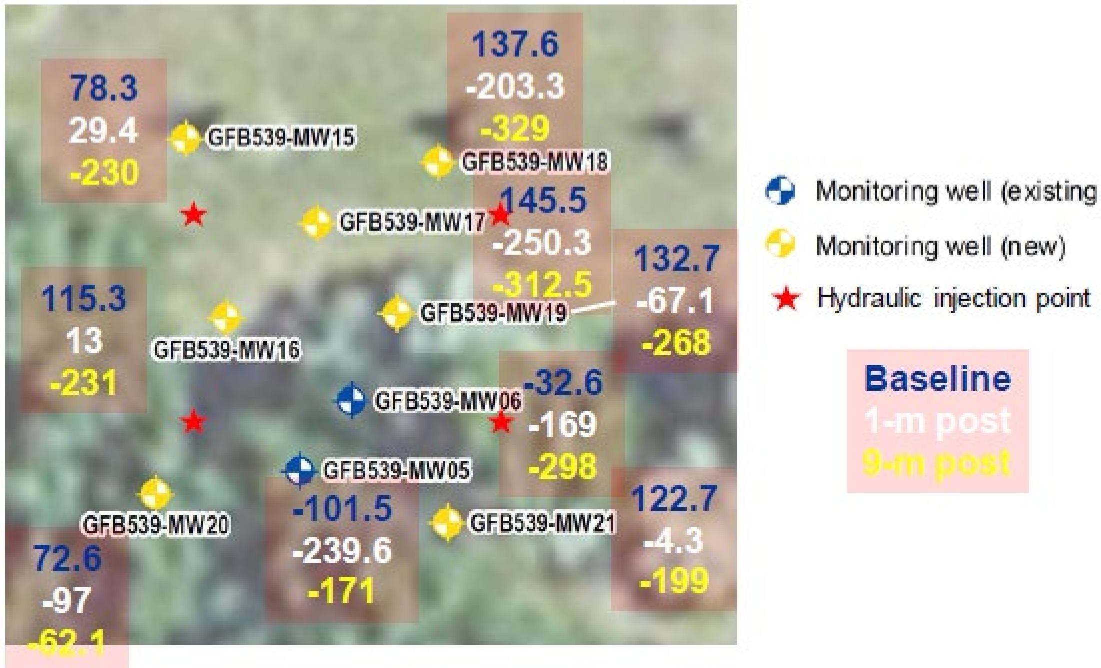

Figure 5.54. Changes in ORP (mV) at GFAFB (Plan View)

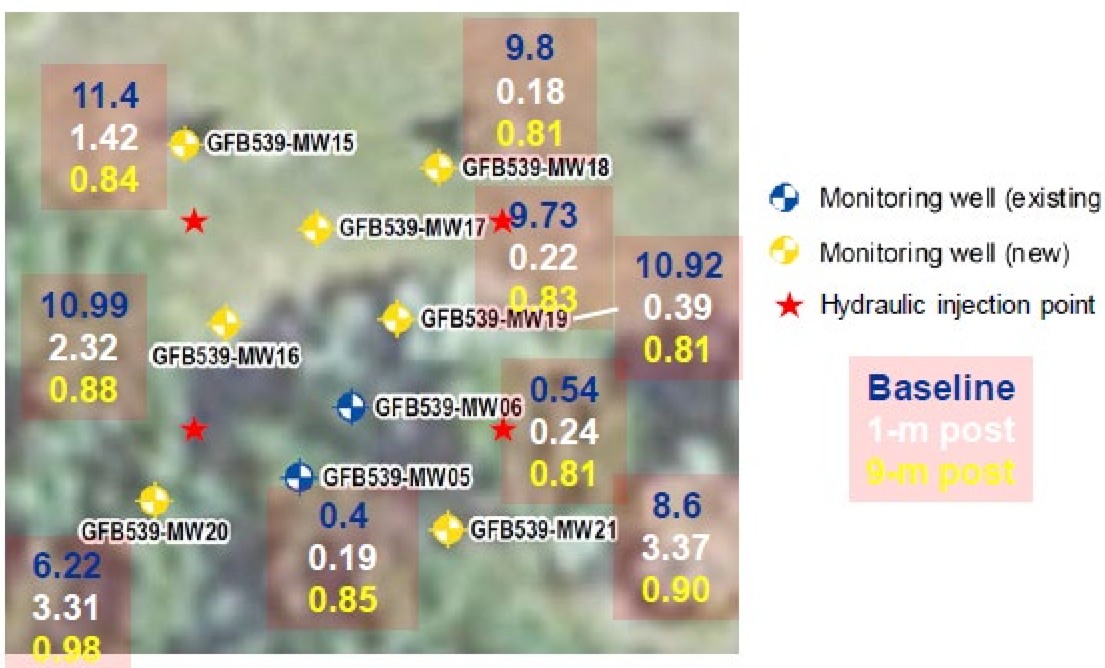

Figure 5.55. Changes in DO (mg/L) at GFAFB (Plan View)

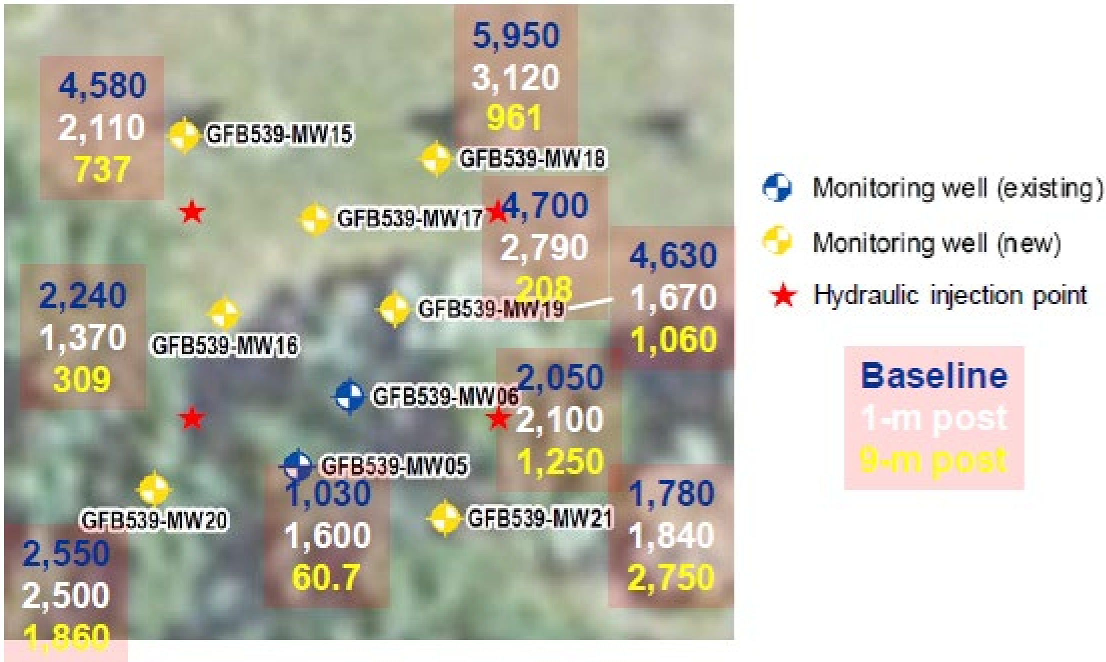

Figure 5.56. Changes in Sulfate (mg/L) at GFAFB (Plan View)

5.5.5.4 Effectiveness of Geophysics and Other Monitoring Tools

Data obtained during tilt meter monitoring were used to generate 3D visualizations to graphically illustrate the vertical and horizontal extent of the fracture network initiated by permeability enhancement at GFAFB as shown in **Figure 5.57**.

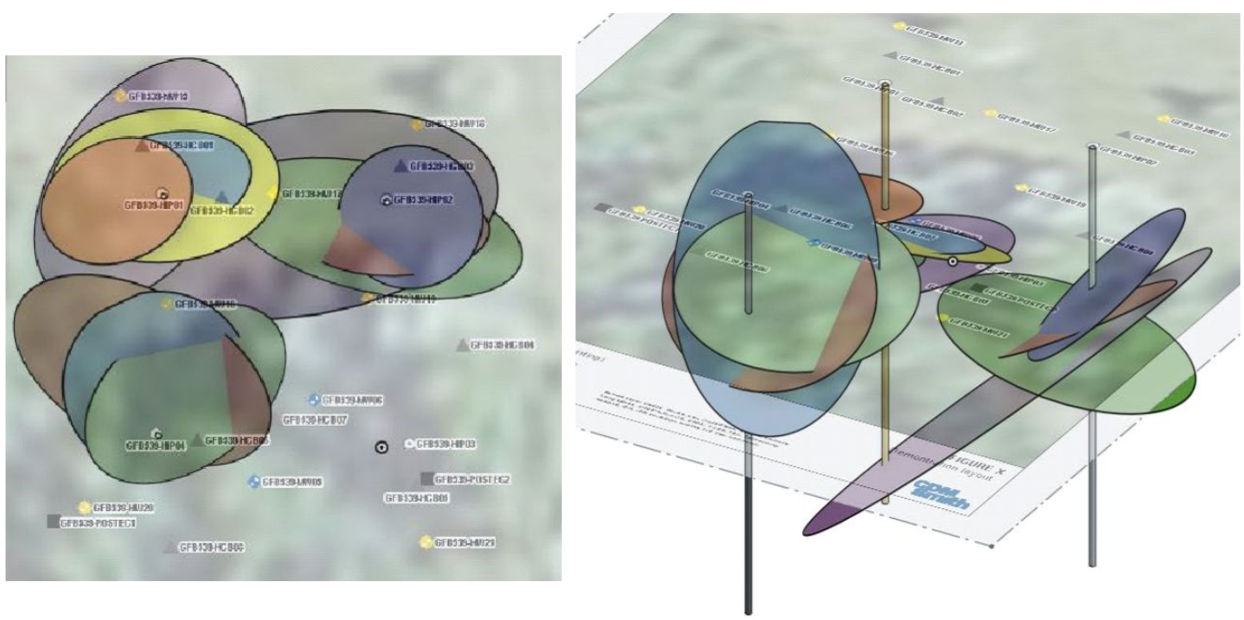

Figure 5.57. 3D Visualization of the Fracture Network at GFAFB

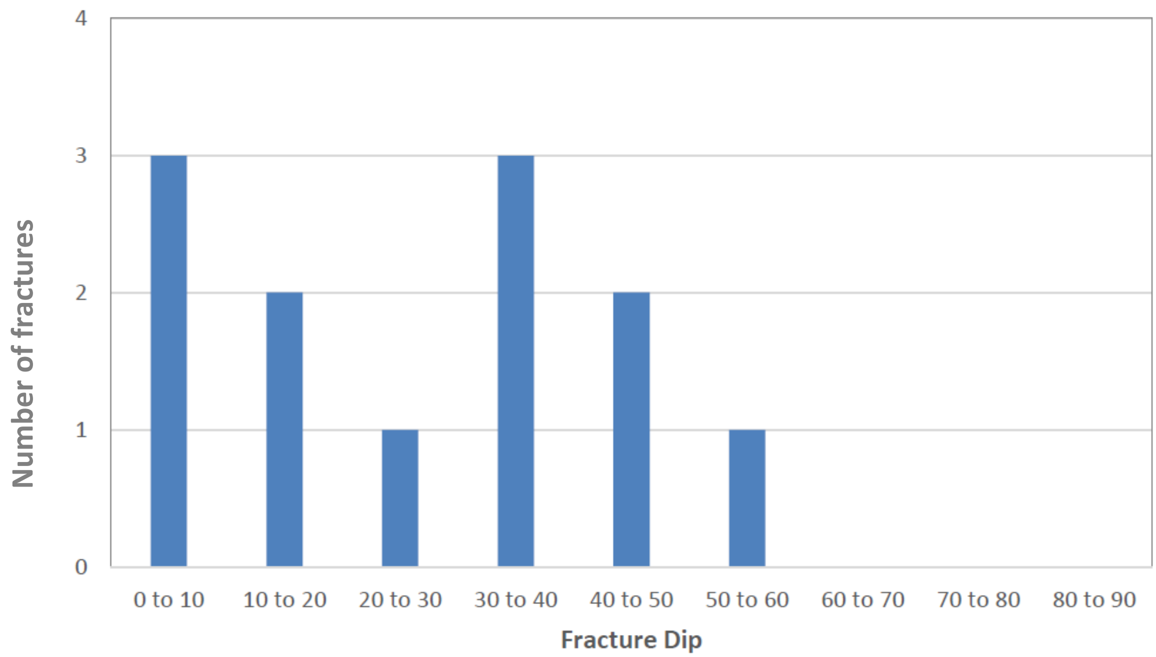

Figure 5.58. Distribution of Fracture Dip Angles at GFAFB

The frequency distribution of fracture dip angles for the hydraulic permeability enhancement demonstration at GFAFB is presented in **Figure 5.58**. All of the initiated fractures monitored using tilt meters were primarily horizontal with dip angles equal to or less than 60 degrees. Note that approximately half of the monitored fractures were very horizontal with dip angles equal to or less than 30 degrees.

Geophysics monitoring tools, including ERT, EC, and tilt meters, were implemented at GFAFB. As an improvement to ERT activities at LCAAP, a second time-lapse imaging event was conducted following amendment emplacement. In contrast to LCAAP, expansive changes in electrical conductivity were detected following amendment emplacement at locations between monitoring wells, suggesting that a substantial volume of the investigated region was impacted by these activities. In addition, changes were observed between the first and second time-lapse measurements, indicating continued migration of the injected amendment. These changes were generally but not completely consistent with other measurements at the site (e.g. TOC and fluorescein), which could partially be due to the limited number of post-enhancement sampling locations compared to the large number of ERT measurements.

In addition, EC generally did not correlate well with analytical verification of the emplaced amendments seen at nearby confirmation boreholes (as shown in **Figures 5.59** and **5.60**, details are provided in **Section 6**). Based on the limited EC data obtained at GFAFB, EC did not appear to be an effective geophysics monitoring tool in application of permeability enhancement. Note that only limited EC monitoring work was performed at GFAFB as per the study design and therefore the aforementioned assessment was made with relatively limited data. Similar to both MCB-CP and LCAAP, tilt meter results correlated well with the field-analyzed fluorescein results obtained at nearby boreholes during post-enhancement confirmation sampling. Additionally, the tilt meter-predicted fracture intercepted depth-intervals, presented in **Table 5.15**, correlate well with the actual depth intervals where increases in fluorescein were observed.

Collectively, these results indicated that it is an effective geophysics monitoring tool to aid evaluation of permeability enhancement applications.

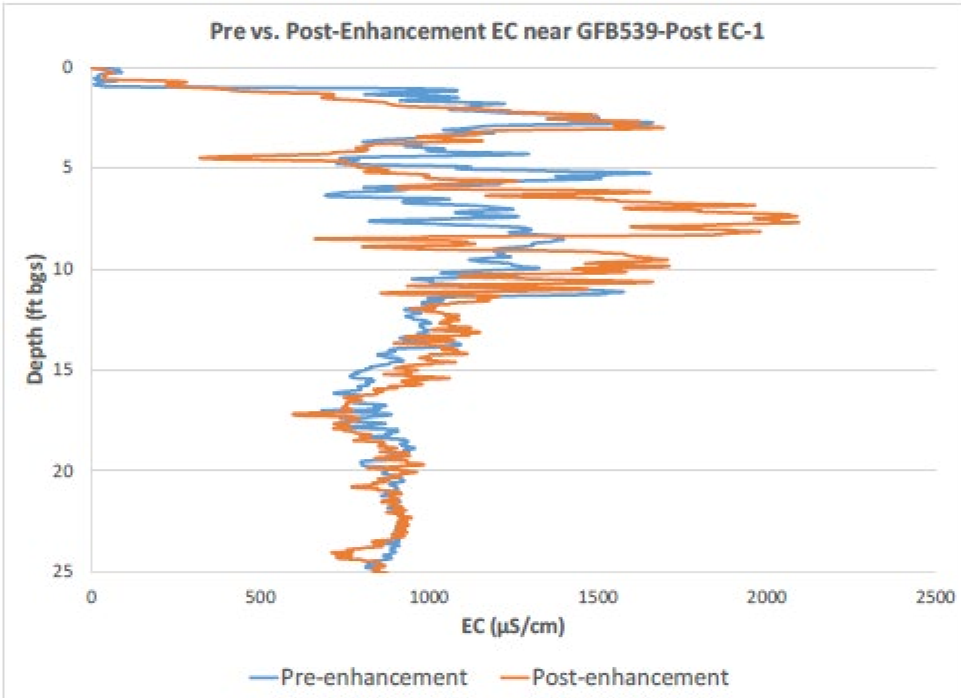

Figure 5.59. Pre- Versus Post-Enhancement EC at GFB539-Post EC-1 at GFAFB

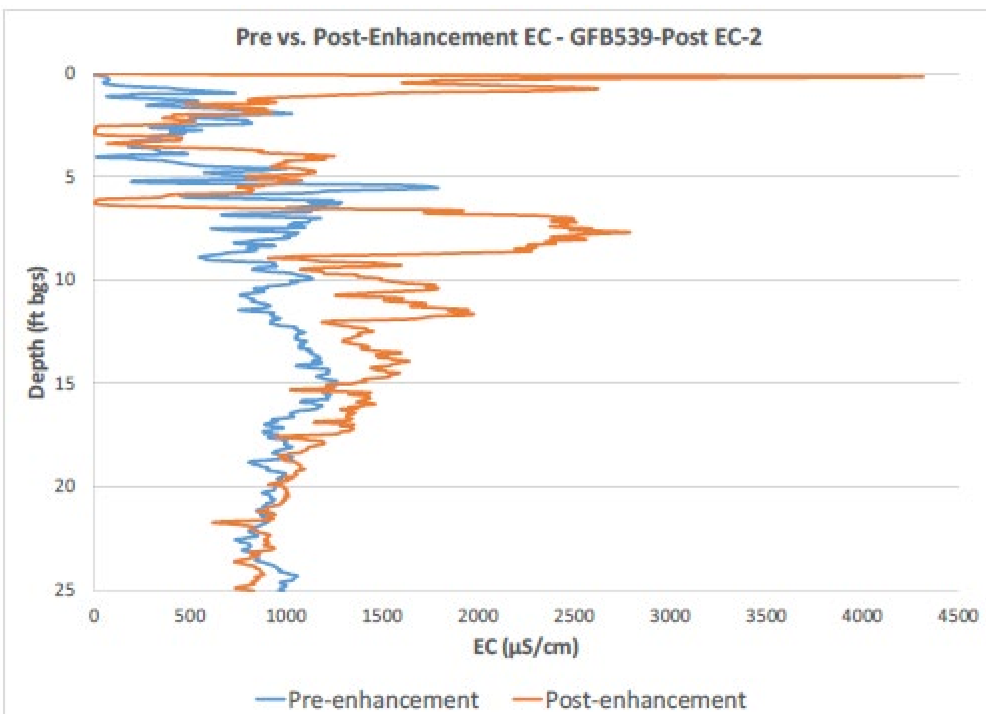

Figure 5.60. Pre- Versus Post-Enhancement EC at GFB539-Post EC-2 at GFAFB

Table 5.15. Predicted Fracture-Intercepting Depths at GFAFB

Confirmation borehole	Predicted Intercept depth (ft bgs)	Originating enhancement location	Frac Rite's comments
GFB539-HCB-01	12.3	HIP-01-1	
	16.2	HIP-01-2a	
	16.5	HIP-01-2b	
	18.1	HIP-01-3a	
	18.1	HIP-01-3b	
	31	HIP-02-4	
GFB539-HCB-02	NI*	HIP-01-1	
	14.2	HIP-01-2a	
	14.2	HIP-01-2b	
	NI*	HIP-01-3a	
	18.8	HIP-01-3b	
GFB539-HCB-03	10.7	HIP-02-1	
	NI*	HIP-02-2	
	16.3	HIP-02-3	
	16.5	HIP-02-4	At edge of modelled fracture
GFB539-HCB-06	18.9	HIP-04-1	
	16.3	HIP-04-2	
	13.3	HIP-04-3	
GFB539-HCB-07	20.1	HIP-04-1	At edge of modelled fracture
	12.7	HIP-04-2	
	14.9	HIP-04-3	Just outside edge of modelled fracture

* NI = not intercepting

6.0 PERFORMANCE ASSESSMENT

This section describes the notable field observations and/or analytical results obtained at all three demonstration sites related to the project-specific performance objectives established in the demonstration plan. A description of each performance objective and its associated data requirements and success criteria, as well as an evaluation of whether the performance objective was met, exceeded, or not met, are provided in **Table 6.1**. Detailed analyses are provided in the subsequent sections.

6.1 PERFORMANCE OBJECTIVE #1

The performance objective of quantifying the horizontal and vertical distribution of emplaced fractures within target treatment volume is evaluated herein using the following success criteria:

- Visual/analytical presence/absence of emplaced materials in post-enhancement soil confirmation boreholes to allow for qualitative assessment of amendment distribution
- Generation of two-dimensional (2D) and 3D visualizations of fracture networks via tilt-meter monitoring
- Statistically significant differences in EC at depth-discrete intervals where fractures are present
- Vertical and horizontal distribution of fractures using ERT

6.1.1 Visual/Analytical Confirmation of Emplaced Materials Following Permeability Enhancement

At all three sites, qualitative assessment of amendment distribution was confirmed. Specifically, depth-discrete intervals where fractures were initiated and treatment amendment introduced via permeability enhancement were identified via visual observations of the emplaced materials (40/50 sand) at MCB-CP and LCAAP in the hydraulic demonstration area and/or field/analytical verification of amendment distribution via analysis of TOC (LCAAP and GFAFB), sulfate and persulfate (MCB-CP), and fluorescein (GFAFB). It should be noted that in some instances, multiple lines of evidence had to be used to qualitatively evaluate amendment distribution due to site-specific conditions. For example, elevated baseline TOC concentrations in soil at GFAFB (at least partially attributable to high concentrations of petroleum hydrocarbons) completely masked the organic carbon that was added as part of the treatment amendment. However, fluorescein analysis allowed for qualitative evaluation of vertical and horizontal amendment distribution at the site. Similarly, the color and texture of the sandstone/siltstone materials made it very difficult to visualize the presence of the 40/50 sand emplaced at MCB-CP. Therefore, the presence of the emplaced silica sand had to be felt by hand. Also, field and laboratory analysis of persulfate and sulfate content of soil samples collected from confirmation borings was also used. Detailed discussions pertinent to each of the three demonstration sites are provided below.

Table 6.1. Evaluation of Performance Objective Success Criteria

Performance Objective	Data Requirements	Success Criteria	LCAAP - Hydraulic		LCAAP - Pneumatic		MCB-CP		GFAFB		Overall evaluation
			Yes/No	Why	Yes/No	Why	Yes/No	Why	Yes/No	Why	
#1 - Quantify horizontal and vertical distribution of emplaced fractures within target treatment volume	Two soil cores for each fracture initiation boring to a depth equaling the deepest fracture interval	Visual/analytical presence/absence of emplaced materials (e.g., ZVI or sand) in soil cores will constitute success as these data will allow for qualitative assessment of amendment distribution.	Yes	- Visual observation of emplaced sand during confirmation soil sampling - Significant changes in soil TOC concentrations	Yes	- No significant changes in soil TOC concentrations relative to baseline	Yes	- Visual observation of sand and analytical confirmation of increased persulfate/ sulfate concentration in depth-discrete post-enhancement soil samples	Yes	- Analytical confirmation of fluorescein in depth-discrete post-enhancement soil samples	- Overall, this performance objective was met; the horizontal and vertical distribution of emplaced fractured within the target treatment volume at each of the three demonstration sites determined quantitatively and/or qualitatively by visual observations, tiltmeter monitoring, and analytical detections of the emplaced amendments directly or indirectly.
	Tilt-meter mapping in a 360° concentric array around fracture borehole	Successful application of tilt-meters will result in mapped injection planes of emplaced amendment within the target treatment volume. These data provide measurements of fracture orientation, extent, and thickness.	Yes	- As provided by tiltmeter subcontractor	Yes	- As provided by tiltmeter subcontractor	Yes	- As provided by tiltmeter subcontractor	Yes	- As provided by tiltmeter subcontractor	
	Continuous down-hole electrical conductivity (EC) logging (one site only)	Successful application of EC will result in statistically different EC results in vertical intervals where fractures are present.	NA	- EC was not performed at this site	NA	- EC was not performed at this site	NA	- EC was not performed at this site	No	- No significant changes in EC within were observed within the target enhancement interval	
	Electrical resistance imaging (ERT) (one or two sites)	Successful application of surface ERT will result in a mapping of the aerial distribution of emplaced fractures.	No	- Cross-borehole visualization was very limited	No	- Cross-borehole visualization was very limited	NA	- ERT was not performed at this site	No	- Cross-borehole visualization was very limited	
		Successful application of ERT may also result in observation of vertical distribution of fractures, although this will likely be masked by multiple vertical fractures in each borehole.	No	- Discrete fractures were not observed via ERT	No	- Discrete fractures were not observed via ERT			No	- Discrete fractures were not observed via ERT	
#2 - Deliver target amendment dose within the target treatment volume	Amendment volume emplaced Soil cores Tilt-meter mapping EC logging ERT	75% of the target injection volume is delivered within the treatment area of interest.	Yes	- Target solid and aqueous amendment injection volumes were achieved	Yes	- Target aqueous injection volume was achieved	Yes	- Target solid and aqueous amendment injection volumes were achieved	Yes	- Target aqueous injection volume was achieved	- Overall, this performance objective was met; near or over 75% of the target treatment volume emplaced at each of the three demonstration sites.
#3 - Evaluate increase in aquifer permeability resulting from permeability enhancement technology	Aquifer pumping/slug testing conducted in treatment area before and after permeability enhancement	Successful conductivity enhancement is as a statistically significant increase, defined herein as an increase of approximately one order of magnitude, in bulk hydraulic conductivity that allows for improved use of wells for injection and/or extraction.	No	- No significant changes in measured hydraulic conductivity via slug testing	No	- No significant changes in measured hydraulic conductivity via slug testing	Yes	- An order of magnitude increase in hydraulic conductivity was observed via slug testing	NA	- No significant changes in measured hydraulic conductivity via slug testing. However, no changes were expected because of the lack of a solid amendment (i.e., proppant)	- Overall, this performance objective was met; orders-of-magnitude increases in hydraulic conductivities observed at sites where such changes were anticipated.

Performance Objective	Data Requirements	Success Criteria	LCAAP - Hydraulic		LCAAP - Pneumatic		MCB-CP		GFAFB		Overall evaluation
			Yes/No	Why	Yes/No	Why	Yes/No	Why	Yes/No	Why	
#4 - Evaluate effectiveness and accuracy of tilt-meter geophysics monitoring	Tilt-meter fracture plane maps Soil coring data Direct-push EC data (one site only)	Visual observation and/or analytical detection of fractures/treatment amendment against predicted tiltmeter results within an acceptable range of error.	Yes	- Strong correlation between the tiltmeter-predicted depths of fracture interception at confirmation boreholes and the actual depths where fractures were visually observed or detected analytically.	Yes	- Strong correlation between the tiltmeter-predicted depths of fracture interception at confirmation boreholes and the actual depths where fractures were detected analytically.	Yes	- Strong correlation between the tiltmeter-predicted depths of fracture interception at confirmation boreholes and the actual depths where fractures were visually observed or detected analytically.	Yes	- Strong correlation between the tiltmeter-predicted depths of fracture interception at confirmation boreholes and the actual depths where fractures were detected analytically.	- Overall, this performance objective was met; 2-D and 3-D visualization generated by tiltmeter monitoring allowed for mapping of the vertical and horizontal fracture network initiated by permeability enhancement. In addition, tiltmeter-predicted fracture-intercepting depths correlated very strongly with visual observations and/or analytical detections of the initiated fractures at nearby confirmation boreholes.
#5 - Evaluate effectiveness and accuracy of EC	Pre-fracture EC values Post-fracture EC values Soil coring data	Statistically significant increase in EC value at predicted depth intervals against actual visual observations and/or analytical detection of fractures /treatment amendment within an acceptable range of error.	NA	- EC was not performed at the site	NA	- EC was not performed at the site	NA	- EC was not performed at the site	No	- No significant changes in EC within were observed within the target enhancement interval	- Overall, this performance objective was met; at the one site where the monitoring technique was implemented (GFAFB), EC was ineffective at evaluating the vertical distribution of the fracture network initiated by permeability enhancement. In addition, EC data did not correlate well with visual observations and/or analytical detections of the initiated fractures at nearby confirmation boreholes.
#6 - Evaluate effectiveness and accuracy of ERT	Pre-fracture surface ERT Post-fracture surface ERT Soil coring data	Statistically significant increase in ERT value at predicted depth intervals against actual visual observations and/or analytical detection of fractures /treatment amendment within an acceptable range of error.	No	- ERT visualization of amendment distribution, especially cross-borehole visualization, was largely limited.	No	- ERT visualization of amendment distribution, especially cross-borehole visualization, was largely limited.	NA	- ERT was not performed at this site.	No	- ERT visualization of amendment distribution, especially cross-borehole visualization, was largely limited.	- Overall, this performance objective was met; at the two sites where the monitoring technique was implemented (LCAAP and GFAFB), ERT was ineffective at evaluating the vertical and horizontal distribution of the fracture network initiated by permeability enhancement. In general, ERT data did not correlated well with visual observations and/or analytical detections of the initiated fractures at nearby confirmation boreholes.

Performance Objective	Data Requirements	Success Criteria	LCAAP - Hydraulic		LCAAP - Pneumatic		MCB-CP		GFAFB		Overall evaluation
			Yes/No	Why	Yes/No	Why	Yes/No	Why	Yes/No	Why	
#7 - Evaluate efficacy of improved amendment delivery for treatment of site contaminants	Contaminant and geochemistry data from existing groundwater monitoring wells	Desired geochemical changes are observed in groundwater consistent with the type of treatment.	Yes	- Significant increases in TOC concentrations in groundwater were observed in many of the monitoring locations within the target ROI following permeability enhancement - Highly reducing conditions were established following permeability enhancement	Yes	- Significant increases in TOC concentrations in groundwater were only observed at one of the monitoring locations within the target ROI following permeability enhancement - Highly reducing conditions were established following permeability enhancement	Yes	- Increasingly aerobic conditions typical of post-persulfate injections were observed	Yes	- Highly reducing conditions were established following permeability enhancement	- Overall, this performance objective was met at all three demonstration sites; development of geochemical conditions conducive to degradation of site-specific contaminants in groundwater using the targeted *in situ* techniques was observed. In addition, significant reduction in contaminant concentrations were observed at many of the sites.
	Previous injection data	Concentrations of the site-specific contaminants of concern in groundwater are reduced by at least 50% at the last performance monitoring event relative to historical trends and most recent groundwater quality data.	Yes	- More than 50% reduction in total contaminant concentrations was achieved in select monitoring locations despite the presence of DNAPL	Yes	- More than 50% reduction in total contaminant concentrations was achieved in select monitoring location despite the presence of DNAPL	Yes	- More than 50% reduction in total contaminant concentrations was achieved in select monitoring locations	Yes	- More than 50% reduction in total contaminant concentrations was achieved in select monitoring locations	
#8 - Evaluate the ease of use/implementation of each permeability enhancement technology and performance monitoring strategy	Level of effort (including availability of equipment) necessary to perform each injection technique	Documentation of the relative availability of equipment and access to appropriate expertise, the level of oversight required, and the types of problems encountered and ease of resolution for each permeability enhancement technology and/or monitoring technique.	Yes								- Overall, this performance objective was met. At all three sites, the availability of equipment and expertise to properly implement permeability enhancement were documented. In addition, issues encountered and ease of resolutions were recorded for future guidance.
	Reporting of problems encountered in the field (including surfacing), and ability to resolve problems quickly										
#9 - Evaluate cost performance of each permeability enhancement technology	Costs for equipment, subcontractors, drilling, field oversight, and data evaluation of each permeability enhancement technology	Documented cost comparisons for equipment, subcontractors, oversight, and data evaluation for each permeability enhancement technology; the costs will be interpreted in the context of the actual distribution of amendments achieved.	Yes								- Overall, this performance objective was met. Cost and performance related information was obtained to aid comparisons between the pneumatic and hydraulic permeability enhancement techniques and among the different novel and conventional injection techniques.

6.1.1.1 MCB-CP

Two soil confirmation boreholes (refer to **Figure 5.1**) were drilled post-enhancement and post-injection to facilitate visual observations of the emplaced and materials (persulfate and 40/50 silica sand), lithologic logging, and collection of depth-discrete soil samples for field analysis of persulfate and analytical determination of sulfate content. Silica sand was visually observed at multiple depth-discrete intervals at only one of the two confirmation borings, consistent with the highly elevated sulfate content observed at HCB-01. On the other hand, the emplaced silica sand was not seen at HCB-02 and only slight increases in post-enhancement sulfate content were observed at this boring. A visual observation of the emplaced silica sand seen at HCB-01 is illustrated in **Figure 6.1**. It should be noted that due to the color and texture of the sandstone/siltstone materials, in some instance, it was difficult to visualize the presence of the 40/50 silica sand emplaced at MCB-CP. However, the texture of the silica sand particles can be felt by hand.

Figure 6.1. Visual Observations of Emplaced Silica Sand at Confirmation Boring HCB-01 at MCB-CP

More than two order-of-magnitude increases in sulfate concentrations were observed at multiple depth-discrete intervals between the depths targeted for hydraulic permeability enhancement (between approximately 30 and 50 feet bgs) at confirmation boring HCB-01 as shown in **Figure 6.2**. Some increases in sulfate content in soil were observed at confirmation boring HCB-02 as shown in **Figure 6.3**; however, such increases were not as pronounced and ranged between approximately 2 and 5 times the pre-enhancement average sulfate concentration.

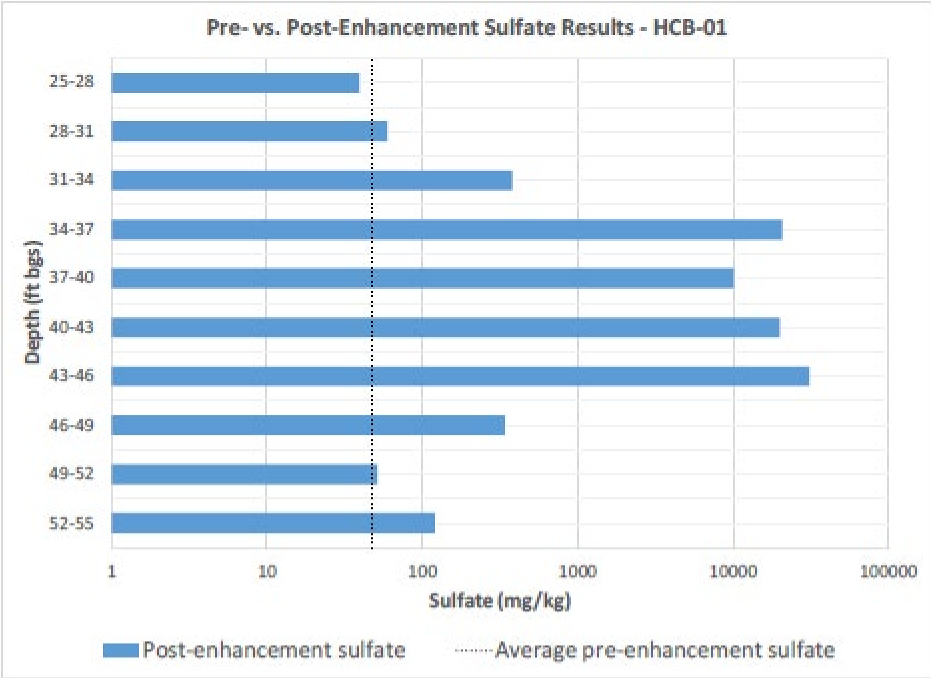

Figure 6.2. Post-Enhancement Sulfate Results at Confirmation Boring HCB-01 at MCB-CP

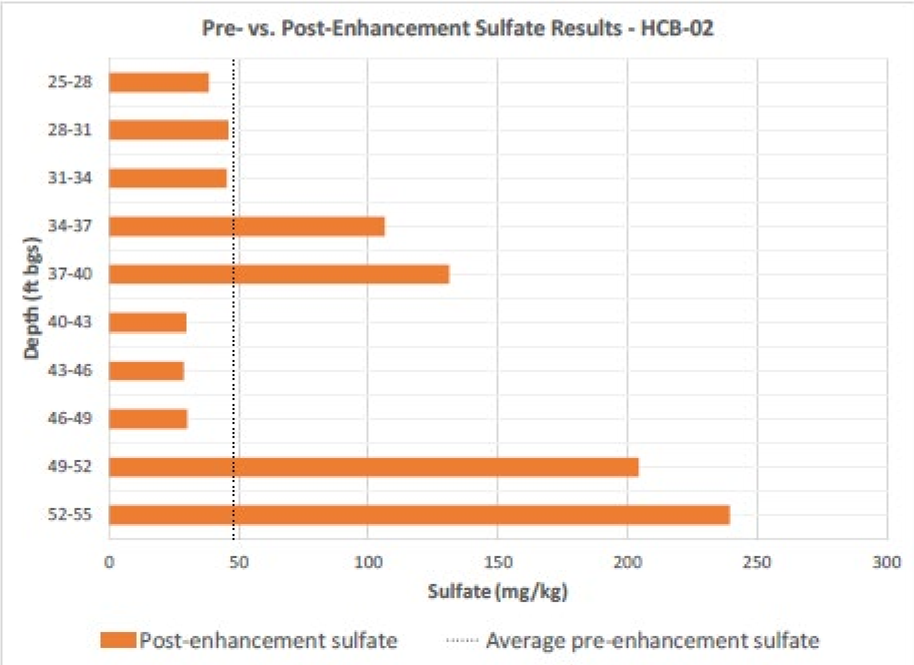

Figure 6.3. Post-Enhancement Sulfate Results at Confirmation Boring HCB-02 at MCB-CP

6.1.1.2 LCAAP

Within the hydraulic demonstration area, two post-enhancement confirmation boreholes were drilled to facilitate visual observations of emplaced materials (LactOil® and 40/50 silica sand), lithologic logging, and collection of depth-discrete soil samples for analytical determination of TOC as an indicator of amendment delivery. These borings were installed within the expected area of influence of amendment; for reference, the locations are shown on **Figure 5.15**. At both confirmation borings, the emplaced silica sand was observed at multiple intervals within the target treatment depths between 20 and 35 feet bgs. An example of visual confirmation of the emplaced sand is shown in **Figure 6.4**.

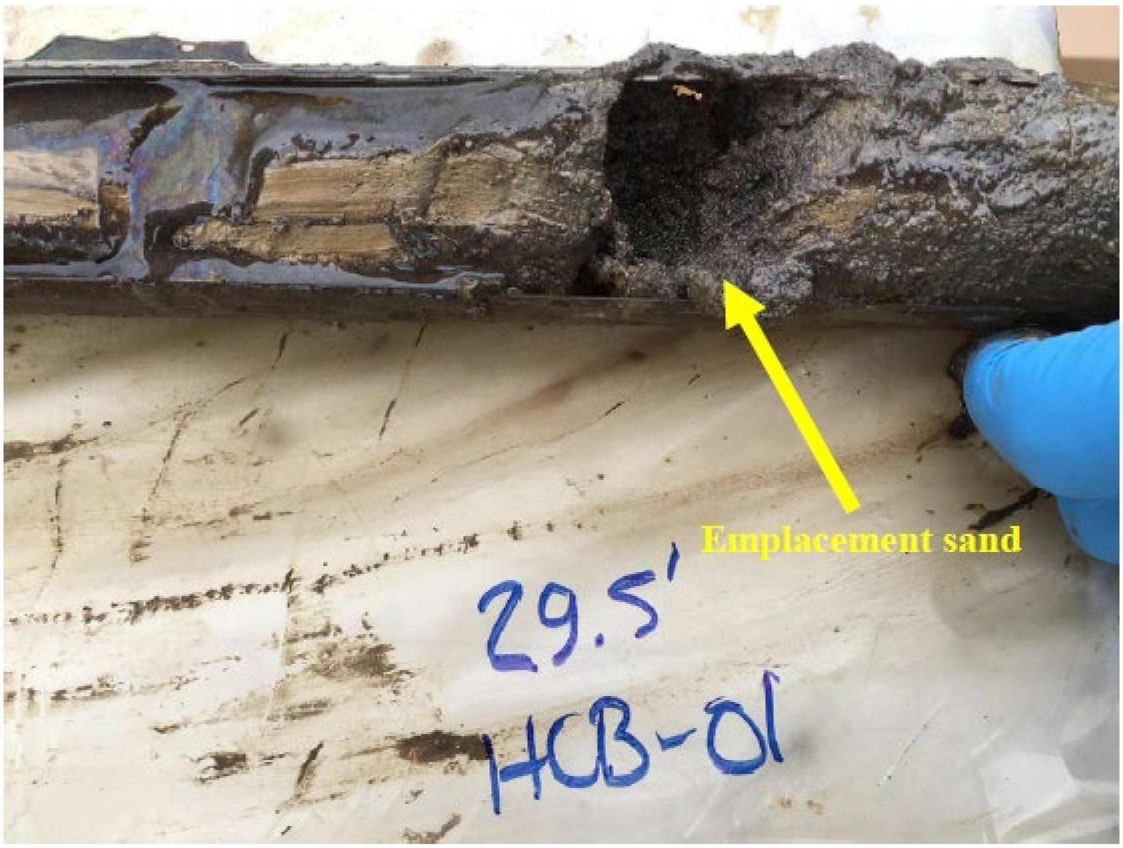

Figure 6.4. Visual Observations of Emplaced Silica Sand at Confirmation Boring HCB-01 within the Hydraulic Demonstration Cell at LCAAP

Significant increases in post-enhancement TOC, which ranges between 2 and 20 times the average pre-enhancement TOC value, were observed at multiple depth-discrete intervals at both confirmation boreholes HCB-01 and HCB-02 as shown in **Figures 6.5** and **6.6**. Because an amendment solution containing high TOC content was introduced into the hydraulic demonstration cell following permeability enhancement, these TOC increases are direct confirmation of amendment delivery.

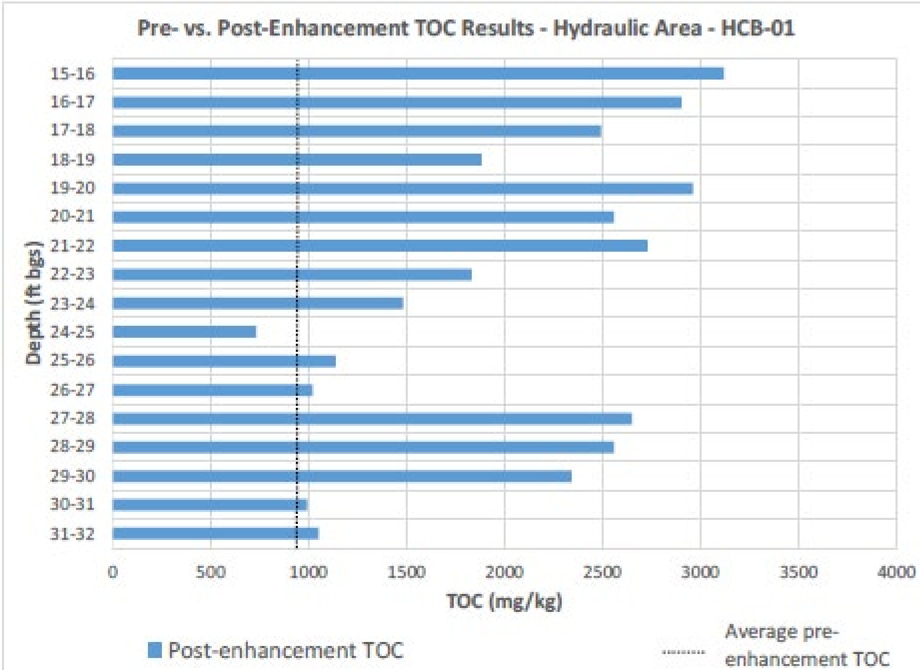

Figure 6.5. Post-Enhancement TOC Results within the Hydraulic Demonstration Cell at Confirmation Boring HCB-01 at LCAAP

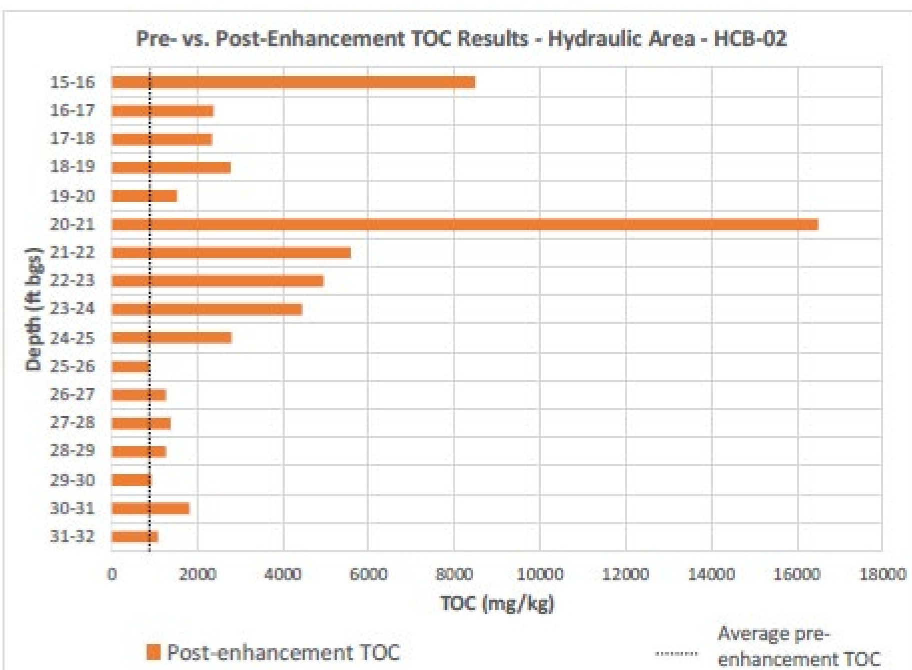

Figure 6.6. Post-Enhancement TOC Results within the Hydraulic Demonstration Cell at Confirmation Boring HCB-02 at LCAAP

Because silica sand emplacement was not performed in the pneumatic demonstration cell, visual observations were not relied upon to qualitatively determine amendment delivery and distribution. Instead, only analytical determination of post-enhancement TOC, relative to the pre-enhancement TOC measurements, was used to assess depth-discrete amendment delivery at three post-enhancement confirmation boreholes PCB-01, -02, and -03. As depicted in **Figures 6.7**, **6.8**, and **6.9**, some increases in post-enhancement TOC (as measured using soil samples) relative to the pre-enhancement value were observed in depth-discrete intervals within the target treatment depth between approximately 20 and 35 feet bgs. However, these increases were much less pronounced that those observed in the hydraulic cell; post-enhancement TOC increases in the pneumatic demonstration cell were generally less than 2 times the pre-enhancement average value. It should be noted that because the same mass of EVO was introduced into both demonstration areas of similar treatment volume, comparable increases in TOC concentrations would have been observed had the amendment delivery performance been similar. The lack of TOC increase in the pneumatic confirmation boreholes suggests that a high percentage of the EVO solution emplaced via hybrid pneumatic permeability enhancement was not introduced into the target treatment depth interval and may have likely surfaced above the target treatment interval. However, such amendment surfacing was not visually observed because of the presence of the third packer installed above the treatment interval.

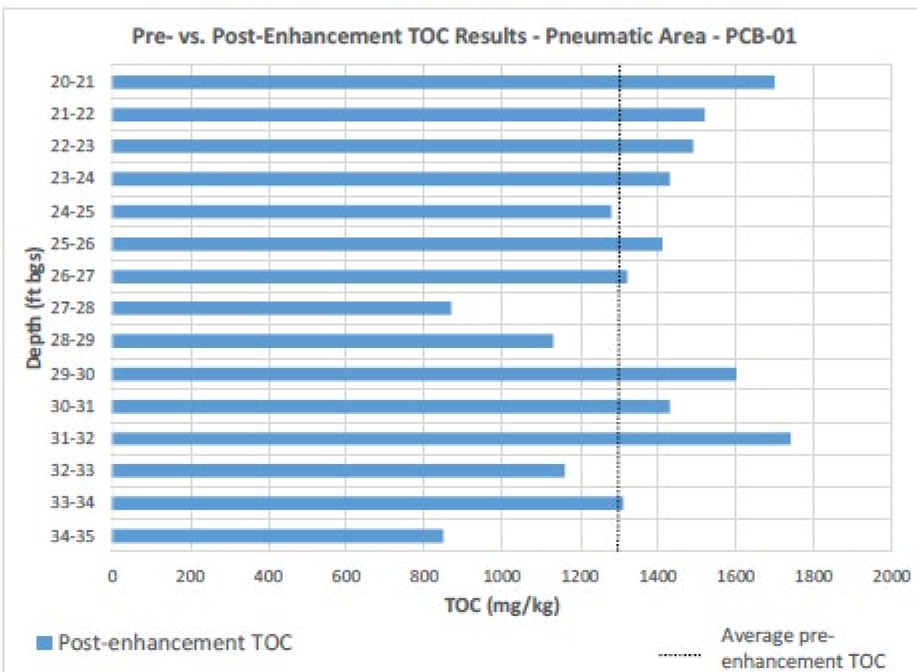

Figure 6.7. Post-Enhancement TOC Results within the Pneumatic Demonstration Cell at Confirmation Boring PCB-01 at LCAAP

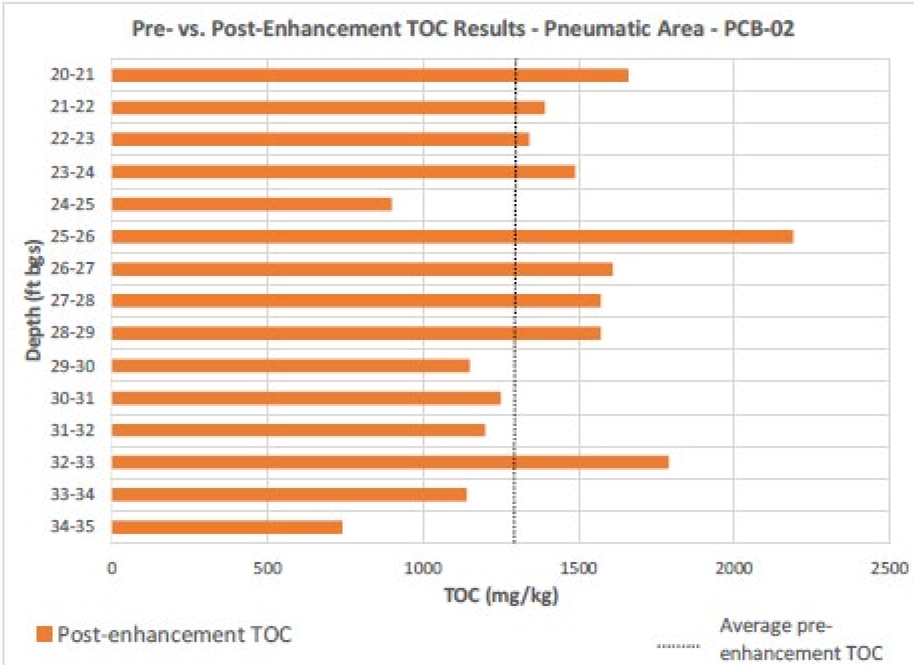

Figure 6.8. Post-Enhancement TOC Results within the Pneumatic Demonstration Cell at Confirmation Boring PCB-02 at LCAAP

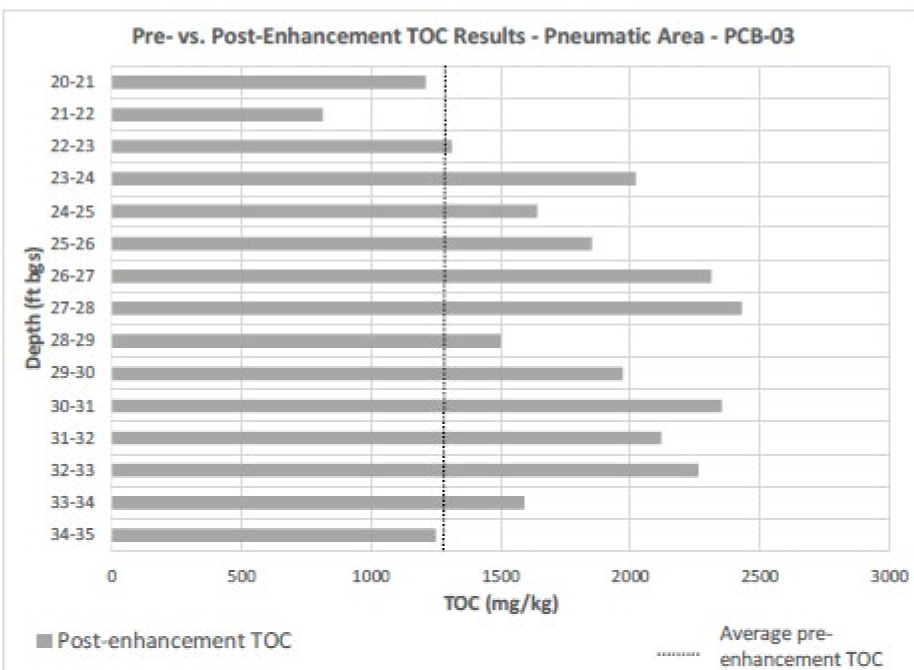

Figure 6.9. Post-Enhancement TOC Results within the Pneumatic Demonstration Cell at Confirmation Boring PCB-03 at LCAAP

6.1.1.3 GFAFB

Following permeability enhancement, eight confirmation boreholes (GFB539-HCB-01 through -08, refer to **Figure 5.34**) were drilled to facilitate visual observations of emplaced materials (LactOil® and fluorescein), lithologic, and collection of depth-discrete soil samples for field analysis of fluorescein and analytical determination of TOC. Visual observations of silica sand were not made because only aqueous amendments were emplaced at GFAFB. Analytical measurements of TOC were not a good indicator of amendment delivery in subsurface soil because of the elevated background TOC (likely attributable to the presence of TPH in the target treatment area) as shown in **Figure 5.36**. On the other hand, fluorescein was a very good indicator of amendment delivery as the fluorescent tracer was added into the injection solution. Elevated fluorescein concentrations were observed at multiple depth-intervals within the target treatment depth interval (between 10 and 20 feet bgs) at select confirmation boreholes that were intercepted by the fracture network propagated from a nearby enhancement borehole (predicted by the tilt-meter model) as shown in **Figure 6.10**. It should be noted that at other boreholes that were not modeled to be intercepted by the fracture network, much lower fluorescein concentrations were detected in depth-discrete soil samples as shown in **Figure 6.11**. Detailed analysis of the accuracy of the tilt-meter monitoring technique is provided in **Section 6.4**.

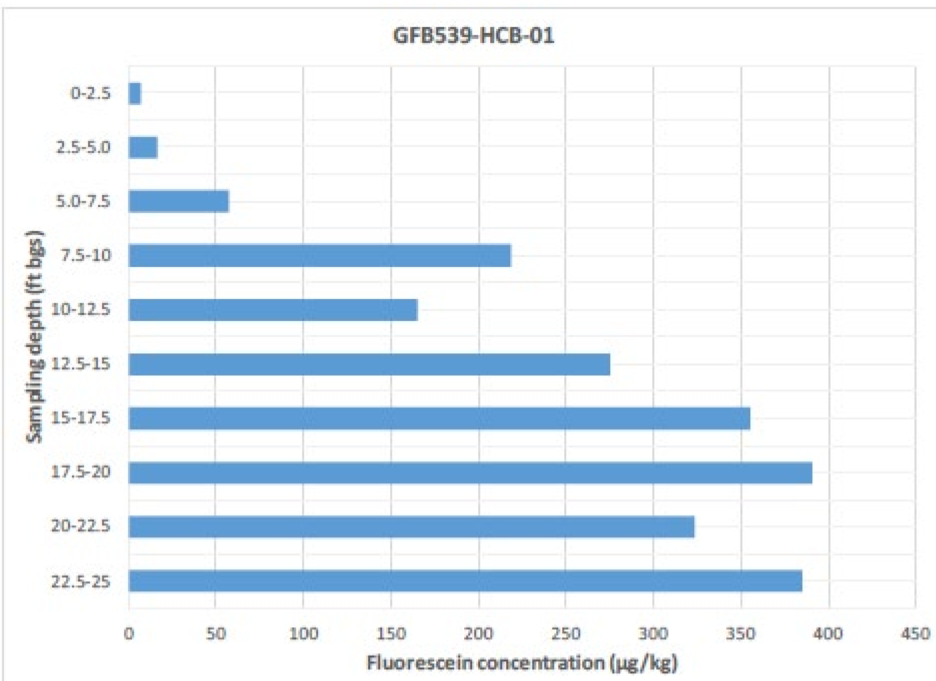

Figure 6.10. Post-Enhancement Fluorescein Results at Confirmation Boring GFB539-HCB-01 at GFAFB

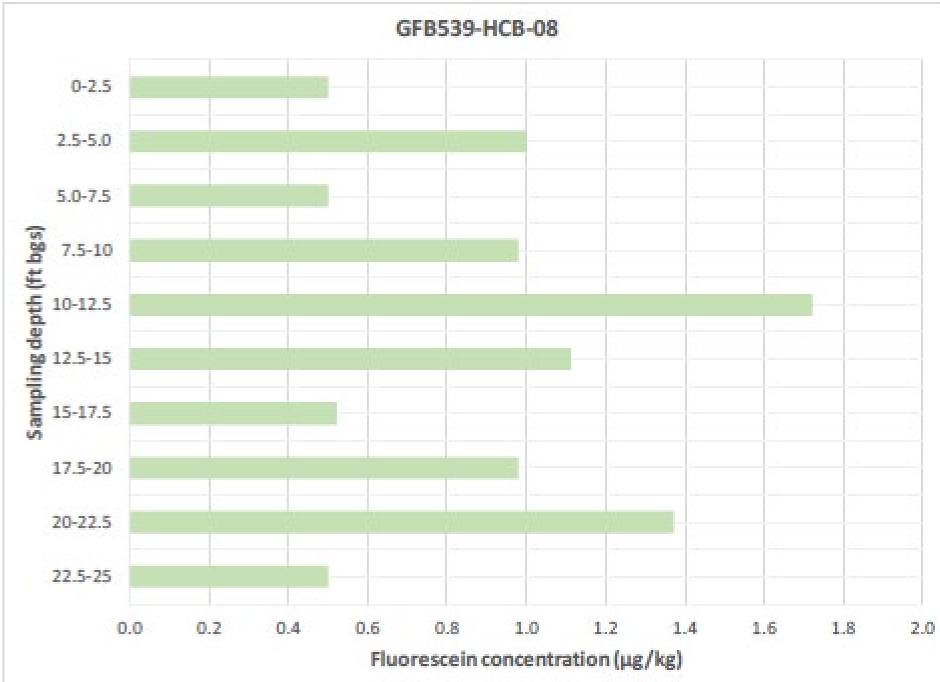

Figure 6.11. Post-Enhancement Fluorescein Results at Confirmation Boring GFB539-HCB-08 at GFAFB

6.1.2 2D and 3D Tilt-meter Visualizations

At all three sites, 2D and 3D renderings of the fracture network were successfully generated using tilt-meter data collected during permeability enhancement as presented in **Section 5**. These visualizations were used to aid evaluating the vertical and horizontal extent of the fracture network initiated via permeability enhancement. Additionally, tilt-meter data were used to predict if, and at which depth-discrete intervals, the initiated fracture network intercepts a given location within the ROI of permeability enhancement. More details regarding this evaluation are provided in **Section 6.4**.

6.1.3 EC Logging

EC logging was performed pre- and post-enhancement at two locations within the target treatment area GFAFB including GFB539-Post EC-1 and -2. No statistically significant changes in EC were observed at depth-discrete intervals ranging between approximately 10 and 20 feet bgs where permeability enhancement was initiated as shown in **Figures 6.12** and **6.13**. However, it should be noted that the EC locations were selected randomly and happened to be located in areas that were not impacted by the hydraulic permeability enhancement. Specifically, the two EC locations were located in the vicinity of GFB539-MW20 and GFB539-MW21. Unlike the other new monitoring wells installed to facilitate performance monitoring including GFB539-MW15 through -MW19, GFB539-MW20 and -MW21 were not impacted by the demonstration work as evident by the lack of changes in TOC and geochemical conditions as presented in **Section 5**.

Therefore, the lack of changes in EC within the depth interval targeted for permeability enhancement (i.e., between approximately 10 and 20 feet bgs) is very consistent with other supporting data. However, given the unfortunate placement of the EC points, it could not be determined if this geophysics monitoring tool would be effective in monitoring of post-fracture initiation amendment delivery and distribution. It should be noted that, similar to ERT, the relatively high background conductivity inherently present at the site could have rendered detections of the KCl-spiked, high-conductivity injection solution difficult. The need for a high degree of contrast in conductivity of background versus the injection solution represents a potential shortcoming of the EC logging technology specifically for purposes of attempting to map fractures because high conductivity soil and groundwater are commonly found at coastal and historic seabed sites such as MCB-CP and GFAFB, respectively.

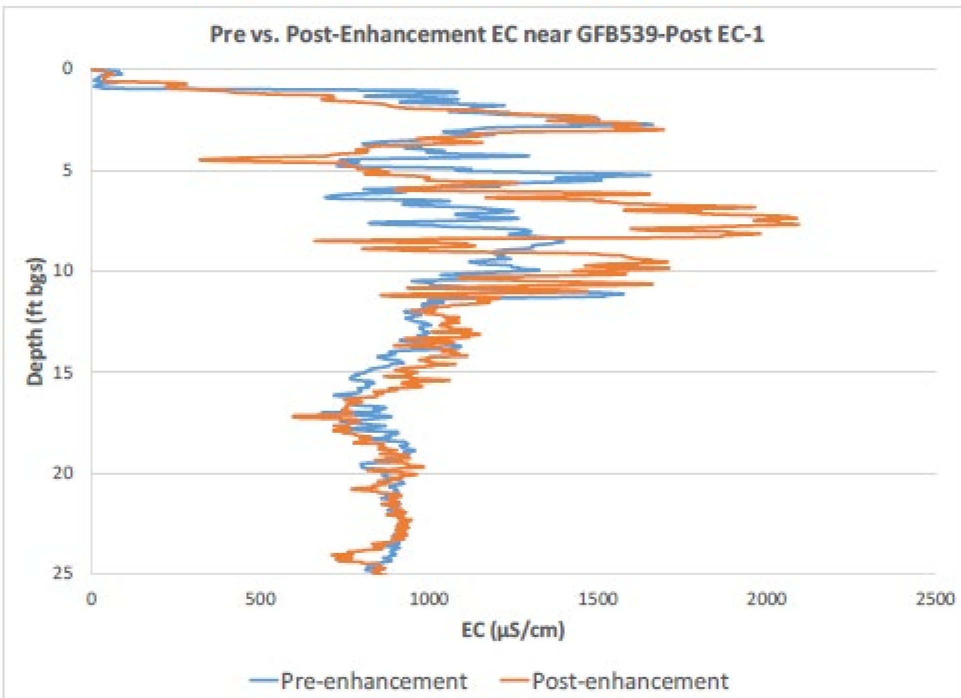

Figure 6.12. Pre- Versus Post-Enhancement EC at GFB539-Post EC-1 at GFAFB

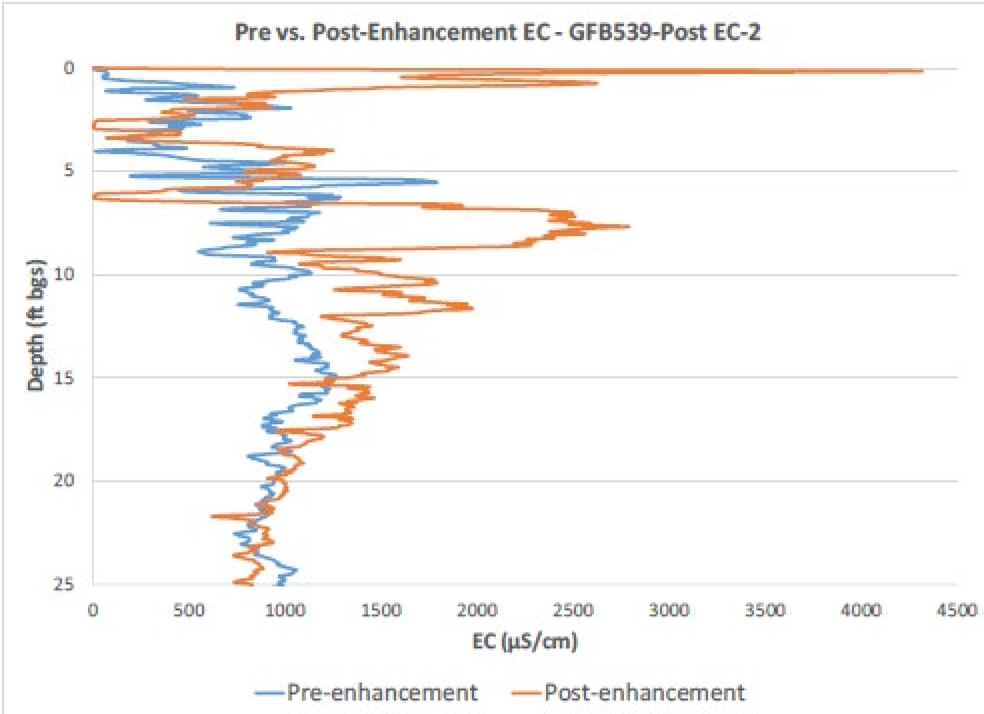

Figure 6.13. Pre- Versus Post-Enhancement EC at GFB539-Post EC-2 at GFAFB

6.1.4 ERT Monitoring

Significant changes in ERT signals were generally correlated with other observations at each of the three demonstration areas (hydraulic and pneumatic at LCAAP and hydraulic at GFAFB). Unlike tilt meters, ERT is not designed nor expected to accurately map individual fracture features at discrete depth intervals. Rather, it can be used to observe volumetric changes in areas surrounding around injection locations in response to amendment additions.

At LCAAP, where ERT was implemented in both the hydraulic and pneumatic cells, cross-borehole visualization could discern some contrast in pre- vs post- fracturing measurements, with the highest signal contrasts being observed within 1 to 2 feet of the ERT borehole.

The differences in pre- and post-enhancement subsurface conductivities measured by downhole ERT at LCAAP for the hydraulic and the pneumatic demonstration cells are graphically illustrated in **Figures 6.14** and **6.15**, respectively. For both areas, ERT technique was most effective in the immediate area surrounding the monitoring boreholes; cross-borehole monitoring via ERT was somewhat limited. In addition, more pronounced changes in conductivity were generally observed in the hydraulic demonstration area, particularly at depths shallower than 10 ft. These results were consistent with other observations, which suggested that better distribution was achieved in the hydraulic cell compared to the pneumatic cell.

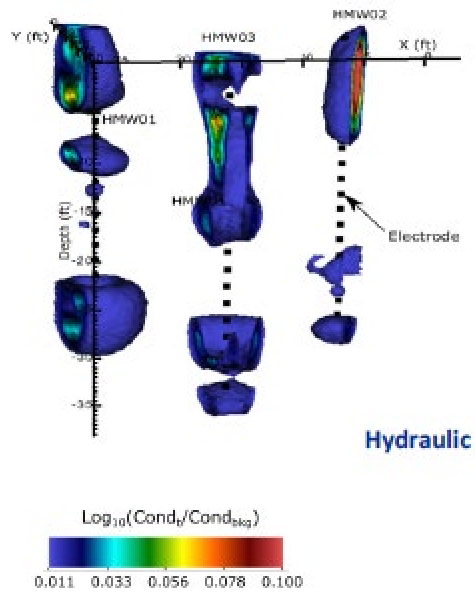

Figure 6.14. Changes in Subsurface Conductivities Observed by Downhole ERT Monitoring in the Hydraulic Demonstration Area at LCAAP

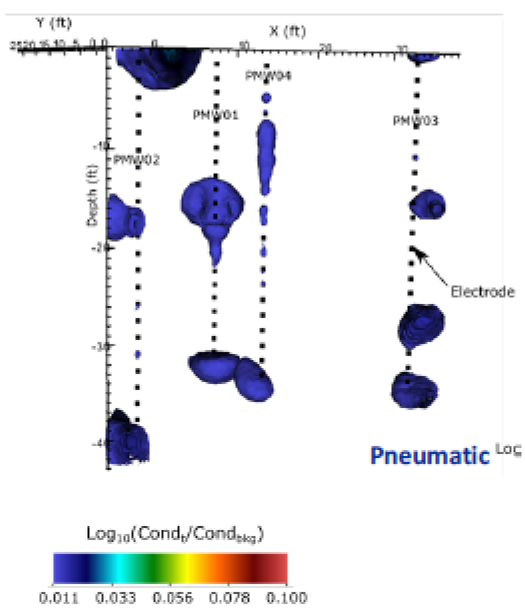

Figure 6.15. Changes in Subsurface Conductivities Observed by Downhole ERT Monitoring in the Pneumatic Demonstration Area at LCAAP

Surface and downhole ERT monitoring techniques were also implemented at GFAFB to facilitate evaluation of amendment delivery and distribution. As shown in **Figure 6.16**, no significant changes in subsurface conductivities were observed in pre- and post-enhancement "scan" using the 2D surface ERT monitoring technique.

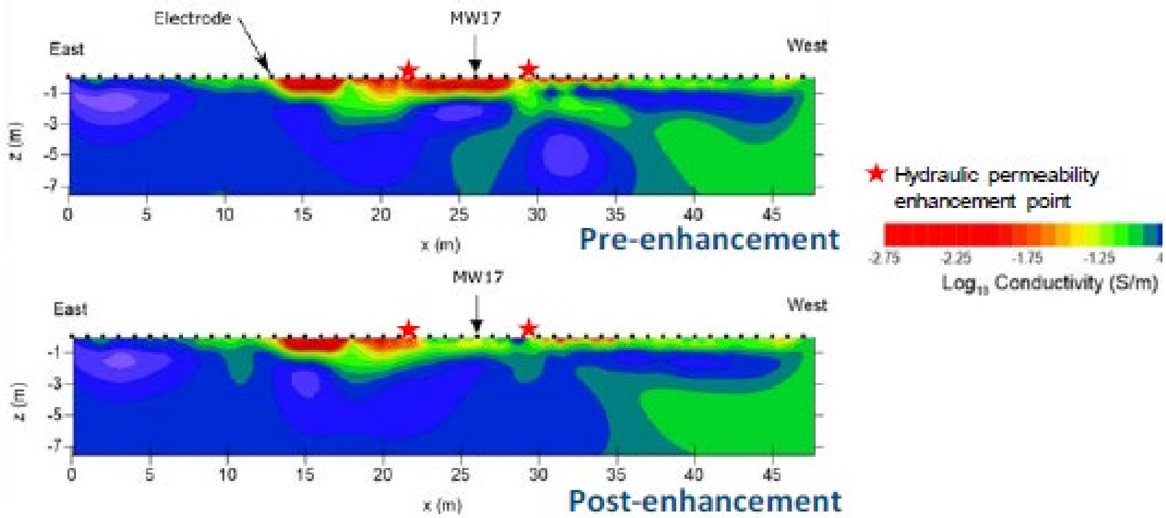

Figure 6.16. Pre- Versus Post-Enhancement Subsurface Conductivities Elucidated by Surface ERT Monitoring Technique at GFAFB

At GFAFB, unlike LCAAP, pronounced changes in subsurface conductivities were observed at locations between monitoring wells. **Figure 6.17** shows changes in conductivity surrounding the 3D borehole ERT arrays where a) and b) reflect time-lapse changes at the first time-step and c) and d) reflect changes at the second time-step. Only changes that reflect increases in conductivity are shown. The logarithmic changes shown correspond to a conductivity change range of 3.5-32%.

From **Figure 6.17,** substantial changes can be seen at the first time-step (images a and b) between wells MW-17 and MW-18, as well as MW-17 and MW-16. The second time-step (images c and d) shows a much more dramatic contrast in conductivity in these same areas, which indicates continued migration of the injected amendment. In particular, significant conductivity increases were observed at shallow depths (down to approximately 10 ft) between MW-17 and MW-18 (images a and c), while deeper impacts were observed between wells MW-15, MW-16, and MW-17 (images b and d).

These changes were compared to other data collected at the site (in particular soil TOC and fluorescein). The results were somewhat mixed in that fluorescein concentrations generally increased with depth in post-enhancement borings (refer to **Figures 6.10** and **6.11**), which is consistent with imaging from the MW-15, -16, and -17 areas, but not with the MW-17 to MW-18 imaging, which showed substantial conductivity changes only down to approximately 10 ft. The ERT images were also compared to soil TOC results; however, from **Figure 5.36** soil TOC did not significantly increase following amendment emplacement, so these comparisons were inconclusive. TOC in groundwater increased by several orders of magnitude within one month following amendment emplacement at all of the ERT wells. Overall, ERT at GFAFB did show substantial changes in response to amendment injections, and was useful in combination with other collected data in evaluating amendment distribution.

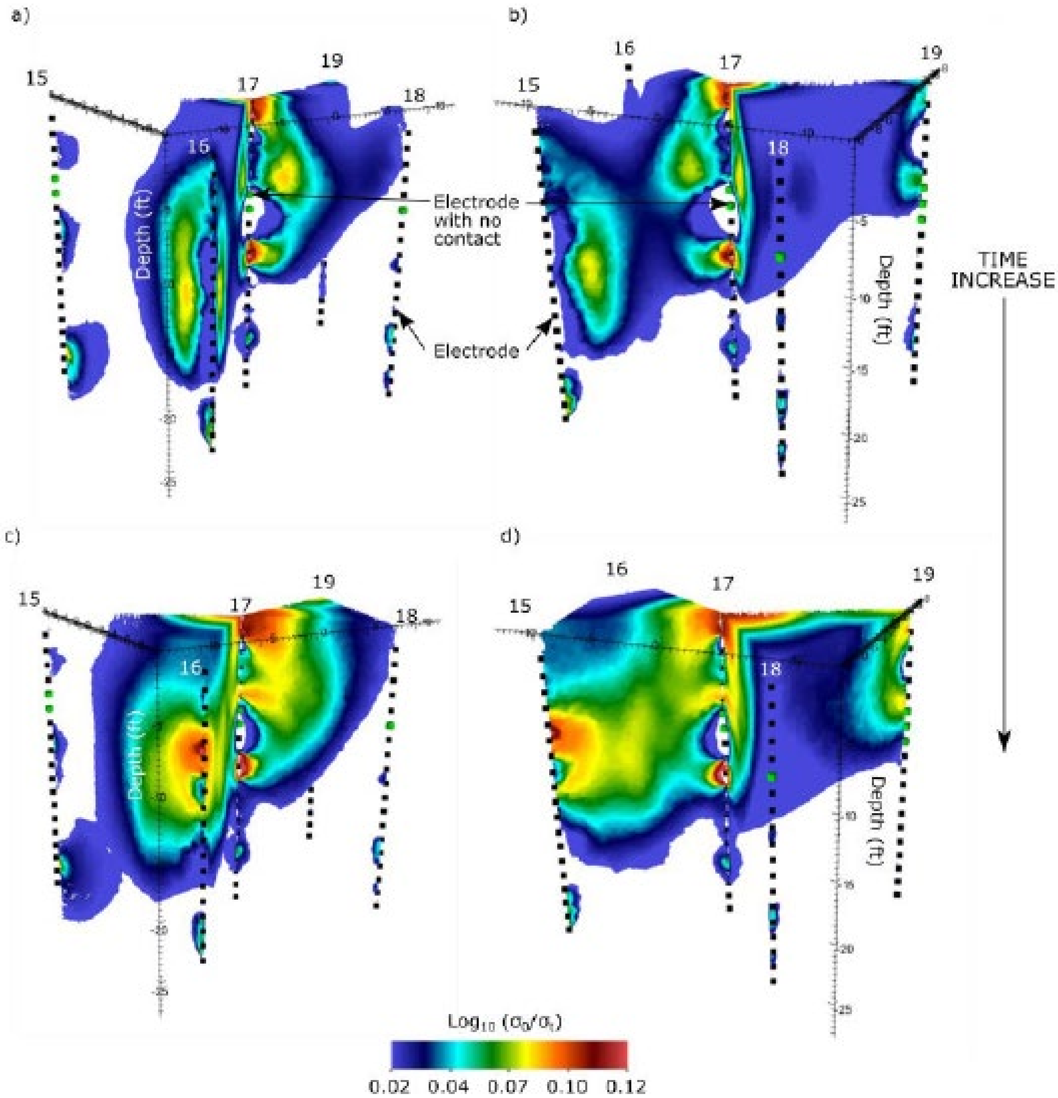

Figure 6.17. Pre- Versus Post-Enhancement Subsurface Conductivities Over Time Elucidated by Downhole ERT Monitoring Technique at GFAFB

6.2 PERFORMANCE OBJECTIVE #2

The performance objective of delivering more than 75% of the target amendment dose within the target treatment volume was achieved at all three sites except for the hydraulic demonstration area at LCAAP, where significant amendment surfacing was observed because of past subsurface disturbances and likely presence of vertical and horizontal preferential conduits that are subject to amendment surfacing. As shown in **Section 5**, despite the challenging subsurface conditions, more than 70% of the target injection volume was introduced into the subsurface via hydraulic permeability enhancement at LCAAP. Between 99 and 100% of the target injection volume was achieved within the treatment area at the remaining demonstration sites.

6.3 PERFORMANCE OBJECTIVE #3

The performance objective of evaluating increases in aquifer permeability resulting from permeability enhancement technology was achieved by performing slug testing pre- and post-enhancement at relevant wells located within the anticipated ROI of permeability enhancement at all three sites. In terms of whether hydraulic conductivity increased due to permeability enhancement activities, the results were generally as expected. For example, no statistically significant changes in hydraulic conductivities were observed at demonstrations sites where a sand proppant was not added, by design, including GFAFB and the pneumatic demonstration area at LCAAP. In the absence of a sand proppant, the fractures initiated because of permeability enhancement are subject to very rapid collapse due to overburden pressures. The lack of changes in hydraulic conductivities following hydraulic permeability enhancement at LCAAP is likely attributable to presences of voids, vertical and horizontal preferential pathways, and other uncertainties in the subsurface due to past disturbances within the hydraulic demonstration area. At MCB-CP, where a sand proppant was hydraulically emplaced, significant increases in hydraulic conductivities ranging between approximately 3 and 40 times were observed. Collectively, these results indicate that hydraulic conductivity measurements via slug testing can generally be used to determine changes in subsurface permeability resulted from permeability enhancement activities.

6.4 PERFORMANCE OBJECTIVE #4

The performance objective of evaluating the effectiveness and accuracy of tilt-meter geophysics monitoring was achieved at all three sites by qualitatively comparing the predicted versus the actual depth-discrete intervals where fractures initiated via permeability enhancement were visually observed or verified via field or laboratory testing. At GFAFB, elevated fluorescein concentrations indicative of amendment delivery were observed within 1 to 2 feet of the tilt-meter-predicted depth-discrete intervals where the initiated fracture network intercepts the confirmation borehole (denoted by the red stars), as shown in **Figures 6.18 through 6.22**. This observation was consistent in all five boreholes that were intercepted by the fractures initiated by permeability enhancement and the injection solution including GFB539-HCB-01, -02, -03, -06, and -07. At the other confirmation boreholes (GFB539-HCB-04, -05, and -08) located outside the ROI of permeability enhancement, as verified by the lack of fluorescein in depth-discrete composite soil samples, the lack of fracture interception was also predicted by tilt meters.

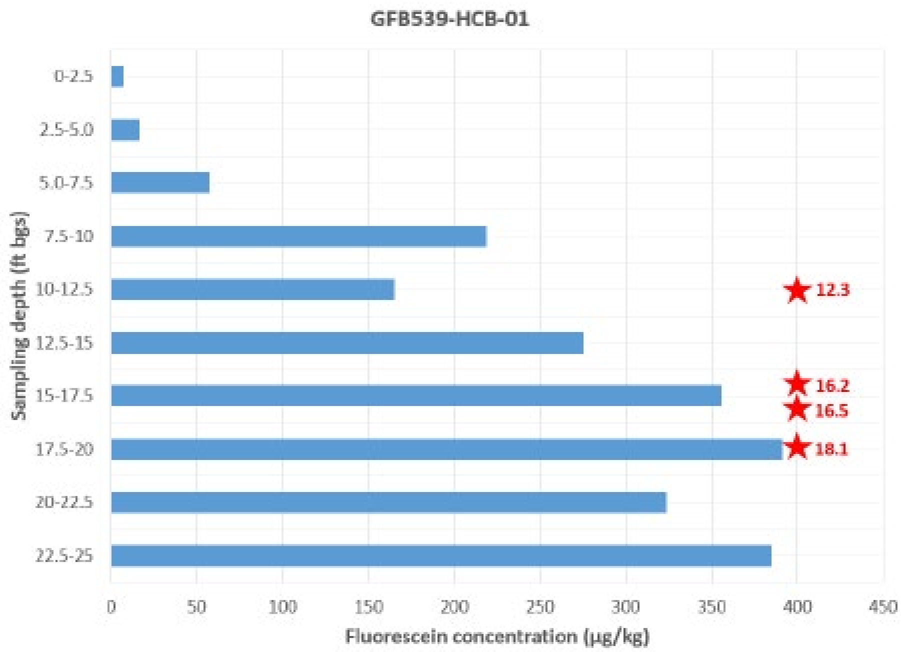

Figure 6.18. Correlation between Intervals with Elevated Fluorescein Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at GFB539-HCB-01 at GFAFB

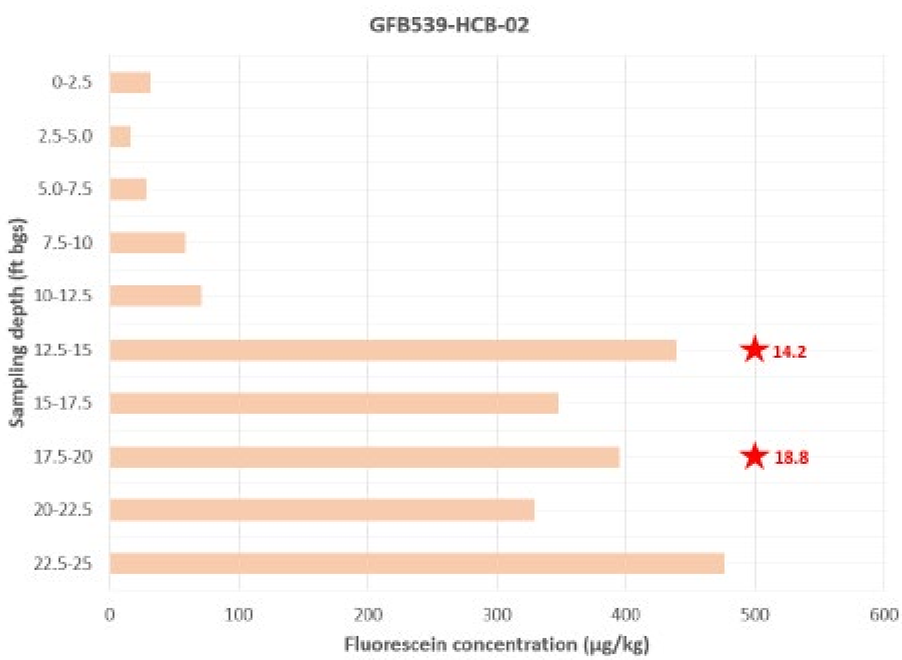

Figure 6.19. Correlation between Intervals with Elevated Fluorescein Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at GFB539-HCB-02 at GFAFB

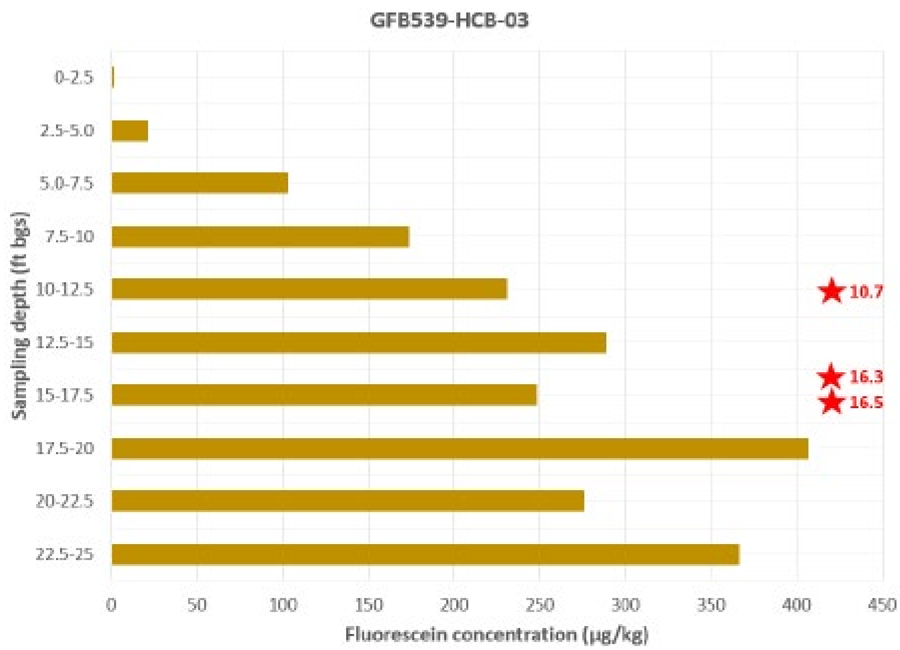

Figure 6.20. Correlation between Intervals with Elevated Fluorescein Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at GFB539-HCB-03 at GFAFB

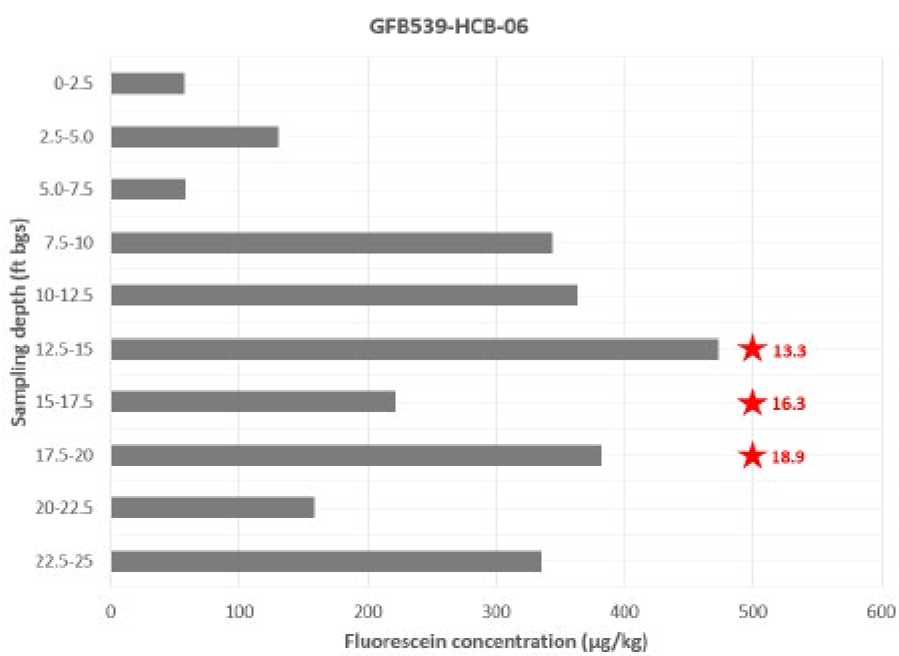

Figure 6.21. Correlation between Intervals with Elevated Fluorescein Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at GFB539-HCB-06 at GFAFB

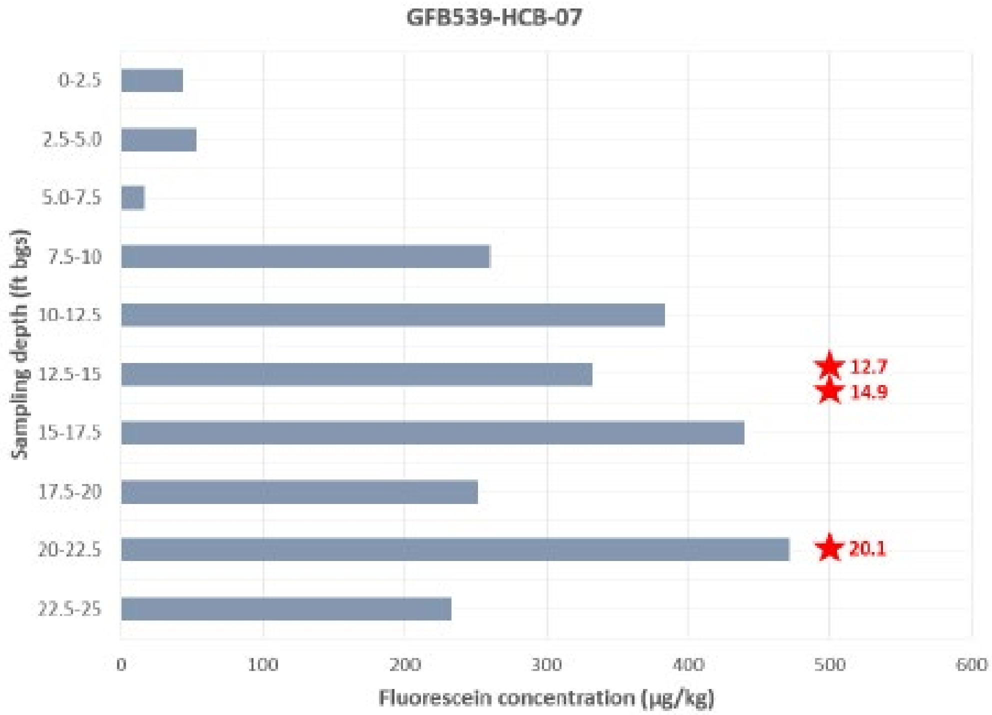

Figure 6.22. Correlation between Intervals with Elevated Fluorescein Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at GFB539-HCB-07 at GFAFB

At MCB-CP, three of the four fracture-intercepting depth-discrete intervals predicted by tilt meter coincided with intervals where fractures were visually observed during post-enhancement confirmation sampling and lithologic logging. Also, orders-of-magnitude increases in total sulfate concentrations were analytically verified at one (HCB-01) of the two post-enhancement confirmation boreholes. The other predicted fracture-intercepting depth interval was above the water table; any persulfate delivered during post-enhancement injection would have been subject to downhole draining, resulting in no significant increases in total sulfate concentration. At the other confirmation borehole (HCB-02), no fractures were visually observed, consistent with the 3D visualization (which shows that this boring location is at the edge of the fracture network) and the absence of the orders-of-magnitude increases in total sulfate concentrations observed at HCB-01. However, increases in post-enhancement total sulfate concentrations ranging between two and five times the pre-enhancement level were observed at all depth intervals predicted by tilt meter that are below the water. In fact, the predicted fracture-intercepting depths were within 1 foot of the intervals exhibiting significant increases in total sulfate concentrations. These results are graphically depicted in **Figures 6.23** and **6.24**.

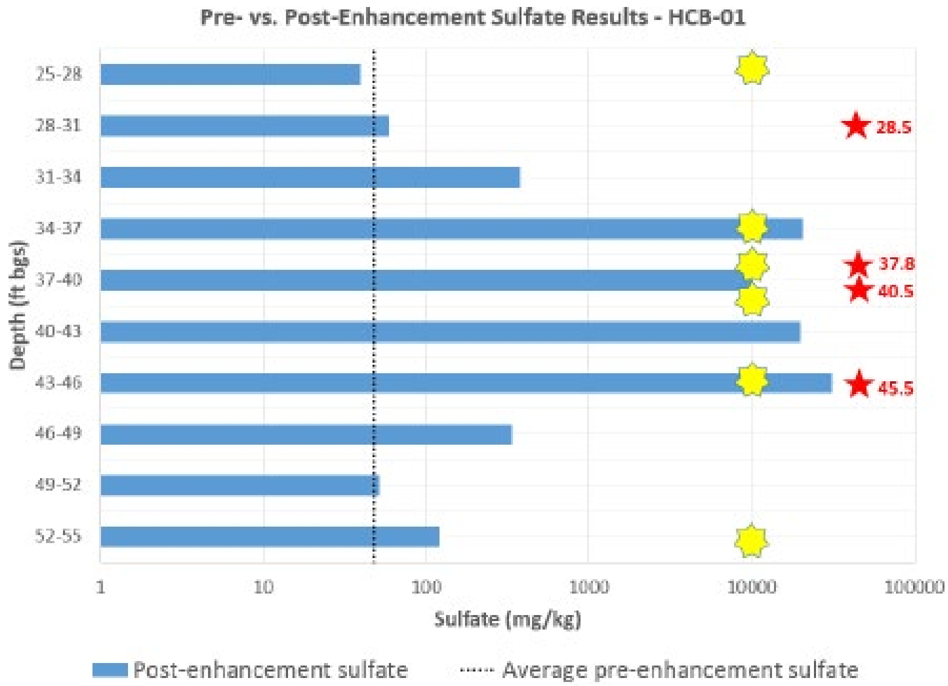

Figure 6.23. Correlation between Intervals with Elevated Sulfate Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) and the Actual Depths where Fractures Were Visually Observed (Denoted by the Yellow Stars) at HCB-01 at MCB-CP

Similar to GFAFB and MCB-CP, tilt-meter results correlate very well with visual observations of fractures and/or analytical verification of the injection solution at LCAAP. Positive correlation was observed within the hydraulic demonstration area despite its subsurface anomalies as shown in **Figures 6.25** and **6.26**. Specifically, at both post-enhancement confirmation boreholes within the hydraulic demonstration area, all six tilt-meter-predicted fracture-intercepting depth intervals were within 1 to 3 feet of those where fractures were either visually observed or the highest increases in TOC concentrations were observed.

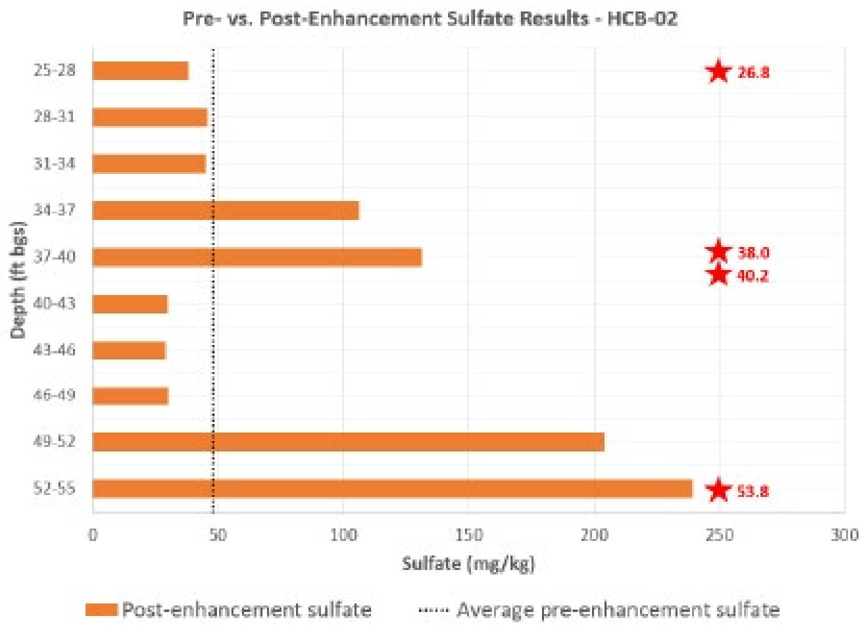

Figure 6.24. Correlation between Intervals with Elevated Sulfate Concentrations and Tilt-Meter-Predicted Interception Depths (Denoted by the Red Stars) at HCB-02 at MCB-CP

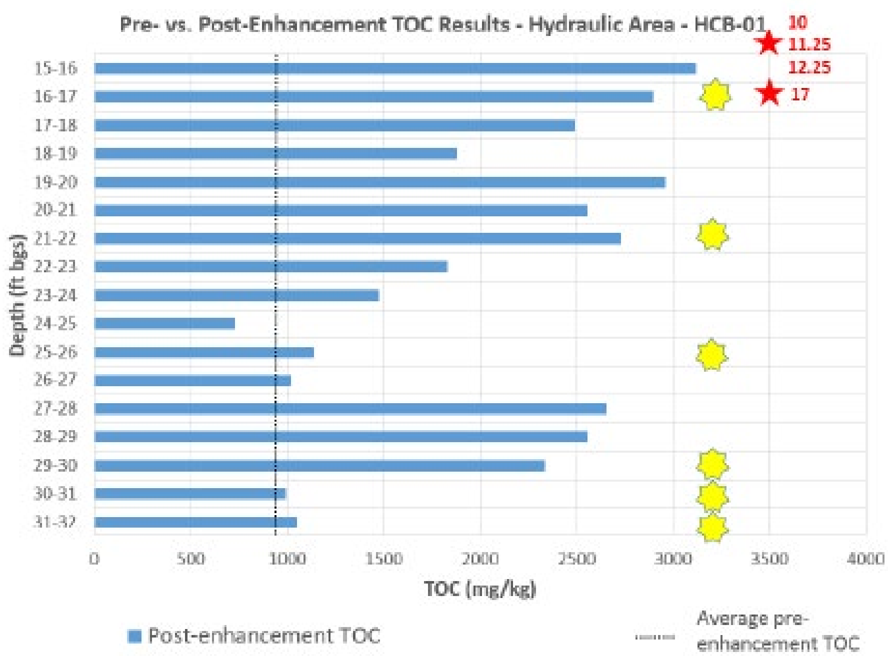

Figure 6.25. Correlation between Intervals with Elevated TOC Concentrations and Tilt-Meter-Predicted Interception Depths (Denoted by the Red Stars) and the Actual Depths Where Fractures Were Visually Observed (Denoted by the Yellow Stars) at HCB-01 at LCAAP

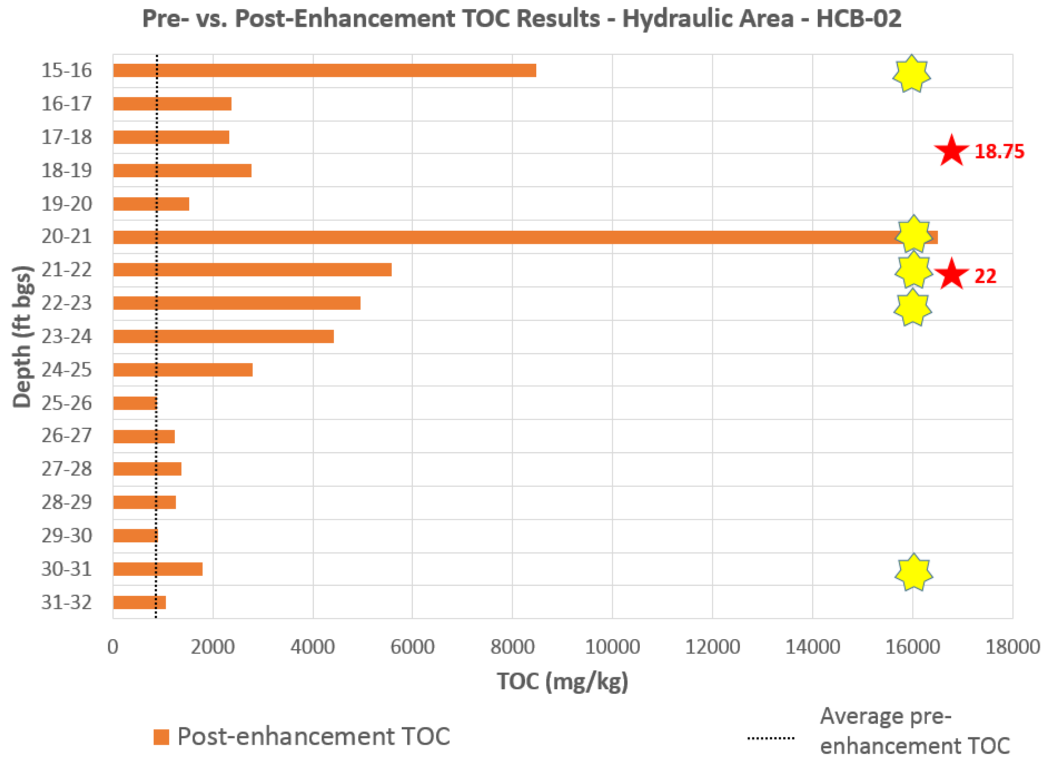

Figure 6.26. Correlation between Intervals with Elevated TOC Concentrations and Tilt-Meter-Predicted Interception Depths (Denoted by the Red Stars) and the Actual Depths Where Fractures Were Visually Observed (Denoted by the Yellow Stars) at HCB-02 at LCAAP

Similar correlations between tilt-meter modeling predictions and confirmation sampling results were observed at two of the three post-enhancement boreholes within the pneumatic demonstration area. Specifically, at PCB-01 and PCB-02, the fracture-intercepting depths predicted by tilt meter were generally within 1 to 2 feet of the highest increases in TOC concentrations as shown in **Figures 6.27** and **6.28**. Such correlation was not observed at PCB-03 as shown in **Figure 6.29**; however, the predicted fracture interceptions thereof might have emanated from the nearby PIW-01 that was not monitored by tilt-metering.

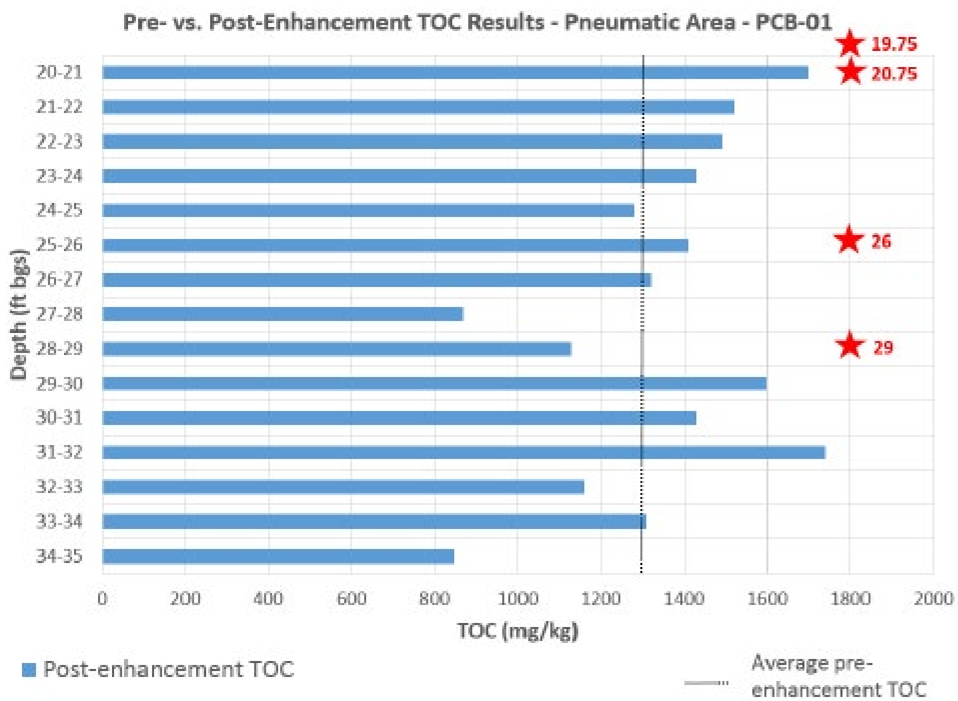

Figure 6.27. Correlation between Intervals with Elevated TOC Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at PCB-01 at LCAAP

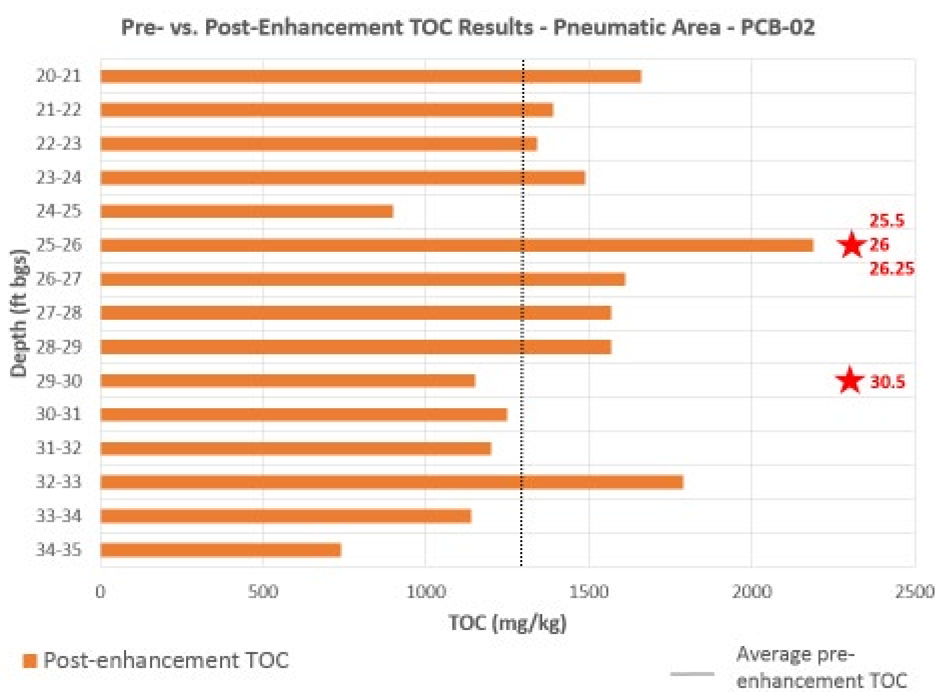

Figure 6.28. Correlation between Intervals with Elevated TOC Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at PCB-02 at LCAAP

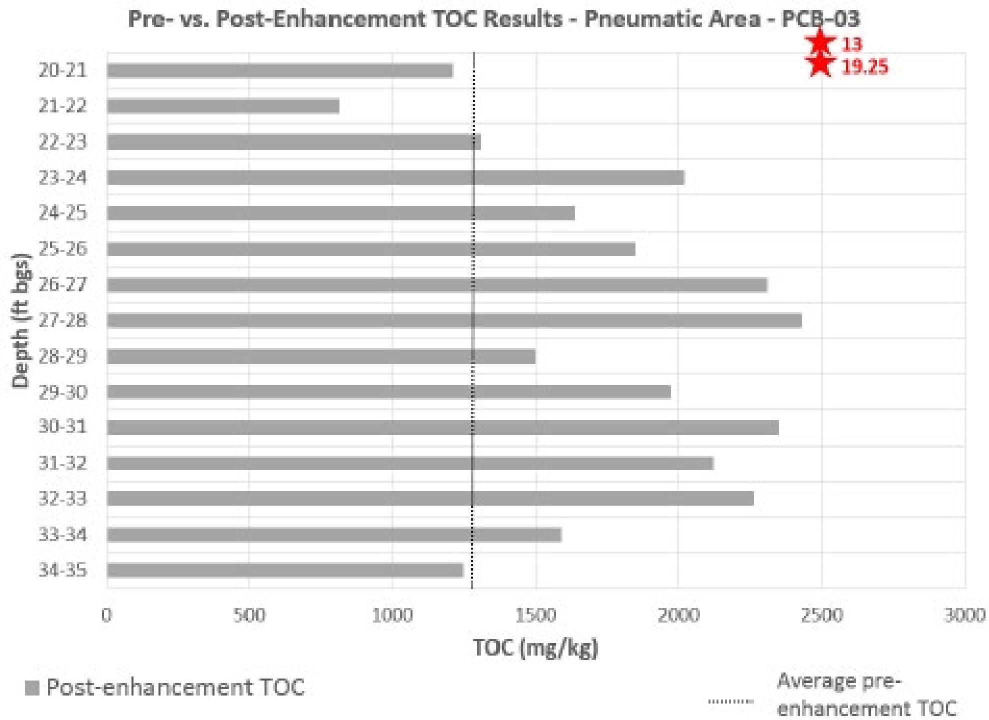

Figure 6.29. Correlation between Intervals with Elevated TOC Concentrations and Tilt-meter Predicted Interception Depths (Denoted by the Red Stars) at PCB-03 at LCAAP

Collectively, results from all three sites indicate that tilt meters can be used to effectively and accurately monitor fracture network initiated during both hybrid pneumatic and hydraulic permeability enhancement. Tilt-meter predictions were qualitatively and quantitatively verified by both visual and analytical methods.

6.5 PERFORMANCE OBJECTIVE #5

The performance objective of evaluating the effectiveness and accuracy of EC was assessed by analyzing pre- and post- enhancement EC logs at GFAFB. No significant increases in EC were observed within the target treatment depth interval at GFAFB. However, no evidence of amendment delivery into the two EC locations was observed. This lack thereof was also analytically confirmed via soil confirmation sampling and subsequent fluorescein analysis. Specifically, no significant detection of fluorescein was detected at the two post-enhancement confirmation boreholes located in the vicinity of the two EC locations. Collectively, the limited data collected at this site renders the evaluation of EC as an effective geophysics tool for fracture monitoring inconclusive.

6.6 PERFORMANCE OBJECTIVE #6

The performance objective of evaluating the effectiveness and accuracy of ERT in assessing amendment emplacement should not be regarded in the same way as tilt-metering, for which a fracture-by-fracture analysis with depth-discrete intervals can be evaluated. Rather, ERT is more suitable for assessing volumetric changes throughout the target treatment zone and is more appropriately evaluated by comparing it to other analytical indicators such as tracers or TOC in groundwater.

Along these lines, significant changes in ERT signals were generally correlated with other observations at each of the three demonstration areas (hydraulic and pneumatic areas at LCAAP and hydraulic at GFAFB). For the pneumatic cell at LCAAP, little change was observed following amendment emplacement, which was consistent with the TOC groundwater data. For the hydraulic cell at LCAAP, modest changes were observed following enhancement activities, with such changes generally localized around the monitoring well locations where the electrodes were deployed. At GFAFB, ERT imaging showed the most dramatic changes pre- and post-injection, and these changes were generally correlated with increases in TOC and fluorescein as measured from the confirmation borings and the groundwater monitoring network. ERT was also able to show a time-lapse evolution of the injected amendment following emplacement.

Overall, while ERT visualization of post-enhancement amendment distribution was not of sufficiently high enough resolution throughout the target areas to map and identify individual fractures, it was useful for assessing overall distribution of the emplaced amendment.

6.7 PERFORMANCE OBJECTIVE #7

The performance objective of evaluating the remedial enhancement gained by applying permeability enhancement at each of the three demonstration sites was assessed by analyzing changes in geochemical/redox conditions as well as contaminant trends over time at performance monitoring wells located within the anticipated ROI and vertical treatment interval of permeability enhancement. Discussions pertinent to each demonstration site are provided in the subsequent sections.

6.7.1 GFAFB

At GFAFB, orders-of-magnitude increases in TOC were observed in nearly all monitoring wells located and screened within the target treatment zone following permeability enhancement. Specifically, pre-enhancement TOC concentrations in relevant monitoring wells at the site were generally less than 20 mg/L, despite repeated attempts to perform amendment injections using conventional techniques. Following permeability enhancement, TOC concentrations increased several orders of magnitude, ranging between approximately 2,500 to 7,200 mg/L, at select monitoring wells located within the anticipated ROI of permeability enhancement. Although a general decrease was observed during the 9-month post-enhancement sampling event, TOC remained elevated and ranged between approximately 200 and 1,000 mg/L. TOC delivery was generally accompanied by significant development of geochemical conditions conducive to reductive dechlorination of TCE, including complete depletion of DO and nitrate, reduction of ORP to as low as -310 millivolts, increases in ferrous iron concentrations, and reduction of sulfate from very high starting sulfate concentrations ranging between approximately 2,000 and 6,000 mg/L to less than 500 mg/L in some cases over the 9-month performance monitoring period.

The lack of methane generally observed at GFAFB was likely attributable to high concentrations of sulfide and subsequent sulfide inhibition of methanogenesis. Collectively, the amendment delivery via hydraulic permeability enhancement at GFAFB completely changed the groundwater chemistry at the site; a highly reducing environment characteristic of sulfate reduction, which is conducive to reductive dechlorination, was developed in the aquifer that had been only slightly reducing pre-enhancement.

Significant changes in contaminant concentrations were also observed following permeability enhancement at GFAFB. TCE concentrations decreased by as much as a factor of 9, from a starting concentration as high as 18,000 micrograms per liter (µg/L). However, cis-1,2-DCE also decreased significantly in many of the wells, which suggests that in addition to biological reduction, some of the observed degradation may be attributed to biogeochemical transformation via the beta elimination pathway, a process whereby reactive iron sulfide minerals are formed from an abundance of reduced iron and production of sulfide from microbially-mediated sulfate reduction (shown below in **Figure 6.30**). It should be noted that daughter products, including VC and ethene, were not detected in significant concentrations because of the lack of the appropriate bacterial community. This was known during the planning phase of the demonstration; however, bioaugmentation was not part of the scope of the demonstration and thus was not performed. Regardless, significant changes in geochemistry and contaminant degradation were observed at the site, and had bioaugmentation been performed, complete dechlorination of TCE to ethene would have been possible.

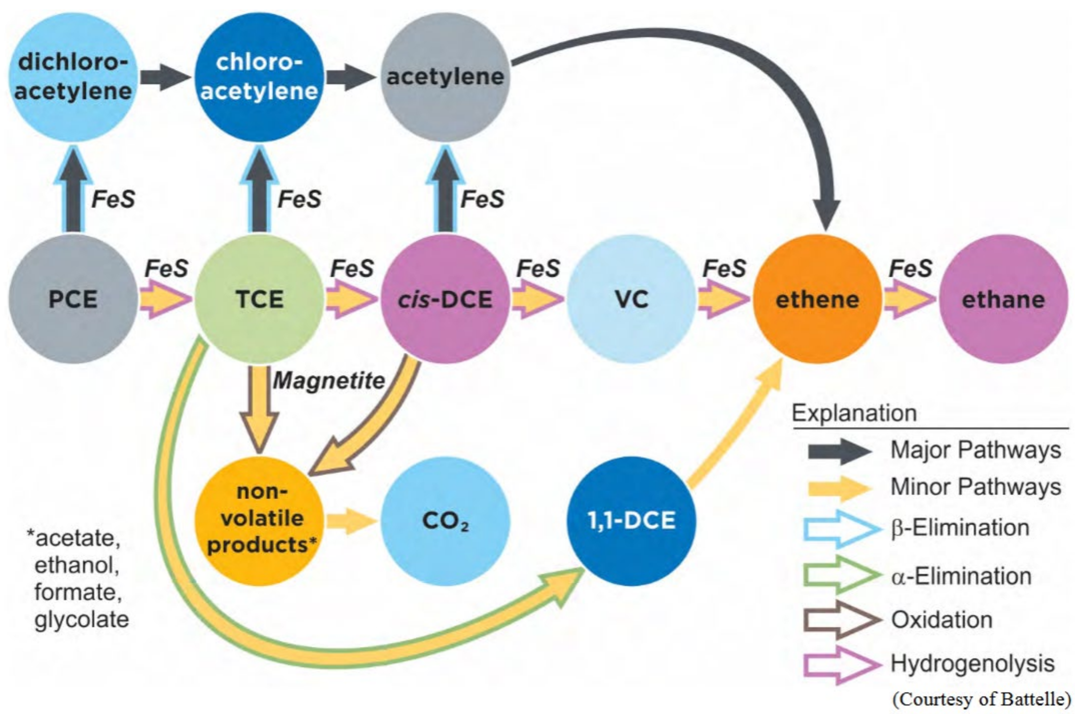

Figure 6.30. Major and Minor Degradation Products of Chlorinated Ethenes with Different Minerals (figure courtesy of Battelle)

6.7.2 MCB-CP

At MCB-CP, aerobic conditions characterized by elevated DO and high ORP were observed at several wells located upgradient, downgradient, and cross-gradient from the permeability-enhanced injection well following amendment injection. At these locations, including 1115-HMW-01 through -03, complete degradation of BTEX compounds were observed. No significant changes in contaminant concentrations were observed at the cross-gradient monitoring well 1115-MW-35. This was expected since this well is located outside of the ROI of permeability enhancement. However, increases in persulfate concentrations accompanied by reduction in BTEX compounds were seen at the downgradient monitoring well 1115-HMW-37 during the 9-month post enhancement monitoring event, which is also located outside of the ROI of permeability enhancement. This suggests that the persulfate migrated downgradient and impacted an area greater than the actual enhancement ROI. Collectively, these results indicated that, as expected, persulfate-aided oxidation of BTEX compounds were achieved in not only wells that were directly impacted by the permeability enhancement and subsequent persulfate injection activities, but also wells located downgradient of the injection well.

6.7.3 LCAAP

Similar to GFAFB, development of a highly reducing environment conducive to reductive dechlorination of TCE was observed at several monitoring wells located within the hydraulic permeability enhancement demonstration area at LCAAP. At these locations, increases in TOC ranging from two- to five-fold, depletion of DO and nitrate, negative ORP, and elevated ferrous iron were observed. While no reduction in chlorinated solvent concentrations was observed at two of the three monitoring wells located within the ROI of hydraulic permeability enhancement, it should be noted that DNAPL was unexpectedly present in this area, which led to baseline TCE concentrations of greater than 100,000 µg/L at all three monitoring wells. However, at one of the monitoring locations (HMW-01), TCE concentrations decreased significantly from 160,000 to 810 µg/L. Such decreases in TCE concentrations were accompanied by an increase in VC from approximately 3,000 to 11,000 µg/L and a slight increase in ethene from 5.3 to 430 µg/L. These concentration trends are indicative of reductive dechlorination. Under these conditions, it can be difficult to observe any decline in TCE concentrations because additional contaminant mass dissolves from the non-aqueous phase as TCE is biodegraded.

Following permeability enhancement, a strongly reducing environment typical of sulfate reduction was developed within the pneumatic demonstration area at LCAAP. Similar to the hydraulic demonstration area, increases in TOC concentrations were observed at wells located within the anticipated ROI of permeability enhancement, relative to pre-enhancement levels. However, it should be noted that the post-enhancement TOC concentrations in both soil and groundwater in the pneumatic area were much less than those in the hydraulic area, despite the same amount of LactOil® being introduced in each area. Although the target amendment injection was achieved by hybrid pneumatic permeability enhancement along with minimal amendment surfacing was observed, it is possible that the amendment leak-off did occur but was not observed at the surface as a result of the downhole assembly used during permeability enhancement. Specifically, in addition to a straddle packer assembly used to isolate the depth-discrete interval of interest for permeability enhancement, another packer was also installed on top of the straddle packer assembly to minimize amendment surfacing. Given the relatively low TOC concentrations observed in both soil and groundwater, it is likely that amendment surfacing did occur between the top packer and the top packer of the straddle assembly.

In monitoring wells that were directly impacted by the hybrid pneumatic permeability enhancement, including PMW-01 through -04, significant changes in contaminant concentrations were observed in addition to changes in geochemical conditions. In many instances, complete degradation of TCE, transient accumulation then removal of daughter products cis-1,2-DCE and VC, and accumulation of ethene, resulting in more than 99% removal of chlorinated VOCs, were observed.

6.8 PERFORMANCE OBJECTIVE #8

This performance objective evaluates the ease of use/implementation of each permeability enhancement technology and performance monitoring strategy. Specifically, the relative availability of equipment and access to appropriate expertise, the level of oversight required, and the types of problems encountered and ease of solution for each permeability technology are described in detail below.

6.8.1 Equipment Availability and Access to Appropriate Expertise

Proper applications of hydraulic permeability enhancement require proprietary injection equipment and materials and therefore highly specialized personnel to aid in project planning, design, execution, and evaluation. It should be noted that while the individual components of the injection skids used for aqueous and solid amendment emplacement via hydraulic permeability enhancement are generally commercially available, the injection skids themselves are custom-made to be modular for enhanced adaptability in different site settings and ease of transport. Their design is also modified and optimized over time. Similar to the aboveground injection equipment, downhole equipment, including inflatable packer and injection rods, are generally commercially available. The downhole tooling used during DPT-aided top-down emplacement of an aqueous amendment, as performed at GFAFB, was custom-designed and built to ensure sufficient seal and minimize leak-off. Of note, there are often multiple variations in design, applicability, cost, and performance associated with a single piece of equipment used in permeability enhancement. For example, there are many designs of pumps that are commercially available for different fluid delivery applications at different costs, performance, and longevity. In some instances, selection of the appropriate equipment, based on technical knowledge and/or professional experience, can make the difference between success and failure.

Unlike most equipment required to perform hydraulic permeability enhancement, proprietary chemical reagents are required to properly inject a solid amendment into the subsurface. Specifically, a proprietary formula is used to achieve a sufficiently high solid-mass loading to ensure suspension of the solid amendment during mixing and injection as well as within the subsurface, and to facilitate rapid breakdown of the high-viscosity fluid following emplacement to negate any adverse impacts on the aquifer's hydraulic conductivity. The compositions of these chemical reagents and their optimal ratios for a particular amendment in a specific application are a result of years of bench-, pilot-, and full-scale testing and implementation of hydraulic permeability enhancement. Therefore, there are very few vendors that have consistently demonstrated the ability to successfully performed hydraulic permeability enhancement.

Similar to hydraulic permeability enhancement, the aboveground and downhole equipment used to facilitate hybrid pneumatic permeability enhancement is mostly commercially available. Injection skids are often constructed in a modular configuration to allow for ease of transport, access, and adaptability to site-specific settings. There are several vendors in North America that have commercialized pneumatic permeability services.

6.8.2 Level of Oversight Required

Real-time decision-making is often required during implementation of both hydraulic and pneumatic permeability enhancement. Therefore, the personnel providing the technical oversight need to be familiar with the site conceptual model, understand the overall objective of the injection program, communicate any issues encountered to the project team, and help make the necessary adjustments. In addition, because some applications of permeability enhancement are performed under relatively high pressures, it is imperative that these personnel be familiar with the health and safety concerns associated with permeability enhancement and are qualified to supervise and provide inputs as necessary.

6.8.3 Types of Problems Encountered

There are several types of issues that may be encountered throughout the different stages of a permeability enhancement project including planning, design, implementation, and evaluation. Despite its recent commercialization as an *in situ* delivery technique at sites with challenging lithologies, permeability enhancement is still a relatively novel technique in the remediation industry. In addition, the technology, especially the hydraulic approach to permeability, also suffers from the poor public perception of hydraulic fracturing in the oil and gas industry, although the two techniques differ vastly as shown in **Table 6.2**. In several instances during the planning phase of this demonstration project, it was necessary to communicate the differences between the permeability enhancement techniques employed for environmental purposes versus oil and gas recovery applications. In other cases, concerns regarding vertical contaminant migration, damages to existing nearby infrastructure, and amendment surfacing had to be alleviated by detailed discussion in planning documents, webinar presentations, and/or telephone conferences among the parties of interest. Overall, concerns were resolved relatively promptly and easily by modifying the approved demonstration plan and preparing additional site-specific planning documents, conducting additional performance monitoring or slightly changing in the injection approach.

Table 6.2. Comparison of Fracturing Techniques Used in the Oil and Gas Industry Versus Environmental Remediation Industry

Parameter	Fracturing in Oil and Gas Industry	Fracturing in Environmental Remediation Industry
Overall objective	Extraction of natural resources	Soil and groundwater remediation
Fracturing orientation	Vertical	Horizontal
Fracturing volume	Hundreds of thousands of gallons	Hundreds to thousands of gallons
Fracturing depth	> 1,000 feet bgs	< 100 feet bgs
Fracture-initiating pressure	1,000 to 10,000 psi	100 to 1,000 psi
Nature of chemicals used	Potentially toxic	Non-toxic, food-grade

Another issue encountered at several sites during demonstration of permeability enhancement was the lack of site-specific information—some information was not known even to the onsite points of contact. For example, past disturbances and presence of DNAPL observed at the hydraulic demonstration area at LCAAP was not known by any party involved, thus rendering the direct comparison between the hydraulic and the pneumatic approach to permeability enhancement incomplete, as the two demonstration areas are vastly different in terms of lithology and contaminant profile. Similarly, the need to be escorted by a government officer for all non-U.S. citizens at LCAAP was not apparent until upon arrival at the site. This issue was immediately resolved with the help of the regulatory agencies involved in environmental restoration efforts at LCAAP.

6.9 PERFORMANCE OBJECTIVE #9

This performance objective evaluates the cost of implementation for each permeability enhancement technology, and includes considerations such as mobilization, drilling costs, permeability enhancement vendor costs, and contractor oversight costs. During the demonstration, the cost for each of these components was tracked, as presented in **Section 7**. Cost tables presented in this section have been simplified for ease of comparison; detailed cost breakout and description is presented in **Section 7**.

For the purpose of comparison, the costs presented in **Tables 6.3** through **6.5** were normalized by dividing the total cost of each implementation method by the approximate treated volume of the aquifer. Per the discussion in **Section 7**, the costs that were tracked for this demonstration for permeability enhancement service may not be representative of actual commercial costs. Therefore, more realistic costs were used as appropriate for knowledge transfer. It is recommended that project managers obtain estimates from vendors prior to budgeting their project based on changes in pricing due to quantity discounts or different mobilization requirements.

Additionally, costs for LCAAP were normalized based on longevity of treatment amendment in the subsurface following implementation of the permeability enhancement. As presented in **Section 5**, longevity of amendment in the pneumatic test cell was approximately 6 months, while that of the hydraulic test cell is anticipated to be at least one year. Therefore, to maintain similar amendment concentrations in the subsurface, two hybrid pneumatic injection events versus one hydraulic injection event were assumed.

Table 6.3. Cost Assessment for Hydraulic Permeability Enhancement with Slurry Injection

Cost Element	Cost	Site Source
Fracturing	$90,000	Lake City
Drilling	$7,600	Lake City
Labor	$8,400	Lake City
Sum	$106,000	
Number of Events	1	
Total Cost	$106,000	
Treatment Volume (ft^3)	29,500	
Cost per Cubic Foot	$3.59	

Table 6.4. Cost Assessment for Pneumatic Permeability Enhancement with Aqueous Injection

Cost Element	Cost	Site Source
Fracturing	$33,400	Lake City
Drilling	$8,300	Lake City
Labor	$3,600	Lake City
Sum	$45,300	
Number of Events	2	
Total Cost	$90,600	
Treatment Volume (ft^3)	18,900	
Cost per Cubic Foot	$4.79	

Table 6.5. Cost Assessment for Hydraulic Permeability Enhancement with Aqueous Injection

Cost Element	Cost	Site Source
Fracturing	$54,500	Grand Forks
Drilling	$8,100	Grand Forks
Labor	$4,800	Grand Forks
Sum	$67,400	
Number of Events	1	
Total Cost	$67,400	
Treatment Volume (ft^3)	18,900	
Cost per Cubic Foot	$3.57	

As shown in the tables, the cost for hydraulic permeability enhancement with aqueous injection of amendment is the most cost-effective by cubic foot of treatment, followed closely by hydraulic permeability enhancement with slurry injection. Of the two technologies implemented in weathered shale at LCAAP, hydraulic permeability enhancement with slurry injection (sand emplacement) was more cost effective due to the longevity of the remedial amendment. Hybrid pneumatic permeability enhancement was less expensive to implement per mobilization, but because the amendment was depleted in less than 6 months, the overall treatment effectiveness was less. While hydraulic permeability enhancement with aqueous amendment injection (and no proppant) was less expensive to implement, it did not obtain as large a radius of emplacement as the slurry injection, and is limited to DPT-appropriate sites.

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7.0 COST ASSESSMENT

The cost assessment includes presentation of the costs associated with this demonstration of permeability enhancement in the cost model (costs are not necessarily reflective of a typical project), as well as analysis of primary drivers for the technology, and comparison of real-world applications of conventional approaches (injection wells) with actual implementation of permeability enhancement technology at three sites (costs are also intended to be representative or scalable to a typical project). As previously discussed, permeability enhancement can be used as a stand-alone remedy (such as through emplacement of ZVI), as well as a method for enhancing conventional technologies, such as in *situ* injection of remedial amendments. Therefore, costs associated with implementation of permeability enhancement include capital costs (cost of completing the permeability enhancement work and installation of associated infrastructure if needed, such as injection wells) and depending on the application, operational costs (periodic injection of remedial amendment). The following sections provide detail on implementation costs for the three variations of permeability enhancement that were demonstrated in this project: hydraulic fracturing for injection of a solid/ slurry solution, pneumatic fracturing with injection of an aqueous solution (hybrid pneumatic), and hydraulic fracturing for injection of an aqueous solution. The cost model section is subdivided into individual analyses of each permeability enhancement approach. Cost drivers are provided for the technology as a whole, as well as individual variations as appropriate. Cost analysis was completed for three real-world site scenarios, with hydraulic, hybrid pneumatic, and conventional technology applications compared as applied onsite.

7.1 COST MODEL

Cost elements for implementing the different approaches to permeability enhancement including hydraulic permeability enhancement for emplacing solid amendments (slurry), hybrid pneumatic permeability enhancement for emplacing aqueous amendments, and hydraulic permeability enhancement for emplacing aqueous amendments are presented in **Tables 7.1**, **7.2**, and **7.3**. The major cost elements include utility locate, survey, permeability enhancement services, drilling services, IDW disposal, and costs for contractor oversight of the fieldwork. The presented costs are a blend of the costs from the different demonstration sites as appropriate, as some cost elements were not required at each site. Only costs that are directly related to permeability enhancement are presented. Therefore, costs associated with monitoring well installation, groundwater sampling, hydraulic testing, and confirmation sampling activities are not included. Travel costs are also not included, as they are site-specific. It should be noted that some vendor costs for permeability enhancement services are not representative of anticipated true costs due to discounts associated with the demonstration nature of this project. However, the cost model provides a general representation of the primary cost elements to be considered for implementing the permeability enhancement technologies at actual sites. In addition to the primary cost elements associated with actual field implementation of permeability enhancement, other cost components pertinent to geophysical monitoring techniques required for fracture emplacement evaluation including tilt-meter, ERT, and EC are discussed herein and presented in **Table 7.4**.

7.1.1 Hydraulic Permeability Enhancement for Emplacing Solid Amendments

Hydraulic permeability enhancement for emplacing 40/50 silica sand to create permanent, sand-propped, and high-permeability pathways followed by aqueous amendment injections was performed at two demonstration sites including LCAAP and MCB-CP. Costs shown in **Table 7.1** are representative of the actual costs incurred at MCB-CP except for the first line item, "utility locate," which was performed by the base. As previously described, the technology demonstration at MCB-CP was performed in a lightly cemented sandstone / siltstone with borings advanced using sonic drilling technology. The hydraulic approach to permeability enhancement was first utilized to emplace 40/50 silica sand at five depth-discrete intervals in an open borehole. Bottom-up emplacement methodology utilizing a straddle packer assembly was employed. All activities pertinent to the hydraulic permeability enhancement were completed within approximately seven days at MCB-CP. As shown in **Table 7.1**, the most expensive cost elements pertinent to the work at MCB-CP are: 1) the permeability enhancement and associated monitoring and reporting, and 2) the sonic drilling service as described in more detail below.

The primary cost components pertinent to the permeability enhancement work at MCB-CP include:

- Preparation and mobilization;
- Field implementation of hydraulic permeability enhancement, which was completed in two days and included the use of a straddle packer assembly to isolate and emplace 40/50 silica sand in five depth-discrete intervals;
- Post-enhancement injection service, which was completed in one day and included use of the fracturing equipment to pump a persulfate and sodium hydroxide into the injection well that was completed in the enhancement borehole;
- Costs of chemical reagents including persulfate and sodium hydroxide; and
- Reporting, including completion of a final report for the site.

The primary cost elements pertinent to the sonic drilling service include:

- Mobilization costs for a mid-sized sonic rig;
- Sonic drilling with continuous soil sampling (6-inch boring to a depth of 59 feet bgs) to create an open borehole for permeability enhancement;
- Permeability enhancement assistance for a period of 2.25 days (onsite preparation with the permeability enhancement vendor and use of the drill rig to raise, lower, and suspend the straddle packer assembly into and out of the borehole);
- Overdrilling of the enhancement borehole and subsequent installation of a 2-inch injection well to a depth of 53 feet bgs; and
- Other miscellaneous costs associated with drilling including decontamination and IDW management, well materials, and patching.

Table 7.1. Cost Model for Hydraulic Fracturing with Slurry Injection Solution

Cost Element	Data Tracked During the Demonstration	Costs Detail	Cost	Site Source
Utility Locate	Vendor costs		$5,700	Lake City
Survey	Vendor costs		$2,400	Pendleton
Fracturing	Vendor costs	Includes preparation and mobilization, fracturing service (2 days to complete 1 boring with 5 intervals), 1 day of injections, and reporting.	$88,300	Pendleton
Drilling	Vendor costs	Mobilization for sonic rig, Sonic drilling with continuous soil sampling (six-inch boring to a depth of 59 ft bgs), Fracturing support 2.25 days, Overdrilling of the fractured borehole and installation of a two-inch injection well to a depth of 53 ft bgs.	$24,500	Pendleton
IDW	Vendor costs		$3,100	Pendleton
Labor	Contractor oversight	Labor to perform oversight for fracturing, injection, and drilling (7 days).	$8,400	Pendleton
Travel			$0	Pendleton
Equipment/ Materials		Persulfate cost and freight.	$6,000	Pendleton
Total			**$138,400**	

7.1.2 Pneumatic Permeability Enhancement for Emplacing Aqueous Amendments

Hybrid pneumatic permeability enhancement for emplacing an aqueous solution (LactOil®) *in situ* was performed at LCAAP, and all costs shown in **Table 7.2** are representative of the actual costs incurred at LCAAP. As previously described, the LCAAP hybrid pneumatic demonstration was performed in a clay/weathered shale residuum, with borings advanced using HSA drilling technology. Similar to MCB-CP, a straddle packer assembly was used to isolate and emplace the amendment solution in five depth-discrete intervals at each of the three enhancement boreholes. Bottom-up emplacement methodology was also employed. All activities pertinent to the hybrid pneumatic permeability enhancement at LCAAP were completed within approximately three days. As shown in **Table 7.2**, the most expensive cost elements pertinent to the hybrid pneumatic permeability enhancement activities at LCAAP are: 1) the permeability enhancement and associated monitoring and reporting, and 2) the HSA drilling service as described in more detail below.

The primary cost components pertinent to the hybrid pneumatic permeability enhancement work at LCAAP include:

- Hybrid pneumatic permeability enhancement services (less than typical due to nature of demonstration), including preparation and mobilization, field implementation of pneumatic permeability enhancement, and hydraulic injection service, which was completed immediately following pneumatic permeability enhancement;

- Cost of chemical reagents including LactOil® and potassium bromide; and
- Reporting, including completion of a final report for the site.

The primary cost elements pertinent to the HSA drilling service include:

- Mobilization costs for a HSA rig; and
- HSA drilling and fracturing support (2.5 days, including drilling of the three enhancement boreholes and use of the drill rig to raise, lower, and suspend the straddle packer assembly into and out of the borehole).

Table 7.2. Cost Model for Pneumatic Fracturing with Aqueous Injection Solution

Cost Element	Data Tracked During the Demonstration	Costs Detail	Cost	Site Source
Utility Locate	Vendor costs		$5,700	Lake City
Survey	Vendor costs		$2,300	Lake City
Fracturing	Vendor costs	Includes preparation and mobilization, fracturing/ injection service (2.5 days to complete 3 borings with 5 intervals each), and reporting.	$27,500	Lake City
Drilling	Vendor costs	Mobilization for hollow stem auger rig, 2.5 days of hollow stem auger drilling and fracturing support.	$8,300	Lake City
IDW	Vendor costs		$7,400	Lake City
Labor	Contractor oversight	Labor to perform oversight for fracturing, injection, and drilling (3 days).	$3,600	Lake City
Travel			$0	Lake City
Equipment/ Materials		LactOil® cost and freight.	$1,900	Lake City
Total			**$56,700**	

7.1.3 Hydraulic Permeability Enhancement for Emplacing Aqueous Amendments

Hydraulic permeability enhancement for emplacing an aqueous solution (LactOil®) *in situ* was performed at GFAFB. Costs shown in **Table 7.3** are representative of the actual costs incurred at GFAFB except for "utility locate" and "IDW disposal," which were not required by the base. As previously described, the technology demonstration at GFAFB was performed in a glacial till, with borings advanced using DPT with augering capability. Top-down emplacement methodology was employed to aid delivery of the aqueous amendment solution into three depth-discrete intervals at each of the four enhancement boreholes. All activities pertinent to the hydraulic permeability enhancement at GFAFB were completed within approximately 4 days. Similar to MCB-CP and the hybrid pneumatic permeability enhancement demonstration at LCAAP, and as shown in **Table 7.3**, the most expensive cost elements pertinent to the permeability enhancement activities at GFAFB are: 1) the permeability enhancement and associated monitoring and reporting, and 2) the HSA drilling service as described in more detail below.

The primary cost components pertinent to the hydraulic permeability enhancement work at GFAFB include:

- Preparation and mobilization,
- The onsite fracturing, which was completed in 2 days and included use of a top-down DPT injection strategy to initiate three fractures in each of four borings,
- Injection service, which was completed immediately following hydraulic fracturing of each interval and included use of the fracturing equipment to pump the emulsified oil solution into each fracture interval,
- Amendment cost of the emulsified oil, and
- Reporting, including completion of a final report for the site.

The primary cost elements pertinent to the DPT drilling service include:

- Mobilization costs for the DPT rig; and
- DPT drilling and permeability enhancement support (2 days, including advancement of the enhancement tooling and use of the drill rig to assist in hydraulic permeability enhancement and injection).

Table 7.3. Cost Model for Hydraulic Fracturing with Aqueous Injection Solution

Cost Element	Data Tracked During the Demonstration	Costs Detail	Cost	Site Source
Utility Locate	Vendor costs		\$5,700	Lake City
Survey	Vendor costs		\$5,600	Grand Forks
Fracturing	Vendor costs	Includes preparation and mobilization, fracturing/ injection service (2 days concurrent with injections to complete 4 borings with 3 intervals each), and reporting.	\$52,000	Grand Forks
Drilling	Vendor costs	Mobilization for DPT rig, 2.5 days of DPT drilling and fracturing support.	\$10,100	Grand Forks
IDW	Vendor costs		\$3,100	Pendleton
Labor	Contractor oversight	Labor to perform oversight for fracturing, injection, and drilling (4 days).	\$4,800	Grand Forks
Travel			\$0	Grand Forks
Equipment/ Materials		LactOil® cost and freight.	\$2,500	Grand Forks
Total			**\$83,800**	

7.1.3.1 Monitoring Technologies

To support evaluation of the permeability enhancement success, three monitoring technologies were utilized: tilt-meter, ERT, and EC. Costs shown in **Table 7.4** are representative of the costs from MCB-CP, LCAAP, and GFAFB, as applicable. It should be noted that vendor costs for tilt-meter services are not representative of anticipated true costs due to discounts associated with the demonstration nature of this project. ERT and EC could not be used at MCB-CP due to the high conductivity (the required change in conductivity would have been difficult to monitor due to high native conductivity at the site) and lithology (EC is a DPT-pushed tool, which cannot be utilized at bedrock sites). Costs associated with tilt-meter included:

- Mobilization;
- Completion of monitoring during permeability enhancement; and
- Data evaluation and reporting.

Costs associated with ERT included:

- Preparation of electrode arrays;
- Mobilization;
- Installation of wells fitted with electrode arrays;
- Completion of pre- and post-enhancement ERT; and
- Data evaluation and reporting.

Costs associated with EC included:

- Mobilization costs for the EC tooling; and
- DPT drilling (0.5 day pre-enhancement, and 1 day post-enhancement).

Table 7.4. Cost Model for Monitoring Technologies

Site Source	Data Tracked During the Demonstration	Costs Detail	Cost
MCB-CP	Tilt-meter	Tilt-meter monitoring and reporting (five fractures)	$5,750
	ERT	Was not performed at this site	$0
	EC	Was not performed at this site	$0
LCAAP	Tilt-meter	Tilt-meter monitoring and reporting (ten fractures)	$11,500
	ERT	CDM Smith labor	$2,400
		Rutgers costs	$26,200
		Drilling costs	$5,600
		ERT Total	$34,200
	EC	Was not performed at this site	$0
GFAFB	Tilt-meter	Tilt-meter monitoring and reporting (11 fractures)	$26,200
	ERT	CDM Smith labor	$4,800
		Rutgers costs	$38,900
		Drilling costs	$4,100
		ERT Total	$47,800
	EC	CDM Smith labor	$1,800
		Drilling costs	$3,000
		EC Total	$4,800

7.2 COST DRIVERS

The most important cost driver for implementation of permeability enhancement is the target lithology and depth. The site lithology influences drilling costs, as well as duration of activities (which lead to additional daily permeability enhancement charges and field labor). At sites where DPT drilling is feasible, the cost to perform permeability enhancement may be less due to use of drilling rods and a downhole injection tool rather than packer assemblies. For more consolidated or deeper formations requiring use of HSA, sonic, or rotary technologies, drilling costs may escalate very quickly due to slower drilling rates, pre-drilling of permeability enhancement boreholes, use of packers, higher mobilization costs, and generally more expensive drilling footage or daily rates.

Another important cost driver is permeability enhancement equipment mobilization charges, which may account for a significant portion of vendor charges depending on the type of equipment required and the overall scope of work to be completed. For sites with limited borings or enhancement intervals, the mobilization charge may account for nearly 25 percent of the total cost to implement the technology, as seen in the demonstration at MCB-CP. As the scope of implementation increases, the proportion of the mobilization charge will be minimized. Location of the site also influences mobilization costs associated with both the drilling and the permeability enhancement services. Few permeability enhancement vendors exist, and depending on the location of the site, cross-country mobilization is often necessary, leading to considerable delivery charges.

Material cost for the remedial amendment is another important cost driver to be considered. As with any *in situ* injection technology, the appropriate type and dosing of amendment for the given formation and contaminant concentration must be assessed. While permeability enhancement allows for better distribution of amendment than standard injections, the longevity of the emplaced amendment must be considered, as some permeability enhancement methods may require remobilization to inject additional amendment later (either via additional permeability enhancement or injection wells). Therefore, careful consideration of amendment type, dosing, and additional infrastructure (e.g., injection wells installed in fractured borings) is needed to minimize the need for remobilization and best utilize the potential long-term improvement in amendment delivery that is realized through permeability enhancement technologies.

For monitoring technologies, including tilt-meter, ERT, and EC, cost drivers vary by technology due to their implementation approach. For tilt-meter, cost components include mobilization, onsite support, and data interpretation. Similar to mobilization of permeability enhancement equipment, the mobilization cost for tilt-meter infrastructure is not insignificant, but its influence on the total project cost is minimized as the scope of work increases (more time in the field, less influence of mobilization). Generally, tilt-meter setup can be completed concurrent to fracturing activities, although DPT-based fracturing may be slowed by tilt-meter setup time (making fracturing less efficient). Therefore, lithology is also important to tilt-meter costs, as emplacement methods requiring packer systems will likely not be impeded by tilt-meter setup time, but shallow, unconsolidated formations where DPT fracturing is applicable will likely be slowed, leading to increased field costs. Analysis of tilt-meter data is not a driver, as there is not an improvement in cost due to increased quantity (each fracture analyzed requires a similar amount of time due to the modeling required).

Cost drivers for ERT and EC primarily are related to lithology and depth. Because ERT requires installation of electrodes on the outside of well casing, the type of drilling and depth of the target formation are of key importance, with increasing difficulty in drilling leading to increased cost for implementation of ERT. Furthermore, drilling costs must account for installation of electrodes to depths that exceed the target injection depth to allow for ideal monitoring and visualization by ERT. EC is only applicable in unconsolidated formations that can be drilled using DPT; the cost for mobilization of the EC tooling is minimal (assuming a DPT rig is already onsite), and overall cost for use is typically tied to a daily rate for use of the DPT rig. Therefore, EC cost drivers are primarily tied to formation depth and ease of DPT drilling; deeper or denser formations will likely require more field time to obtain data due to slower drilling conditions than shallower, less dense formation types.

7.3 COST ANALYSIS

A cost analysis was developed for three low permeability sites where both conventional technologies (amendment delivery through injection wells) and permeability enhancement have been completed. Cost data and parameters controlling costs, as observed during this demonstration, have been used to develop the costs presented herein. Assumed costs for implementation of the conventional approaches were developed using site-specific details for how the injections were actually completed. A cost comparison was completed by using the actual percent of contaminant degradation achieved by the conventional and permeability enhancement approaches, as further discussed below.

Cost assessment includes life-cycle costing for the various technologies based on a 30-year operating life for full-scale remediation. Costs include capital, operations and maintenance (O&M), and long-term monitoring. Capital costs comprised installation of full-scale injection and monitoring wells, initial permeability enhancement, and installation and construction of support equipment and infrastructure. O&M costs include periodic amendment injection for conventional approaches. Long-term monitoring costs include sampling, analysis, and reporting for each site, and extend for two years beyond the assumed period for active treatment (completion of periodic injections or permeability enhancement) with quarterly sampling.

7.3.1 Scenario 1 – Clay / Weathered Shale Source Area

Scenario 1 is based on the conventional and hybrid pneumatic approaches that were applied at LCAAP. A treatment volume of roughly 12,000 cubic feet was assumed, based on the area immediately downgradient of a series of injection wells (bio-barrier) installed within the plume that represent the conventional approach at this site. Data from a five-year operational period of the injection wells, as well as the six-month period following hybrid pneumatic permeability enhancement, were used as a basis for comparison of the technologies. The site lithology consists of silty clay and weathered shale residuum, with contamination present at depths of approximately 20 to 30 feet bgs. The approach for each technology is discussed below, and associated costs are presented in **Table 7.5**.

7.3.1.1 Conventional Injections through Injection Wells

The site uses gravity-fed permeation injection via injection wells to deliver a two-percent molasses solution to the subsurface. An inject and drift approach is used, with four injection wells spaced 15 to 20 feet apart, perpendicular to groundwater flow. Approximately 2,500 gallons of dilute molasses solution is delivered to each well during each injection event, generating an ROI of approximately 8.5 feet assuming a porosity of 0.15 and screen length of 10 feet. A monitoring well located approximately 35 feet downgradient of the injection wells is used to monitor performance. For cost analysis, it was assumed that a period of four days was required to install the four injection wells, and each injection event requires a total of two days for preparation of the stock two percent molasses solution, setup of injection hoses, and periodic checks of the system. Over the five-year period of operation that was evaluated, a total of eight injection events were completed. During the five-year period, data from the downgradient monitoring well indicated that a 2.3 percent reduction in total molar mass (sum of TCE, DCE, and VC) was achieved.

7.3.1.2 Hybrid Pneumatic Permeability Enhancement

Hybrid pneumatic permeability enhancement with subsequent injection of emulsified oil was completed as discussed previously, with no additional infrastructure installation. Approximately 200 gallons of a three percent LactOil® solution was hydraulically pumped into each pneumatically-initiated interval (1,000 gallons total per borehole). It is assumed based on the demonstration data that hybrid pneumatic permeability enhancement will result in an approximate ROI of 10 feet, and thus one additional permeability enhancement boring is assumed as part of this analysis to provide a similar treatment volume as the conventional injection approach (approximately 12,000 cubic feet). Based on the LCAAP demonstration, the combined coring and hybrid pneumatic permeability enhancement is anticipated to proceed at a rate of 1.25 borings per day, requiring a total of 4 days. A single permeability enhancement event has been assumed for the cost analysis. Data obtained from the pre-enhancement sampling event and six-month post-enhancement sampling event were used to interpolate contaminant contours and subsequently develop mass estimates within the treated aquifer interval, as shown in **Figure 7.1**. **Figure 7.1(a)** presents the pre-enhancement TCE concentrations, while **(b)** presents the post-enhancement TCE concentrations. The same exercise was completed for DCE and VC (data not shown). The estimate of total molar mass contained within the treatment interval indicated that an 86.8 percent reduction in mass was achieved.

a) b)

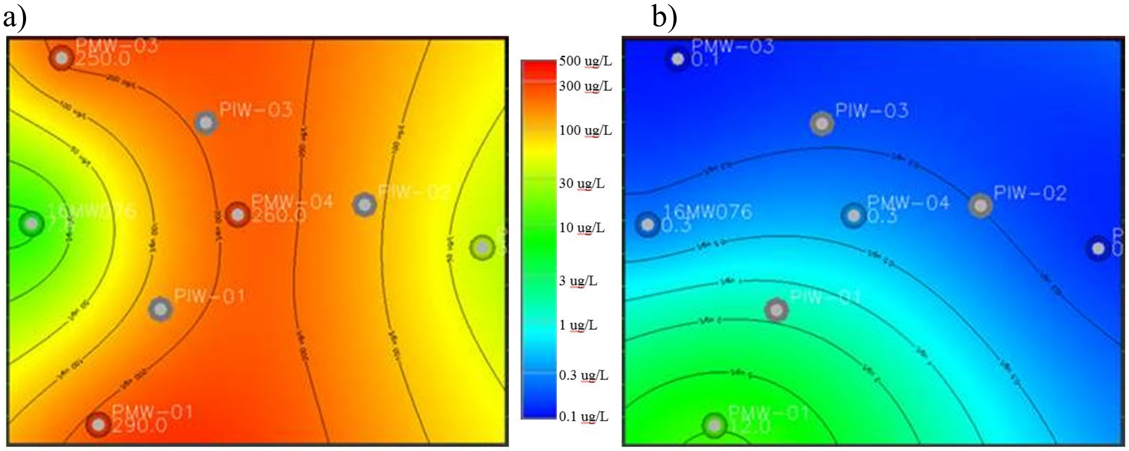

Figure 7.1. Pre- Versus Post-Enhancement TCE Concentrations in the Hybrid Pneumatic Test Cell at LCAAP

7.3.1.3 Discussion

Using the site-specific molar mass percent reduction achieved by each technology, the timeframe to achieve a similar percent reduction by each technology was calculated. A logarithmic performance was used for the conventional approach (first period achieved 2.3 percent reduction, next period achieved 2.3 percent reduction of the prior period's remaining mass, and so on). Using the 86.8 percent reduction by hybrid pneumatic permeability enhancement (a one-time event), and 2.3 percent reduction by conventional injections (8 injection events over 5 years), a timeframe of 87, five-year periods (with 8 injection events each) would be required using the conventional approach to achieve the same percent of contaminant degradation that was achieved by the hybrid pneumatic approach. As shown in **Table 7.5**, the resulting net present value costs for the hybrid pneumatic approach resulted in a fraction of the total project cost. Furthermore, the estimate for the conventional approach is greatly understated because costs presented only extend through 30 years post initiation, representing just 6 of the 87 five-year periods required to achieve similar results. It should also be noted that a significant portion of the hybrid pneumatic costs are the performance monitoring completed following injections. In all scenarios, it was assumed that two years of quarterly monitoring would be necessary following completion of active remediation. In cases where cleanup is achieved relatively quickly with permeability enhancement, the net present value of the monitoring cost is greater than that of conventional remedies requiring longer durations, when those two years of quarterly monitoring fall 10, 20, or 30 years (or more) beyond the timeframe for permeability enhancement technologies. Overall, while the annual operating cost of the conventional approach is low, the limited reduction and significant time requirement ultimately result in a dramatically larger cost. The results must be caveated by the fact that beginning contaminant concentrations in the hybrid pneumatic test area were approximately two orders of magnitude less than those present in the conventional area (approximately 300 µg/L and 30,000 µg/L, respectively). Had the hybrid pneumatic test been completed in an area with similar concentrations, the same percent reduction might not have been accomplished due to the relatively low electron donor concentrations observed during the demonstration with the hybrid pneumatic permeability enhancement.

Table 7.5. Cost Analysis for Scenario 1

Conventional	**Year Cost is Incurred with 5% Discount Factor**										**Total NPV Costs[1]**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10 to 30**	
	0.9524	0.907	0.8638	0.8227	0.7835	0.7462	0.7107	0.6768	0.6446	8.2644	
Capital Costs											
Well Installation	$29,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$29,000**
Injections (Including system capital)	$20,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$20,000**
Operation and Maintenance Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Periodic Injections	$20,000	$19,000	$18,000	$9,000	$17,000	$16,000	$15,000	$14,000	$14,000	$170,000	**$312,000**
Long Term Monitoring Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Sampling/Analysis/Reporting	$96,000	$91,000	$87,000	$83,000	$79,000	$75,000	$72,000	$68,000	$65,000	$827,000	**$1,543,000**
Total NPV Costs	**$165,000**	**$110,000**	**$105,000**	**$92,000**	**$96,000**	**$91,000**	**$87,000**	**$82,000**	**$79,000**	**$997,000**	**$1,904,000**

1. The total NPV costs are for the first 30 years only. The anticipated timeframe for remediation is greater than 400 years.

Hybrid Pneumatic	**Year Cost is Incurred with 5% Discount Factor**										**Total NPV Costs**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10 to 30**	
	0.9524	0.907	0.8638	0.8227	0.7835	0.7462	0.7107	0.6768	0.6446	8.2644	
Capital Costs											
Fracturing	$73,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$73,000**
Operation and Maintenance Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Periodic Injections	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Long Term Monitoring Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Sampling/Analysis/Reporting	$96,000	$91,000	$87,000	$0	$0	$0	$0	$0	$0	$0	**$274,000**
Total NPV Costs	**$169,000**	**$91,000**	**$87,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$347,000**

7.3.2 Scenario 2 – Glacial Till Source Area

Scenario 2 is based on the conventional and hydraulic permeability enhancement approaches that were applied at GFAFB. A treatment volume of roughly 7,000 cubic feet was assumed, based on the approximate ROI for both the conventional injection well and hydraulic permeability enhancement approaches as they were actually applied at the site. Data from a one-year operational period of the injection wells, as well as the nine-month period following hydraulic permeability enhancement, were used as a basis for comparison of the technologies. The site lithology consists of glacial till, with contamination present at depths of approximately 5 to 20 feet bgs. The approach for each technology is discussed below, and associated costs are presented in **Table 7.6**.

7.3.2.1 Conventional Injections through Injection Wells

The site uses low pressure permeation injection via injection wells to deliver an average twenty-percent LactOil® solution to the subsurface. A total of 30, 1-inch injection wells with 3-foot screen lengths were installed using DPT throughout the source area, and an average of approximately 150 gallons of the dilute LactOil® solution was injected into each well, generating an ROI of approximately 2 feet assuming a porosity of 0.15 and screen length of 3 feet. Several monitoring wells located across the source area were used to gather baseline and one-year post injection data (a single injection was completed). Actual site information was used for cost analysis, with injection wells installed in two days, and injections completed in 11 days. Data obtained from the baseline sampling event and one-year sampling event were used to interpolate contaminant contours and subsequently develop mass estimates within the treated aquifer interval, as shown in **Figure 7.2**. **Figure 7.2(a)** presents the baseline TCE concentrations, while **(b)** presents the one-year TCE concentrations. The same exercise was completed for DCE (data not shown). The estimate of total molar mass contained within the treatment interval indicated that a 28 percent reduction in mass was achieved.

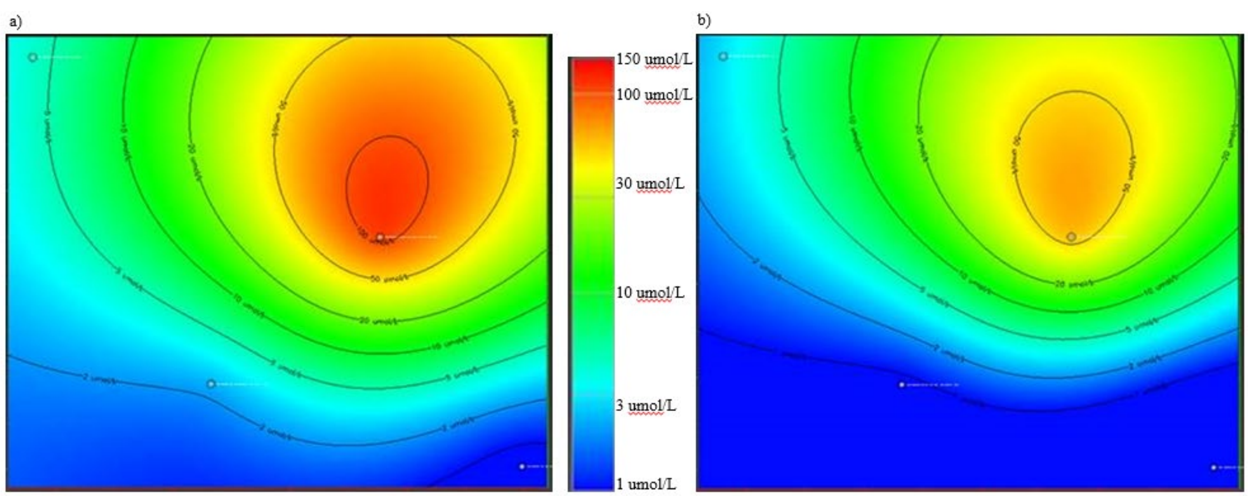

Figure 7.2. Pre- Versus Post-Conventional Injection TCE Concentrations at GFAFB

7.3.2.2 *Hydraulic Permeability Enhancement*

Hydraulic permeability enhancement with injection of emulsified oil was completed as discussed previously, with no additional infrastructure installation. Approximately 130 gallons of a three percent LactOil® solution was hydraulically pumped into each interval (390 gallons total per borehole). It is estimated based on the demonstration data that hydraulic permeability enhancement resulted in an approximate ROI of 10 feet. Based on the GFAFB demonstration, a total of three days were required for setup and completion of the permeability enhancement. A single permeability enhancement event was included for the cost analysis. Data obtained from the pre-enhancement sampling event and nine-month post-enhancement sampling event were used to interpolate contaminant contours and subsequently develop mass estimates within the treated aquifer interval, as shown in **Figure 7.3**. **Figure 7.3(a)** presents the pre-enhancement TCE concentrations, while **(b)** presents the post-enhancement TCE concentrations. The same exercise was completed for DCE (data not shown). The estimate of total molar mass contained within the treatment interval indicated that a 64 percent reduction in mass was achieved.

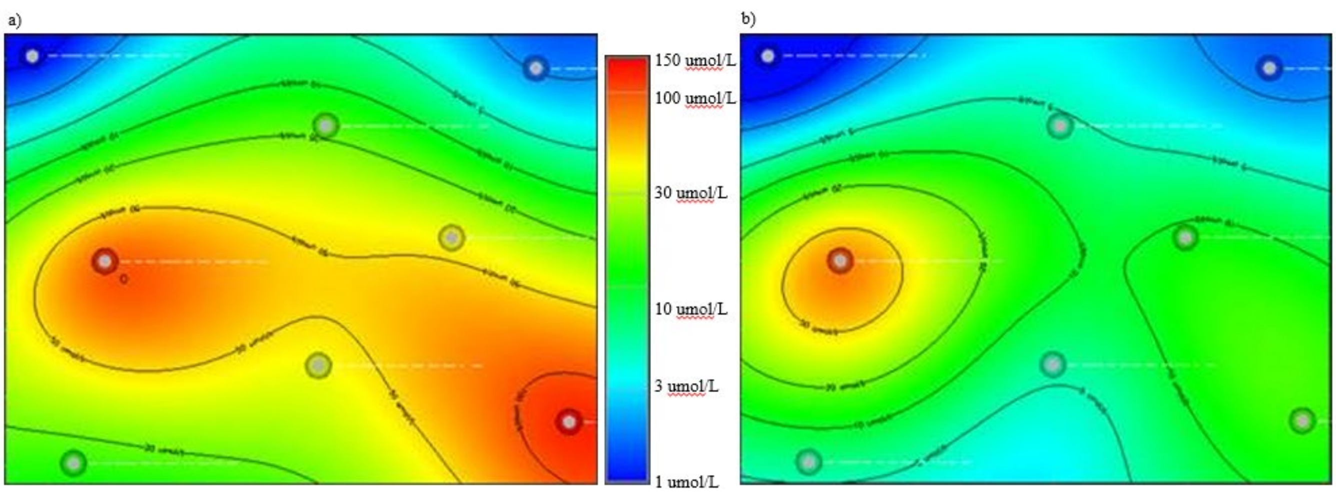

Figure 7.3. Pre- Versus Post-Enhancement TCE Concentrations at GFAFB

7.3.2.3 *Discussion*

Using the site-specific molar mass percent reduction achieved by each technology, the timeframe to achieve a similar percent reduction by each technology was calculated. A logarithmic performance was used for the conventional approach (first period achieved 28 percent reduction, next period achieved 28 percent reduction of the prior period's remaining mass, and so on). Using the 64 percent reduction by hydraulic permeability enhancement (a one-time event), and 28 percent reduction by conventional injections (1 injection event over 1 year), a timeframe of approximately 3 years (1 injection completed per year) would be required using the conventional approach to achieve the same percent of contaminant degradation that was achieved by the hydraulic approach. As shown in **Table 7.6**, the resulting net present value costs for the hydraulic approach resulted in significantly less total project cost.

The initial cost of implementation of both technologies was very similar, but the total cost of the conventional approach was estimated to be almost 70% higher because of all the applications required. In reality, it is not clear that multiple applications of the conventional injections would have resulted in further treatment due to the inefficient electron donor distribution. In fact, electron donor and corresponding geochemical impacts from the conventional injection approach were rarely observed in monitoring wells. In contrast, the electron donor solution and related impacts were obvious and widespread in monitoring wells following the hydraulic permeability enhancement. Bioaugmentation of the site would almost certainly have increased mass removal significantly, but that was beyond the scope of this study.

Table 7.6. Cost Analysis for Scenario 2

Conventional	**Year Cost is Incurred with 5% Discount Factor**										**Total NPV Costs**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10 to 30**	
-	0.9524	0.907	0.8638	0.8227	0.7835	0.7462	0.7107	0.6768	0.6446	8.2644	
Capital Costs											
Well Installation	$23,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$23,000**
Injections (Including system capital)	$69,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$69,000**
Operation and Maintenance Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Periodic Injections	$0	$43,000	$41,000	$0	$0	$0	$0	$0	$0	$0	**$84,000**
Long Term Monitoring Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Sampling/Analysis/Reporting	$96,000	$91,000	$87,000	$83,000	$79,000	$0	$0	$0	$0	$0	**$436,000**
Total NPV Costs	**$188,000**	**$134,000**	**$128,000**	**$83,000**	**$79,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$612,000**

Hydraulic	**Year Cost is Incurred with 5% Discount Factor**										**Total NPV Costs**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10 to 30**	
-	0.9524	0.907	0.8638	0.8227	0.7835	0.7462	0.7107	0.6768	0.6446	8.2644	
Capital Costs											
Drilling Support	$16,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$16,000**
Fracturing	$73,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$73,000**
Operation and Maintenance Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Additional Fracturing	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Long Term Monitoring Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Sampling/Analysis/Reporting	$96,000	$91,000	$87,000	$0	$0	$0	$0	$0	$0	$0	**$274,000**
Total NPV Costs	**$185,000**	**$91,000**	**$87,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$363,000**

7.3.3 Scenario 3 – Interbedded Sands/Silts/Clays Source Area

Scenario 3 is based on the conventional and hydraulic approaches that were applied at the Bountiful/Woods Cross Operable Unit 1 Superfund Site (BWC OU1 Site). The work presented for this site was funded by EPA Region 8 separately from this demonstration. However, the permeability enhancement injections were performed in 2017 in large part based upon the successful injections at the ESTCP demonstration sites. Thus, the application at the BWC OU1 Site can be viewed as an early transfer of the ESTCP technology at another federal site. While the BWC OU1 Site was not a part of the ESTCP-funded demonstration, it was selected for cost evaluation due to the ability to compare amendment injection via injection wells, followed by use of hydraulic permeability enhancement for emplacement of sand and ZVI. Data from a one-year operational period of the injection wells, as well as the first year following hydraulic permeability enhancement, were used as a basis for comparison of the technologies. The site lithology consists of interbedded sands, silts, and clays, with TCE and associated daughter products being the contaminants of concern. The highest contaminant concentrations in the hot spot are present between approximately 35 and 50 feet bgs, primarily sorbed to the low-permeability materials. Historic chlorinated ethene concentrations have exceeded 100 ppm. The source area hot spot covers an area of approximately 1,500 square feet (50 feet by 30 feet). The approach for each technology is discussed below, and associated costs are presented in **Table 7.7**. Note that extensive site characterization using high-resolution techniques including membrane interface probe and HydroPunch groundwater sampling was performed to delineate the vertical and lateral extent of contamination at the site. Performance of the high-resolution characterization allowed for installation of targeted injection wells during implementation of the conventional approach, as well as targeted implementation of permeability enhancement at the locations and depths where elevated concentrations were present.

7.3.3.1 Conventional Injections through Injection Wells

In 2014, a series of targeted injection wells were installed to directly treat the contaminated depth interval in the vicinity of the known hot spot. Pressurized permeation injection via injection wells was used to deliver a three-percent sodium lactate solution to the subsurface. A total of 10 injection wells were installed within the footprint of the hot spot. Approximately 1,500 gallons of dilute lactate solution was delivered to each well during each injection event, generating an ROI of approximately 8 feet assuming an effective porosity of 0.1 and screen length of 10 feet. A monitoring well located within the treatment area is used to monitor performance. For cost analysis, a period of 9 days was required to install the 10 injection wells, and each injection event requires a total of 6 days for mobilization and completion of the injections. Over the one-year period of operation that was evaluated, a total of three injection events were completed. During the one-year period, data from the hot spot monitoring well indicated that a 44 percent reduction in total molar mass (sum of TCE, DCE, and VC) was achieved.

7.3.3.2 Hydraulic Permeability Enhancement

Hydraulic permeability enhancement with injection of sand and ZVI was completed to address the high concentration hot spot. Approximately 140 gallons of a 50% sand/ZVI blend (4.2 pounds per gallon each, suspended in cross-linked guar) was pumped into each emplacement interval. Small-volume intervals were intentionally utilized due to the interbedded lithology, recognizing that the enhancement intervals emplaced in low-permeability silts and clays likely would not remain at the depth of initiation and would thus intercept sand lenses, resulting in leak-off.

Leak-off is the term for injected material penetrating out into the formation, rather than propagating outward with the planar injection feature. This tends to decrease the ROI, but has the potential benefit of delivering amendment into the formation away from the injection plane.

A total of 9 permeability enhancement points, with up to three depth intervals each, were used to treat the hot spot, with a total of approximately 12,000 pounds of sand and ZVI emplaced. Using the tilt meter-derived data, enhancement intervals were generally elliptical, with ROI ranging from 5 to over 30 feet. The permeability enhancement injections generated a dense network of interconnected intervals as visualized using tilt meters (**Figure 7.4**) and confirmed in post-enhancement soil borings. Based on the BWC OU1 Site implementation, emplacement required a total of 6 days onsite. Data obtained from the pre-enhancement sampling event and four-month post-enhancement sampling event indicate that a 99.4 percent reduction in total molar mass was achieved.

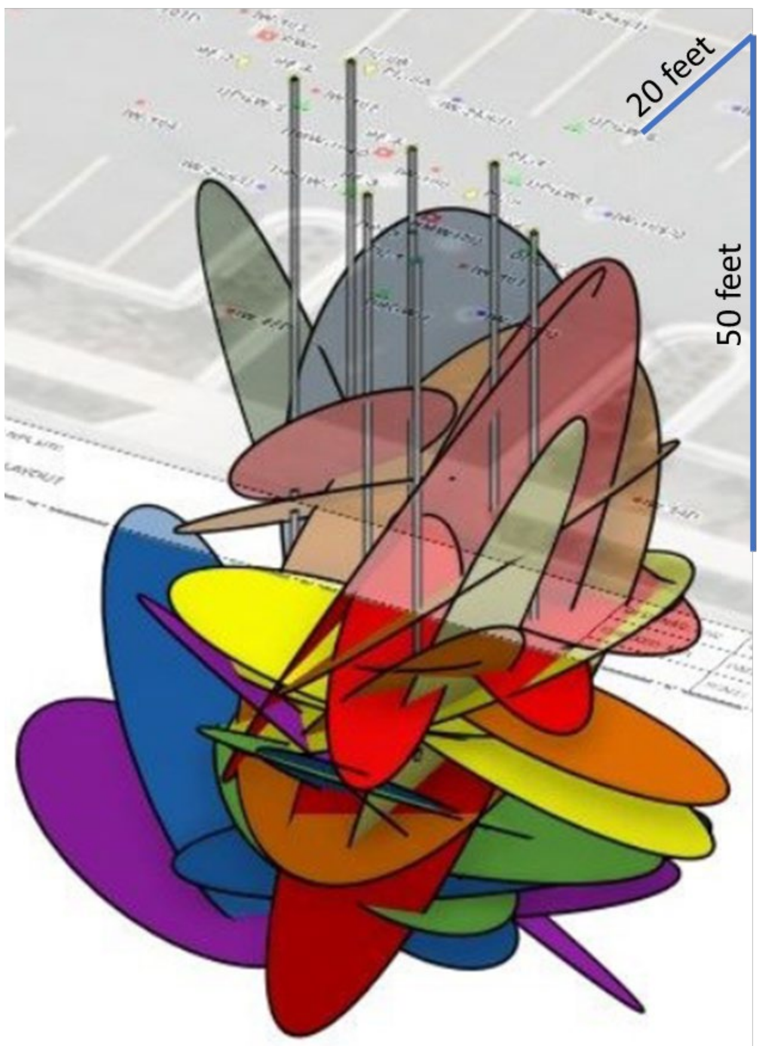

Figure 7.4. Visualization of Enhancement Intervals at the BWC OU1 Site (figure provided by GeoTactical Remediation)

7.3.3.3 Discussion

Using the site-specific molar mass percent reduction achieved by each technology, the timeframe to achieve a similar percent reduction by each technology was calculated. A logarithmic performance was used for the conventional approach (first period achieved 44 percent reduction, next period achieved 44 percent reduction of the prior period's remaining mass, and so on). Using the 99.4 percent reduction by hydraulic permeability enhancement (a one-time event), and 44 percent reduction by conventional injections (3 injection events over 1 year), a timeframe of 9 years (with 3 injection events each) would be required using the conventional approach to achieve the same percent of contaminant degradation that was achieved by the hydraulic approach. Contaminant degradation observed following hydraulic permeability enhancement at the HMW-17D monitoring well located within the contaminant hotspot area at BWC OU1 site is shown in **Figure 7.5**. As shown in **Table 7.7**, the resulting net present value costs for the hydraulic approach were approximately one-third the cost of the conventional approach, and the time required was more than 8 years less. As previously noted, the net present value of the performance monitoring makes up a significant portion of the hydraulic permeability enhancement cost, especially when compared to the net present value of performance monitoring at the end of the conventional treatment approach.

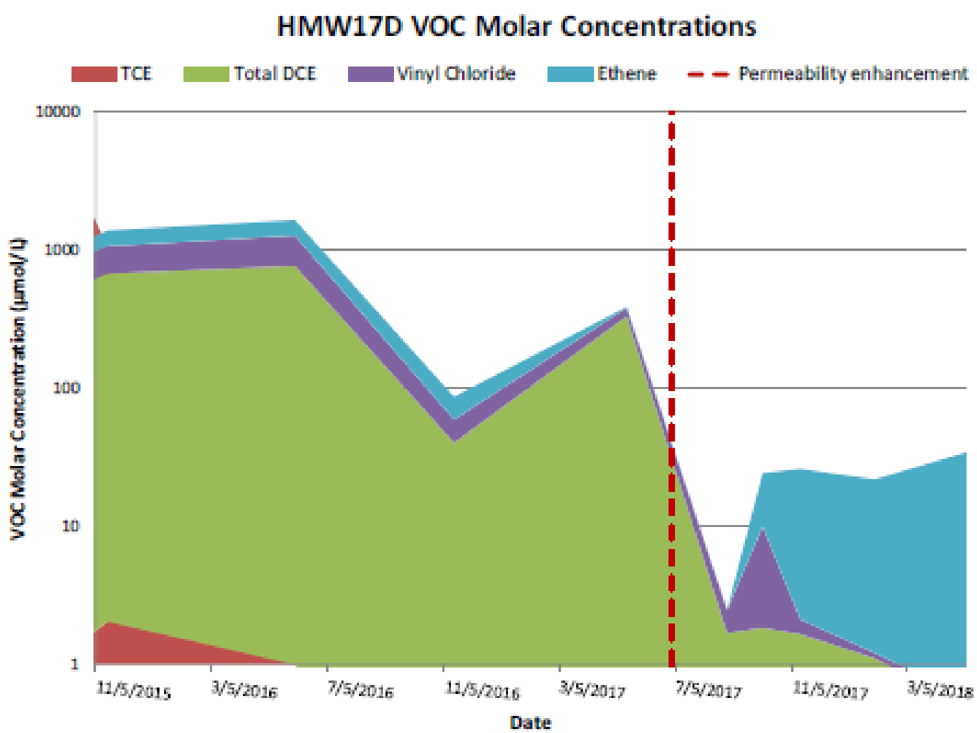

Figure 7.5. Contaminant Degradation Observed at Monitoring Well HMW-17D at the Bountiful/Woods Cross Superfund Site Following Hydraulic Permeability Enhancement

While the conventional approach was successfully degrading contaminants, its effectiveness was limited due to contaminant absorption to low-permeability materials, diffusion of mass into low permeability zones, and probably DNAPL dissolution kinetics that all limited mass transfer. Therefore, hydraulic permeability enhancement was selected by the project team due to its ability to distribute remedial amendments into the low-permeability lithology, to create greater contact with sorbed mass and DNAPL, and to create permanent sand lenses to aid long-term remediation, if necessary. As shown by the significant improvement in contaminant destruction, the hydraulic permeability enhancement successfully intercepted the high concentration intervals and dramatically improved contact with contaminant mass, providing nearly complete degradation within the hot spot in a single injection and a considerable cost savings over the conventional injection approach. It should be noted that the strongly reducing conditions already present in the treatment zone probably expedited mass destruction by the permeability enhancement injections to some extent.

Table 7.7. Cost Analysis for Scenario 3

Conventional	**Year Cost is Incurred with 5% Discount Factor**										**Total NPV Costs**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10 to 11**	
-	0.9524	0.907	0.8638	0.8227	0.7835	0.7462	0.7107	0.6768	0.6446	1.1986	
Capital Costs											
Well Installation	$51,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$51,000**
Injections (Including system capital)	$99,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$99,000**
Operation and Maintenance Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Periodic Injections	$0	$71,000	$68,000	$65,000	$62,000	$59,000	$56,000	$53,000	$51,000	$0	**$485,000**
Long Term Monitoring Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Sampling/Analysis/Reporting	$96,000	$91,000	$87,000	$83,000	$79,000	$75,000	$72,000	$68,000	$65,000	$120,000	**$836,000**
Total NPV Costs	**$246,000**	**$162,000**	**$155,000**	**$148,000**	**$141,000**	**$134,000**	**$128,000**	**$121,000**	**$116,000**	**$120,000**	**$1,471,000**

Hydraulic	**Year Cost is Incurred with 5% Discount Factor**										**Total NPV Costs**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10 to 30**	
-	0.9524	0.907	0.8638	0.8227	0.7835	0.7462	0.7107	0.6768	0.6446	8.2644	
Capital Costs											
Drilling Support	$27,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$27,000**
Fracturing	$162,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$162,000**
Operation and Maintenance Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Additional Fracturing	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Long Term Monitoring Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Sampling/Analysis/Reporting	$96,000	$91,000	$87,000	$0	$0	$0	$0	$0	$0	$0	**$274,000**
Total NPV Costs	**$285,000**	**$91,000**	**$87,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$463,000**

8.0 IMPLEMENTATION ISSUES

This section provides a discussion of the potential implementation issues associated with use of permeability enhancement technologies at sites.

8.1 REGULATIONS

Regulatory requirements vary by state, but the often-negative connotation associated with hydraulic fracturing for oil and gas could lead to regulatory hold-ups with implementation in some states, though it was not an issue at any of the demonstration sites or the EPA site, which encompassed four different sites. Therefore, the term "permeability enhancement technology" was coined as an alternative descriptor. Proper education of reviewers to explain the significant differences between environmental permeability enhancement and fracturing typically used in oil and gas production may be necessary. As with many newer technologies, project managers who are considering use of permeability enhancement should build time into review and approval schedules to accommodate extra meetings and regulatory interface. Some states have started to require fracturing-specific permitting, and project managers should determine if those rules apply. It should be noted that for some states, almost all of the chemicals reagents used for hydraulic permeability enhancement (including the silica sand, the shear-thinning fluid, and the polymer-based crosslinkers) are on the approved list of chemicals to be used for *in situ* treatment applications and should be stated as such to avoid unnecessary delays due to the permitting process.

Vertical migration of site contaminants as a result of permeability enhancement was one of the major concerns expressed by several regulatory agencies during this demonstration project. Therefore, performance monitoring of wells screened much deeper than the permeability enhancement interval of interest was required in some instances. Results from this demonstration project showed that vertical contaminant migration did not occur at any of the sites. Additional monitoring to aid evaluation of downward contaminant migration should be considered and planned, if needed, to address regulatory concerns with permeability enhancement; however, it has not been observed to date.

8.2 PROCUREMENT ISSUES

Hydraulic and pneumatic permeability enhancement require highly specialized, proprietary equipment for proper application. Few vendors are available who can properly implement the technologies. Furthermore, emplacement of solid-phase amendments (e.g., ZVI) is patented under U.S. patent number 7,179,381. As stated previously, a variety of drilling vendors claim they can provide fracturing service, but the methods used and results are not comparable to what is performed by those with specialty equipment and patents. Care should be taken when selecting a vendor; inquiries should be made as to whether the potential vendors are licensed under applicable patents for implementing the technologies. Experience in permeability enhancement must be provided and evaluated as part of the procurement process.

Because of the limited number of vendors, scheduling of work should be completed as soon as possible once permeability enhancement is selected as an appropriate remedial option. While this demonstration project did not experience any challenges with scheduling the work, as permeability enhancement becomes a more widely-accepted technology, the availability of equipment may become a limitation. Similarly, coordination between drillers and permeability enhancement vendors should be initiated early to ensure availability at the same time.

8.3 END-USER CONCERNS

Implementation issues that were encountered during the project demonstration differed between sites and specific approaches used. The following sections describe the issues for the different approaches.

8.3.1 Permeability Enhancement

Issues associated with both methods of permeability enhancement are summarized below:

- **Nonstandard equipment required for implementation** – As discussed above, specialty equipment is required, and adequate time should be built into the schedule to ensure availability at the desired time.
- **High pressure** – Permeability enhancement technologies require relatively high pressures (approximately 100 to 200 psi) to initiate subsurface pathways and inject remedial amendments. Proper health and safety requirements should be applied to protect workers from injury, including limiting access to the immediate vicinity of fracturing equipment and drill locations, avoidance of high pressure hoses, and general awareness of the ongoing activities. Surfacing was observed during implementation of both hydraulic and hybrid pneumatic technologies. Hydraulic surfacing observed during the demonstration was a gradual seeping of material to the ground surface, although more rapid releases of fluid could occur if short circuiting occurred from shallow initiation depths. Pneumatic surfacing was more sudden due to use of high pressure gas to initiate the fractures; during implementation at one borehole, the seal between the upper packer and soil failed and a burst of soil and gas was observed around the drill rod. The vendor prohibits personnel access near the drill location during application, which prevents injury if this occurs.
- **Surfacing** – As stated above, surfacing did occur with both technologies. In addition to the health and safety concern associated with the high pressures, surfacing can also result in release of concentrated remediation amendment solutions. Therefore, proper spill control should be available onsite to mitigate surfacing.

Issues specific to hydraulic permeability enhancement are summarized below:

- **Pumps fail to operate properly** – Hydraulic permeability enhancement relies on positive displacement pumps to generate high pressures and inject slurries. Because of the manufacturing of the pumps, which have valves that push the solution, the type of sand and remedial amendment is important for proper operation. If angular sand or amendments are used, or if particle sizes are too large, friction within the valves can cause the pump to seize and fail. It is recommended that project managers discuss the appropriate sand and amendments with permeability enhancement vendors prior to ordering materials.

8.3.2 Monitoring Techniques

Issues involving DPT-aided EC monitoring technique are summarized below:

- **Depth/lithology limitation** – Because EC is a DPT-based tool, it is only applicable in lithologies where DPT is feasible.
- **Conductivity limitation** – Use of EC to identify fractures or injected fluids requires addition of conductive materials (e.g., salts) to the fracture fluid/injected amendment. The difference in conductivity of the formation versus conductivity of the fluid must be substantial enough to ascertain changes. In some formations, background conductivity may be too high for this approach to be practical or recommended, as salt solutions that are sufficiently conductive to provide the proper contrast may inhibit biological activity or may result in density-driven flows.

Issues involving ERT monitoring technique are summarized below:

- **Complications with well installation** – The use of ERT requires modification of the well casings and screens, including attachment of wire leads and metallic clamps to the outside of the casing. This not only takes time to prepare, but also slows the well installation process to avoid tangling wires and confusing depths of specific leads.
- **Additional wells or monitoring points or adjustments to planned wells** – To obtain adequate coverage of the area to be monitored, additional wells may be required and locations modified for planned wells. Also, to obtain the proper resolution at depth, the electrodes must be present below the intervals to be fractured, so wells must either be installed to deeper depths or a blank casing added to the bottom of each well to extend the depth of monitoring. The additional drilling requirements will add cost to the project, and may not be insignificant depending on the formation type or the target depth of the treatment zone of interest.
- **Conductivity limitation** – Similar to EC, ERT requires changes in conductivity to monitor changes associated with the permeability enhancement. Background conductivity of the formation must be considered when designing the monitoring approach.

Issues involving the tilt-meter monitoring technique are summarized below:

- **Nonstandard equipment required for implementation** – While not proprietary, tilt meters are specialty equipment that require trained operators to use them properly.
- **Sensitivity and disturbance** – Because of the highly sensitive nature of the tilt meters, any disturbance requires recalibration/resetting of the instrument. Thus, care must be taken when working around tilt meters, which is sometimes difficult considering the substantial operation involved in permeability enhancement (number of people, drill rigs, and equipment). Fortunately, the instruments are relatively easy to reset, but if not handled properly, data quality could be affected.
- **Setup time** – Again, because of the high sensitivity, the proper setup of tilt meters requires some time (approximately 1 hour per permeability enhancement location). Proper location of the tilt-meter array is required, including accurate measurements of distance and orientation from the permeability enhancement initiation point. This can add time to the mobilization, and potentially slow operations onsite. However, the data provided by tilt meters has proven to be unmatched in terms of documenting exactly where amendment is distributed.

- **Resolution (time)** – Because pneumatic permeability enhancement creates temporary fracture intervals, the resolution of tilt-meter readings may not be appropriate for monitoring all pneumatic injections. Tilt meters record changes every 10 seconds, which may not be sufficient to capture short-term changes during pneumatic injections. Nevertheless, at the LCAAP demonstration site, the tilt meters appeared to capture the pneumatic injections.

8.4 LESSONS LEARNED

Several lessons learned were noted during implementation of this demonstration project. First, regarding work completed at the LCAAP, comprehensive review of site historical data is necessary. Base representatives were unaware of the historical use of the hydraulic demonstration area, which was later determined to be a dump pit. The voids and disturbed overburden above the permeability enhancement depths created pathways that led to amendment surfacing. Detailed review of historical photographs, pre-work site walks, and perhaps investigation borings in the immediate vicinity of enhancement locations are likely worthwhile at sites where little historical information is available.

Second, because high pressures are involved, proper abandonment of existing boreholes is critical, as is proper well installation (including adequate time for grout curing). Some surfacing that was observed during the demonstration may have been related to historical borings that were not properly abandoned. Similarly, if grout used in well completion does not have time to fully cure, surfacing may occur through or around the borehole. It is recommended that a period of at least 48 hours be allowed from grout emplacement to implementation of permeability enhancement.

Finally, proper testing of equipment with remedial amendments to be injected should be performed prior to mobilization. Seizing of the hydraulic pump occurred due to issues with emplacement of the sand lenses during work at LCAAP. The vendor had recently changed the pump, which may have caused challenges with operation of the pump.

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APPENDIX A APPENDIX A - POINTS OF CONTACT

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APPENDIX B DEMONSTRATION PLAN AND SITE SELECTION MEMORANDUM

FINAL TECHNOLOGY DEMONSTRATION PLAN

A Rigorous Demonstration of Permeability Enhancement Technology for *In Situ* Remediation of Low Permeability Media

ESTCP Project Number ER-201430

October 2015

Kent Sorenson, Nathan Smith, Dung Nguyen, and Michael Lamar
CDM Smith Inc.

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ACRONYMS

%	percent
µg/L	microgram per liter
3-D	three dimensional
AAP	Army Ammunition Plant
AFB	Air Force base
ALI	atomized liquid injection
amsl	above mean sea level
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, xylene
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
cis-1,2-DCE	cis-1,2-dichloroethene
cm/s	centimeter per second
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	Department of Defense
DPI	direct-push injection
EAB	enhanced anaerobic bioremediation
EC	electrical conductivity
EPA	United States Environmental Protection Agency
EQL	estimated quantitation limit
ERT	electrical resistivity tomography
ESTCP	Environmental Security Technology Certification Program
ft	feet
gpm	gallon per minute
H&S	health and safety
HASP	health and safety plan
HCl	hydrochloric acid
HPET	hydraulic permeability enhancement technology
H_2SO_4	sulfuric acid
ISCR	*In situ* chemical reduction
LNAPL	light non-aqueous phase liquid
LTM	long-term-monitoring
MCL	maximum contaminant level
MDL	method detection limit
MEEA	methane, ethane, ethene, acetylene
mg/L	milligram per liter
mL	milliliter
m/sec	meters per second
MTBE	methyl tertiary butyl ether
MW	monitoring well
NA	not applicable/not available

NP	not published
O&M	operations and maintenance
^{o}C	degree Celsius
ORP	oxidation reduction potential
oz	ounce
PAL	project action limit
PPET	pneumatic permeability enhancement technology
PRW	permeable reactive wall
QA/QC	quality assurance/quality control
QAPP	quality assurance project plan
RL	reporting limit
ROI	radius of influence
RPM	remediation project manager
RSSL	residential soil screening level
SVE	soil-vapor extraction
TCE	trichloroethene
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TPH-G	total petroleum hydrocarbons gasoline range
TSOP	technical standard operating procedure
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
UST	underground storage tank
UXO	unexploded ordinance
VC	vinyl chloride
VOC	volatile organic compound
ZVI	zero-valent iron

1.0 INTRODUCTION

Environmental Security Technology Certification Program (ESTCP) Project Number ER-201430 involves the demonstration and validation of using hydraulic and pneumatic permeability enhancement technologies to enhance the delivery of remediation amendments to low permeability zones. This demonstration will provide a rigorous comparison of the costs and benefits of the hydraulic and pneumatic approaches for enhanced amendment delivery and distribution in low permeability media, as well as an analysis of the state-of-the-art tilt-meter monitoring tool to quantify the emplaced fracture networks.

The results from this demonstration will be used to develop a guidance document that outlines the technical and financial advantages and disadvantages of each of the permeability enhancement technologies. The guidance document will be made available in a format to help remediation project managers (RPMs) better assess the applicability of this technology for amendment distribution and verification for a given site, as well as to help practitioners select and procure the optimal remediation technique. The guidance will also document the value of real-time tilt-metering and electrical resistivity tomography (ERT) in remedial application, verification, and optimization.

This document details the field activities that will be conducted at three sites selected for this technology demonstration, which were discussed in the Site Selection Memorandum provided in **Appendix A**. This section includes a brief summary of the project background, objectives, and associated regulatory drivers.

1.1 BACKGROUND

When reagents that stimulate biological or chemical destruction of contaminants can be mixed with target contaminants in the subsurface, remediation practitioners can have a high degree of confidence that treatment will be reasonably effective. While this represents an enormous opportunity for the industry, the formidable challenge remains of ensuring that mixing and/or contact of biological or chemical treatment reagents with target contaminants occurs in a reasonable timeframe in low permeability or fractured geological settings.

Conventional injection wells are typically adequate for delivering reagents in homogeneous geologic formations with a bulk hydraulic conductivity of 10^{-4} centimeters per second (cm/s) or greater; however, practitioners are well acquainted with the shortcomings of amendment injection using conventional wells in lower permeability settings (USDOE 1996). For instance, in a silty formation with a bulk hydraulic conductivity of approximately 10^{-5} cm/s and assuming a 50 percent (%) efficient injection well with a 10-foot screen and 30 feet of head, one can calculate an injection rate of approximately 0.02 gallons per minute (gpm). Assuming an effective porosity of 10%, 587 gallons of amendment would be required to achieve a radius of influence (ROI) of 5 feet. That means the injection time required to achieve the target ROI of 5 feet for a single well would be 19 days, assuming 24-hour operation. Another problem with conventional injection wells in low permeability settings is that a high degree of heterogeneity typically exists even within a 10-foot well screen, often ranging over multiple orders of magnitude of permeability. Given that the volumetric flow rate entering different vertical horizons in the injection well screen is proportional to the hydraulic conductivities of those horizons, the vertical distribution of injected amendment can be highly preferential; that is, 90% of the total volume might easily be pushed out into soils adjacent to less than 10% of the well screen interval.

In recent years, a number of technologies have been developed in an attempt to address the challenge of achieving a uniform and effective distribution of treatment amendments in low permeability and fractured media. These advances include hydraulic and pneumatic permeability enhancement technologies, both of which are able to emplace amendments into low permeability media. Emplacing treatment amendments using these techniques can help overcome the aforementioned limitations of traditional amendment injection systems where low permeability soils can impede delivery. Significant confusion currently exists in the industry as to the differences among hydraulic and pneumatic permeability enhancement technologies and permeation injections. While one technology may be more warranted for a particular application, practitioners often do not have the information required to make good decisions regarding which delivery technique to use. Definitive guidance for selecting the most appropriate technique is needed.

In addition, significant advances have been made in technologies that can provide high resolution mapping of the subsurface distribution of amendments. However, a rigorous comparison of such methods in different geologies of low hydraulic conductivity has never been made, in part because the high resolution mapping and data processing tools are proprietary and have not been widely available. Consequently, no guidance is available for practitioners or RPMs to assist in the selection or specification of amendment distribution and monitoring techniques for assessing amendment delivery within low permeability media.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project is to compare the performance and cost benefits of hydraulic and pneumatic permeability enhancement for *in situ* treatment at low permeability sites. The technical objectives of this demonstration/validation project are to:

- Demonstrate the amendment distribution capabilities of permeability enhancement techniques in three different geologic settings with low permeability
- Demonstrate and validate the use of tilt-meter monitoring as a novel, high-resolution, and non-invasive mapping technique to aid in evaluating the performance of permeability enhancement technology
- Collect sufficient performance and cost data to develop a concise guidance document to help RPMs and practitioners select and/or specify the optimal *in situ* delivery technique for a given low permeability site, as well as the monitoring approach to quickly validate its performance
- If possible, compare *in situ* delivery performance results using permeability enhancement techniques to those of more conventional injection approaches

1.3 REGULATORY DRIVERS

The Department of Defense (DoD) has many contaminated sites in complex hydrogeological settings and with unique contaminant characteristics where aquifer restoration within a reasonable timeframe may be extremely difficult. For example, in the presence of a dense non-aqueous phase liquid (DNAPL), technologies specific to treatment of the dissolved components of the contaminants are limited by the DNAPL dissolution rates. This can result in contaminant persistence on the order of hundreds of years. In geologic settings of low hydraulic conductivity such as tight clays and fractured rocks, effective and uniform delivery of remediation amendments to the zones of interest is rarely achieved using conventional techniques. Collectively, these sites present significant technical and financial challenges to the DoD due to the long remedial timeframe and high cleanup costs.

2.0 TECHNOLOGY

Permeability enhancement technology offers unique benefits to address the many challenges present at contaminated sites with low hydraulic conductivity. This section provides a description of the technology and presents its advantages and limitations.

2.1 TECHNOLOGY DESCRIPTION

At sites with low hydraulic conductivities of approximately 10^{-5} cm/s or lower, specialized *in situ* delivery techniques are required to distribute amendments effectively. The three most prevalent methods in use today are pressurized direct-push injection (DPI), hydraulic permeability enhancement, and pneumatic permeability enhancement (ESTCP 2014). Pressurized DPI is commonly used because of its low initial cost. However, distribution of amendments using this technique is often uncontrolled and unverified. Unfortunately, the high life-cycle cost of poor amendment distribution is seldom considered when selecting an appropriate *in situ* delivery strategy. In addition, rapid diagnostic tools for assessing amendment distribution to facilitate real-time optimization of the selected strategy have not been well documented. In recent years, a number of technologies have been developed in an attempt to address the challenge of achieving an effective distribution of treatment amendments in low permeability and fractured media. These advances include hydraulic and pneumatic permeability enhancement technologies, both of which are able to emplace amendments into low permeability media, as well as advancements in tilt-meter monitoring for high resolution mapping of the subsurface distribution of amendments.

2.1.1 Hydraulic Permeability Enhancement

Invented by the oil and gas industry, permeability enhancement technology was modified to aid remediation of soil and groundwater in the late 1980s (USEPA 1993 & 1994). The goal of permeability enhancement technology is to increase bulk hydraulic conductivity and amendment delivery ROI to facilitate enhanced *in situ* remediation in low-permeability formations. A low- or high-viscosity fluid is introduced into a borehole at a rate and pressure high enough to overcome the *in situ* confining stress and the material strength of a geologic formation, resulting in the formation of a fracture. In high-viscosity permeability enhancement applications, sand can be injected simultaneously with a solid amendment such as zero-valent iron (ZVI) to maintain the integrity of the propagated fractures that can otherwise become restricted or closed up entirely, particularly in plastic geologic materials. This typically results in an increase in hydraulic

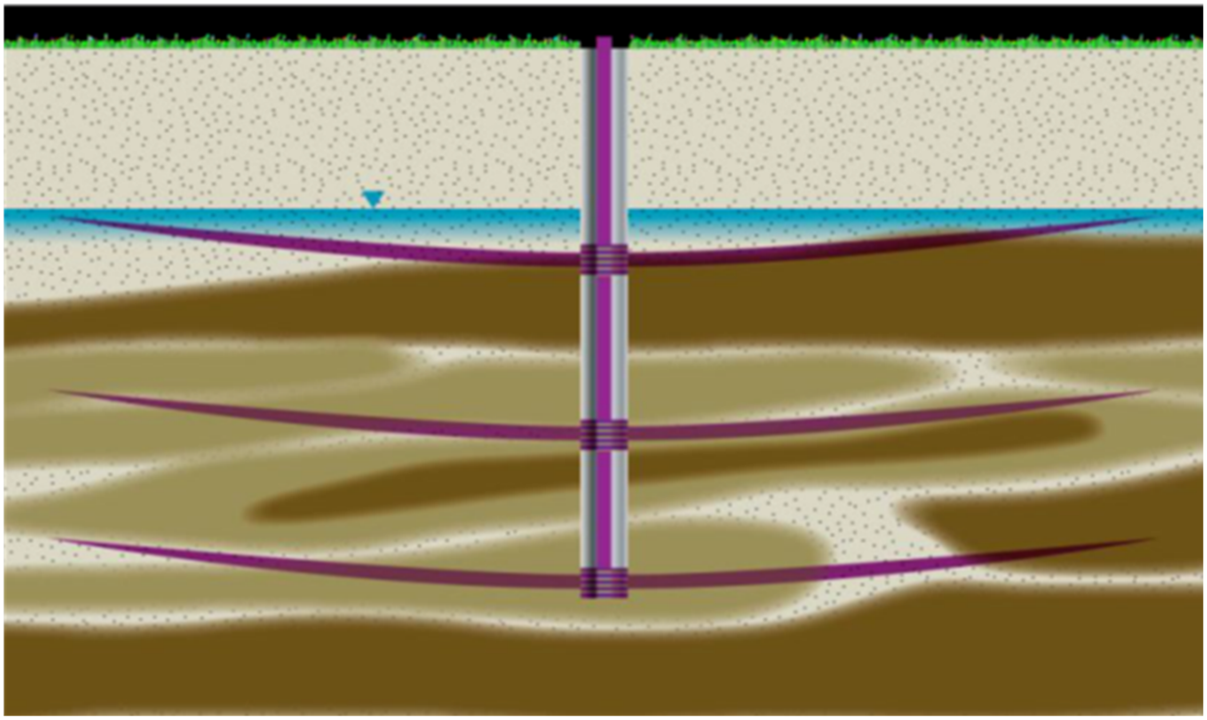

Figure 2.1: **An Illustration of Hydraulic Permeability Enhancement Technology**

conductivity by about an order of magnitude and allows for more effective injections or extractions. Hydraulic permeability enhancement can be performed using almost any drilling technique, including direct-push. **Figure 2.1** provides a visual perspective on the processes involving hydraulic permeability enhancement where a series of long, depth-discrete fractures were initiated using the top-down approach.

2.1.2 Pneumatic Permeability Enhancement

Pneumatic permeability enhancement technology utilizes a gas at flow volumes exceeding the natural permeability of the formation to generate high enough pressures to overcome the *in situ* confining stress and the material strength of a formation such that fractures are formed (USEPA 1995). The result is the enhancement of existing fractures and planes of weakness (for example, bedding planes) and the propagation of a dense fracture network surrounding the *in situ* delivery well. Once a geologic zone has been fractured, the injection of the amendment can be performed in an integrated process. For example, the amendment liquid or slurry can be blended into a nitrogen gas stream above ground and become atomized. Relatively low pressures are required to sustain the flow into the formation. The atomization apparatus is a down-hole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the target interval. Using this method, the amendment might be distributed to a distance of 10 to 25 radial feet depending on site-specific conditions. As with hydraulic permeability enhancement, this fracture network enhances the overall effective bulk permeability of the formation and extends the ROI for injection, thus enhancing *in situ* treatment. **Figure 2.2** provides a visual perspective on the processes involving pneumatic permeability enhancement where a series of hairline fractures are initiated at the depths of interest.

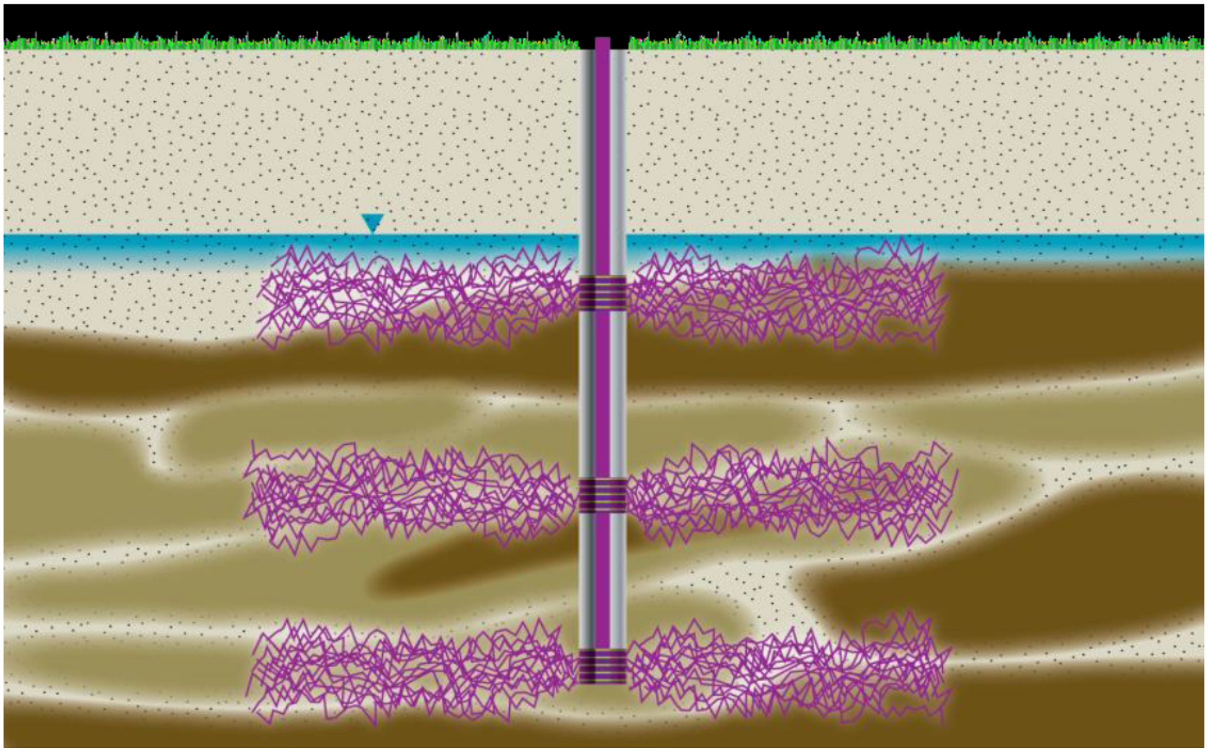

Figure 2.2: **An Illustration of Pneumatic Permeability Enhancement Technology**

The nature of permeability enhancement induced by pneumatic techniques is thought to be quite different from hydraulically induced fractures. Conventional wisdom suggests that hydraulic permeability enhancement has the advantage of a larger *in situ* delivery radius and propped fractures that can be used for multiple injections or extractions, while pneumatic permeability enhancement is expected to produce a more dense fracture network for the same cost but within a smaller zone. However, no studies have been published comparing and documenting the performance of either of these techniques at multiple, low permeability sites (ESTCP 2014).

2.1.3 Tilt-metering

Although much more sophisticated, tilt-meters operate on the same principle as a carpenter's level (Dunnicliff, 1993). Tilt-meters contain two tilt sensors (on orthogonal axes) and precision electronics. As the tilt-meter tilts, the gas bubble must move to maintain its alignment with the local gravity vector. The movement of the gas bubble within the conductive liquid causes a change in the total resistance between the electrodes. This resistance change is measured with a resistance bridge or voltage divider circuit to precisely detect the amount of tilt. While simple in theory, the instruments are remarkably sensitive. Utilizing sophisticated electronics and signal processing, tilt-meters are able to achieve a resolution on the order of nanoradians. This is equivalent to the tilt produced by lifting one end of a rigid beam spanning from New York to San Francisco by less than 1 inch. Proper installation and operation of the instruments are required to utilize this resolution. The instruments must be adequately coupled to solid earth and significantly isolated from the large thermal fluctuations of the earth's surface. This is accomplished by setting up ground surface-mounted tilt-meters in a concentric array.

The changes in resistance created by tilting the bubble sensor are electronically converted to a voltage which is proportional to the tilt of the instrument. The voltage is then recorded either by a local data acquisition unit at each tilt-meter site or via cable to a central data acquisition system for the whole tilt-meter array. Data acquisition is most often accomplished with remote data acquisition at each tilt-meter site because it removes the need to run cables over the surface area surrounding the wellbore. Real-time monitoring and analysis can still be performed with remote data acquisition units using radio telemetry to send the data to a central computer system for display and analysis. Remote data acquisition units have sufficient storage capabilities to allow periodic data acquisition with a portable computer.

After tilt data are collected and analyzed to determine the tilt vectors due to the fracture stimulation, an inverse problem is solved to determine the nature of the source that produced the observed tilt field. Various models exist that predict surface deformations due to subsurface disturbances. Currently a dislocation model is used to calculate the theoretical surface deformation (and therefore tilt field) due to hydraulic fractures with arbitrary orientation, dimensions, and location. The resulting output is then converted into a dynamic, three-dimensional (3-D) graphical output that can be viewed in any perspective in space, and can be manipulated to view individual fracture configurations as well as the fracture network as a whole. Tilt-metering will be performed at all three demonstration sites.

2.1.4 Other High-Resolution Characterization Tools

Other high-resolution characterization tools including direct-push electrical conductivity (EC) and electrical resistivity tomography (ERT) can be used to aid validation of amendment delivery via permeability enhancement and to verify the performance of tilt-metering monitoring.

2.1.4.1 Direct-Push Electrical Conductivity

EC logging is utilized for high-resolution characterization of hydrostratigraphic conditions in unconsolidated media (Schulmeister et al. 2007). Direct-push EC probes typically operate using a four-electrode Wenner array, passing current through the outer two electrodes and measuring voltage across the inner two electrodes. The sensors are capable of collecting 20 measurements per second, and collect data at a vertical resolution of 0.05 foot. Clayey materials tend to have higher electrical conductivity and charge characteristics compared to sandy or gravelly soils. The high vertical resolution of the probe readings allows the user to identify fine-scale features, such as low-permeability clay or silt lenses or sand stringers, which are important for transport of injected amendments in the subsurface. The electrical conductivity of the groundwater also affects the conductivity measurements, but the conductivity of groundwater is typically relatively constant over the scale of a shallow, unconsolidated aquifer. By injecting an electrically conductive tracer or amendment solution and measuring electrical conductivity before and after injection activities, intervals impacted by the tracer can be evaluated using the direct-push probes, thereby delineating the vertical distribution of injected amendments. Direct push EC logging will be conducted before and after the permeability enhancement at one of the demonstration sites.

2.1.4.2 Electrical Resistivity Tomography

ERT is a geophysical visualization technique used to study hydrogeological characteristics of the subsurface. Resistivity, an inherent property of all materials, measures the degree to which a material resists the flow of an electrical current. As resistivity depends on chemical and physical properties such as saturation, concentration, and temperature, ERT can be used to monitor natural and anthropogenic processes responsible for changes in such properties (Daily et al.1992). In the context of environmental engineering, ERT can aid in monitoring active remedial progress and provide insights into material emplacement and deformational processes, both of which are very relevant to *in situ* treatment technologies in general and the permeability enhancement technology in particular (Halihan et al. 2005 and Wilkinson et al. 2008). ERT is planned for two of the three demonstration sites.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGIES

Advantages of permeability enhancement technology include:

- In many instances, permeability enhancement represents the best practices remediation approach, especially at low permeability sites. The technology is a cost-effective, environmentally sustainable, and non-disruptive alternative to conventional remediation practices.
- Effectiveness and uniform delivery of treatment amendments into the target zones can be achieved and verified with a high degree of confidence, thus minimizing the potential need for additional treatment and remediation costs.
- Permeability enhancement is a very versatile technology; its various applications range from aggressive source treatment to enhancement of monitored natural attenuation.
- Equipment used in permeability enhancement generally has a small footprint, making the technology applicable at sites with limited working space.

Limitations associated with permeability enhancement technology include:

- Highly specialized equipment and chemicals are often used in permeability enhancement technology, which results in a high initial cost relative to some conventional *in situ* remedial technologies.
- There exists a potential risk in vertical migration of contaminants as a result of permeability enhancement. This risk, more or often than not, can be mitigated by a comprehensive understanding of site hydrogeological conditions.
- High-pressure injection also raises legitimate health and safety (H&S) concerns, which can be mitigated by proper planning and H&S adherence.
- Permeability enhancement also suffers from the poor public perception of the applications of fracturing in the oil and gas industry. In instances where it is applicable, it may be very beneficial to hold public hearings to educate the community about the remediation work being performed.

3.0 PERFORMANCE OBJECTIVES

The performance objectives of this demonstration project are presented in **Table 3.1**. A description of each performance objective, specific data requirements, and success criteria is provided in subsequent subsections.

Table 3.1: Performance Objectives

#	Performance Objective	Data Requirements	Success Criteria
1	Quantify horizontal and vertical distribution of emplaced fractures within target treatment volume	• Two soil cores for each fracture initiation boring to a depth equaling the deepest fracture interval	• Visual/analytical presence/absence of emplaced materials (e.g., ZVI or sand) in soil cores will constitute success as these data will allow for qualitative assessment of amendment distribution.
		• Tilt-meter mapping in a 360° concentric array around fracture borehole	• Successful application of tilt-meters will result in mapped injection planes of emplaced amendment within the target treatment volume. These data provide measurements of fracture orientation, extent, and thickness.
		• Continuous down-hole electrical conductivity (EC) logging (one site only)	• Successful application of EC will result in statistically different EC results in vertical intervals where fractures are present.
		• Electrical resistance imaging (ERT) (one or two sites)	• Successful application of surface ERT will result in a mapping of the aerial distribution of emplaced fractures. • Successful application of ERT may also result in observation of vertical distribution of fractures, although this will likely be masked by multiple vertical fractures in each borehole.
2	Deliver target amendment dose within the target treatment volume	• Amendment volume emplaced • Soil cores • Tilt-meter mapping • EC logging • ERT	• 75% of the target injection volume is delivered within the treatment area of interest.
3	Evaluate increase in aquifer permeability resulting from permeability enhancement technology	• Aquifer pumping/slug testing conducted in treatment area before and after permeability enhancement	• Successful conductivity enhancement is as a statistically significant increase, defined herein as an increase of approximately one order of magnitude, in bulk hydraulic conductivity that allows for improved use of wells for injection and/or extraction.

#	Performance Objective	Data Requirements	Success Criteria
4	Evaluate effectiveness and accuracy of tilt-meter geophysics monitoring	• Tilt-meter fracture plane maps • Soil coring data • Direct-push EC data (one site only)	• Visual observation and/or analytical detection of fractures/treatment amendment against predicted tiltmeter results within an acceptable range of error.
5	Evaluate effectiveness and accuracy of EC	• Pre-fracture EC values • Post-fracture EC values • Soil coring data	• Statistically significant increase in EC value at predicted depth intervals against actual visual observations and/or analytical detection of fractures /treatment amendment within an acceptable range of error.
6	Evaluate effectiveness and accuracy of ERT	• Pre-fracture surface ERT • Post-fracture surface ERT • Soil coring data	• Statistically significant increase in ERT value at predicted depth intervals against actual visual observations and/or analytical detection of fractures /treatment amendment within an acceptable range of error.
7	Evaluate efficacy of improved amendment delivery for treatment of site contaminants	• Contaminant and geochemistry data from existing groundwater monitoring wells • Previous injection data • Newly installed monitoring wells	• Desired geochemical changes are observed in groundwater consistent with the type of treatment. • Concentrations of the site-specific contaminants of concern in groundwater are reduced by at least 50% at the last performance monitoring event relative to historical trends and most recent groundwater quality data. • Permeability enhancement techniques are demonstrated to be more cost-effective over life cycle of remedy than conventional techniques based on site-specific data.
8	Evaluate the ease of use/implementation of each permeability enhancement technology and performance monitoring strategy	• Level of effort (including availability of equipment) necessary to perform each injection technique • Reporting of problems encountered in the field (including surfacing), and ability to resolve problems quickly	• Documentation of the relative availability of equipment and access to appropriate expertise, the level of oversight required, and the types of problems encountered and ease of resolution for each permeability enhancement technology and/or monitoring technique.

9	Evaluate cost performance of each permeability enhancement technology	• Costs for equipment, subcontractors, drilling, field oversight, and data evaluation of each permeability enhancement technology	• Documented cost comparisons for equipment, subcontractors, oversight, and data evaluation for each permeability enhancement technology; the costs will be interpreted in the context of the actual distribution of amendments achieved.

3.1 Performance Objective #1

This objective is focused on quantifying the fracture distribution in the low permeability zones of interest at the three selected sites.

3.1.1 Data Requirements

Data to be collected to quantify the distribution of the emplaced fractures within the target treatment volume include at least two soil cores from each fracture initiation boring to a depth equaling the deepest fracture interval, tilt-meter mapping using a 360-degree concentric array around the fracture borehole, continuous down-hole EC logging (one site only), and ERT (two sites only).

3.1.2 Success Criteria

Success will be determined based on visual and/or analytical presence or absence of emplaced materials (e.g., ZVI, sand, or EVO) in soil cores as these data will contribute to quantification of amendment distribution. Successful application of tilt-meters will result in mapped injection planes of emplaced amendment within the target treatment volume to provide measurements of fracture orientation, extent, and thickness. Successful application of EC and ERT activities will further aid in achieving this performance objective. Amendment detections using all the methods will also be compared to determine whether they provide consistent data and to enable use of multiple lines of evidence to estimate distribution.

3.2 Performance Objective #2

This objective is focused on evaluating the accuracy of amendment delivery using the hydraulic and pneumatic permeability enhancement technologies within the target contaminated zones at the three selected sites.

3.2.1 Data Requirements

Analysis of the amendment volume emplaced, as well as post-demonstration confirmation sampling of soil cores, tilt-meter mapping, EC logging, and ERT will be completed to determine the extent of the propagated fracture networks within and (potentially) outside the target treatment zone.

3.2.2 Success Criteria

A target amendment dose that is delivered into the intended treatment volume (not into surrounding areas) would be considered a successful *in situ* delivery.

3.3 Performance Objective #3

This objective is focused on quantifying the impacts of permeability enhancement technology on bulk hydraulic conductivity.

3.3.1 Data Requirements

Data to be collected to evaluate the increase in permeability from the permeability enhancement activities include aquifer pumping or slug tests conducted in the treatment area before and after permeability enhancement.

3.3.2 Success Criteria

A success criterion for the enhancement of aquifer hydraulic conductivity is defined as approximately an order of magnitude increase in hydraulic conductivity that allows for improved use of wells for future injection and/or extraction work.

3.4 Performance Objective #4

This objective is focused on evaluating the effectiveness and accuracy of the tilt-metering tool in measuring and estimating fracture emplacement.

3.4.1 Data Requirements

Data to be collected to evaluate the effectiveness and accuracy of tilt-metering for estimating fracture emplacement include visual and/or analytical detection of emplaced amendment and confirmation of fractures and/or amendment during post-enhancement soil confirmation sampling.

3.4.2 Success Criteria

Post-permeability enhancement soil confirmation sampling will be used to evaluate the effectiveness and accuracy of tilt-meter technology. Two evaluation criteria will be considered including the vertical and horizontal extent of the initiated fracture networks. Preliminary tilt-meter results as well as available data associated with implemented mapping techniques such as electrical resistivity tomography (ERT) will first be used to guide the soil confirmation sampling locations. Visual observations and analytical sampling of post-enhancement soil cores will allow for determination of actual depth intervals of fracture initiation as well as the horizontal extent of the fracture networks. Subsequently, the estimated horizontal extent of the fracture network based on tilt-meter analysis will be compared against that observed during soil confirmation sampling. A relative percent difference (RPD) between these values will be calculated. An average RPD, calculated for all permeability enhancement intervals and boreholes, equal to or less than 40 percent (%) will be considered acceptable.

The accuracy of tilt-meter in predicting the depth intervals where permeability enhancement occurs will be evaluated similarly; the depth at which individual fractures are expected to be encountered in the soil cores will be compared against that where fractures are visually observed or confirmed analytically during post-permeability enhancement soil confirmation sampling. An average RPD for all initiated fracture intervals will be calculated and is considered acceptable if it is equal to or less than 30 percent.

3.5 Performance Objective #5

This objective is focused on evaluating the effectiveness and accuracy of EC in predicting fracture emplacement.

3.5.1 Data Requirements

Pre- and post-enhancement EC data will be collected and will be compared against depth intervals where fractures were visually observed and/or analytically detected during post-enhancement confirmation sampling.

3.5.2 Success Criteria

Similar to the aforementioned evaluation of tilt-meter, the effectiveness and accuracy of EC will be determined by comparing the estimated fracture depth interval and extent against the actual values obtained during post-enhancement soil confirmation sampling. Again, soil confirmation sampling locations will first be guided using available mapping data such as tilt-meter. Subsequently, RPDs between the estimated and the actual fracture depth and fracture extent will be calculated. RPD values comparisons between EC and visual observations and/or analytical results collected during post-enhancement soil confirmation sampling will be used to evaluate the accuracy of these monitoring tools. Specifically, the depths at which significant differences (50% or greater) in pre- and post-permeability enhancement EC measurements are observed will be compared against those where visual and/or analytical detections of initiated fractures. An average RPD value equal to or less than 50% between these depths for all tested intervals and boreholes will be considered acceptable. The acceptable RPD value for EC is somewhat higher than for the tiltmeters because those parameters are not measuring the actual fracture, but rather the impact of injected amendment on water properties, which can extend beyond the primary fractures both horizontally and vertically.

3.6 Performance Objective #6

This objective is focused on evaluating the effectiveness and accuracy of ERT in predicting fracture emplacement.

3.6.1 Data Requirements

Pre- and post-enhancement ERT data will be collected and will be compared against depth intervals where fractures were visually observed and/or analytically detected during post-enhancement confirmation sampling.

3.6.2 Success Criteria

The effectiveness and accuracy of ERT will be determined by comparing the estimated fracture depth interval and extent against the actual values obtained during post-enhancement soil confirmation sampling. Again, soil confirmation sampling locations will first be guided using available mapping data such as tilt-meter. Subsequently, RPDs between the estimated and the actual fracture depth and fracture extent will be calculated. RPD values comparisons between EC and ERT and visual observations and/or analytical results collected during post-enhancement soil confirmation sampling will be used to evaluate the accuracy of these monitoring tools. Specifically, the depths at which significant differences (50% or greater) in pre- and post-permeability enhancement ERT measurements are observed will be compared against those where visual and/or analytical detections of initiated fractures are observed. An average RPD value equal to or less than 50% between these depths for all tested intervals and boreholes will be considered acceptable. The success criteria for ERT will be evaluated similarly to tilt-meter where both the modeled depth interval of fracture initiation and the horizontal extent of the fracture networks will be compared against those obtained during guided soil confirmation sampling. The acceptable RPD value for ERT is somewhat higher than for the tiltmeters because those parameters are not measuring the actual fracture, but rather the impact of injected amendment on water properties, which can extend beyond the primary fractures both horizontally and vertically.

3.7 Performance Objective #7

This objective is focused on evaluating the remedial enhancement gained by applying the permeability enhancement technologies at the contaminated sites.

3.7.1 Data Requirements

Data to be gathered for evaluating the efficacy of improved amendment delivery for the removal of site contaminants includes the post-injection collection and analysis of groundwater samples for geochemistry and contaminants from onsite monitoring wells. Where possible, data from previous conventional amendment injections will also be obtained and analyzed for site-specific comparison to permeability enhancement techniques.

3.7.2 Success Criteria

Preliminary success criteria for this objective are that the geochemical conditions change as desired for the intended treatment, and the historically known contaminants in the groundwater within the vicinity of the permeability enhancement emplacement are reduced by at least 50% in the last performance monitoring events. Additionally, for sites with previous *in situ* injection data, cost comparisons should show that *in situ* delivery via permeability enhancement technology is demonstrably more cost effective (over the life-cycle) than conventional injections.

3.8 Performance Objective #8

This objective is focused on evaluating the ease of use of the permeability enhancement technologies.

3.8.1 Data Requirements

As permeability enhancement activities are completed, data on the level of effort (including the availability of equipment) necessary to perform each injection technique will be collected. These data include reporting of problems encountered in the field and the ability of field crews to resolve problems quickly.

3.8.2 Success Criteria

Success in this case depends simply on documenting the issues related to ease of use. Of course it is hoped that the data will demonstrate that the injection and monitoring activities can be used with a level of effort similar to conventional injections, and that the results are sufficient to justify whatever additional level of effort is required.

3.9 Performance Objective #9

This objective is focused on evaluating the cost performance of the permeability enhancement technologies.

3.9.1 Data Requirements

Data to be collected for evaluating the cost performance of each permeability enhancement technology include costs for equipment, subcontractors, drilling, field oversight, and data evaluation.

3.9.2 Success Criteria

The success of this objective requires that the costs for equipment, subcontractors, oversight, and data evaluation are captured and compared for each permeability enhancement technology. The costs will be interpreted in the context of the actual distribution of amendments achieved and compared against those associated with the conventional remediation techniques previously employed at the demonstrated sites.

4.0 SITE DESCRIPTION

This section describes the criteria used for selecting the three sites for this technology demonstration. In addition, details regarding each site's history, hydrogeology, contaminant type and distribution, previous work, and proposed demonstration activities are provided.

4.1 SITE SELECTION

A total of 10 candidate sites were received for consideration from the United States Army Corps of Engineers (USACE), Air Force, and Navy personnel. As described in the Site Selection Memorandum dated February 2015 (**Appendix A**), site selection was based on two primary criteria sets: threshold criteria and other criteria. Threshold criteria are minimum requirements that need to be met for the demonstration. Threshold criteria include soil hydraulic conductivity, depths to bedrock and water table, site lithology, and vertical interval available for demonstration. **Table 4.1** provides a summary of the threshold criteria used to evaluate the sites received for consideration. If a site passed these threshold criteria, the site was further evaluated using the "other" criteria listed in **Table 4.2**, which include contaminant presence in the groundwater and site logistical concerns.

Table 4.1: Site Selection Threshold Criteria

Metric	Preferred Value	Description
Hydraulic Conductivity	<10^{-5} cm/s	Sites will have low-permeability lithologies (hydraulic conductivity ranging from approximately 10^{-5} to 10^{-7} cm/s) present at varying depths in order to allow for comparison of performance and cost of amendment delivery at varying depths. Sites with hydraulic conductivities greater than 10^{-5} cm/s may be acceptable if previous *in situ* injection activities indicate that effective distribution is limited by subsurface lithology.
Depth to Competent Bedrock	>5 ft below injection	Sites ideally will have competent bedrock (i.e., bedrock not suitable for environmental permeability enhancement technologies) >5 ft deeper than the lowest target injection interval to avoid any interference with drilling and permeability enhancement activities. Specialized permeability enhancement techniques not budgeted for this demonstration would be necessary to fracture hard rock.
Lithology	Clays and silts	Each site selected will ideally have a different type of low-permeability geologic setting (e.g., glacial till, alluvial or lacustrine deposits, fractured bedrock, or siltstone/sandstone) to provide evaluation of permeability enhancement technologies in a variety of conditions. If two different geologic formations are present at one site, then that site may be used for two demonstrations to reduce overall mobilization costs. The preference is for one site with clay or clay till, one siltstone/sandstone, and one other (not hard rock).
Vertical Interval	>10 ft saturated interval, >5 ft from ground surface	The demonstration interval would ideally include a 10-15 ft thick (at minimum) saturated zone. The target interval would also not extend within 4-5 ft of ground surface or bedrock.

Table 4.2: Other Site Selection Criteria

Metric	Preferred Value	Description
Contamination	--	Preference for aged sites with contaminants dissolved into groundwater; i.e., no DNAPL present (for simplicity); preference for sites with data from previous conventional injections
Previous *in situ* remediation activities	--	Preference for sites with previous *in situ* groundwater remediation activities
Site Footprint	--	Preference for sites with minimal interaction with existing surface activities
Downgradient Receptors	--	Minimal groundwater to surface water interactions
Site Access	--	Few obstacles to scheduling field activities
Permitting/ Regulatory Concerns	--	Preference for states where permitting agency regularly allows injection of ZVI, EHC®, other electron donors, permanganate or persulfate; preference for states where permeability enhancement is expected to be allowed without significant discussion
Drilling Activities/ Training	--	Quick mobilization and training of drilling/field crews is preferred

4.2 CAMP PENDLETON SITE 1115

The Camp Pendleton Site 1115 in San Diego, California was selected for the demonstration upon review and approval of the Site Screening Memorandum dated February 2015 (**Appendix A)**. The site map is provided in **Figure 4.1** and the building and well layouts for Site 1115 are shown in **Figure 4.2.** Site 1115 is located on the eastern portion of Camp Pendleton, southwest of the intersection of Vandergrift Boulevard and 16th Street, and is approximately 14.5 acres in size. The site once served as a motor pool for vehicle maintenance and a repair, painting, washing, and fuel service station for the base. A total of nine underground storage tanks (USTs), which stored a variety of fuels and solvents, were used to support aforementioned activities at the site. All buildings and USTs have been removed or closed in place. The site is currently paved with asphalt and is used for vehicle and equipment staging (Parsons 2012).

Site 1115 is relatively flat and mostly slopes at a 5 to 7% grade toward the north. Elevations of the site range from 325 to 365 feet above mean sea level (amsl). There is no permanent surface water present at Site 1115, and rainfall drains to the west and also to the swales along 16th Street, which lies north of the site.

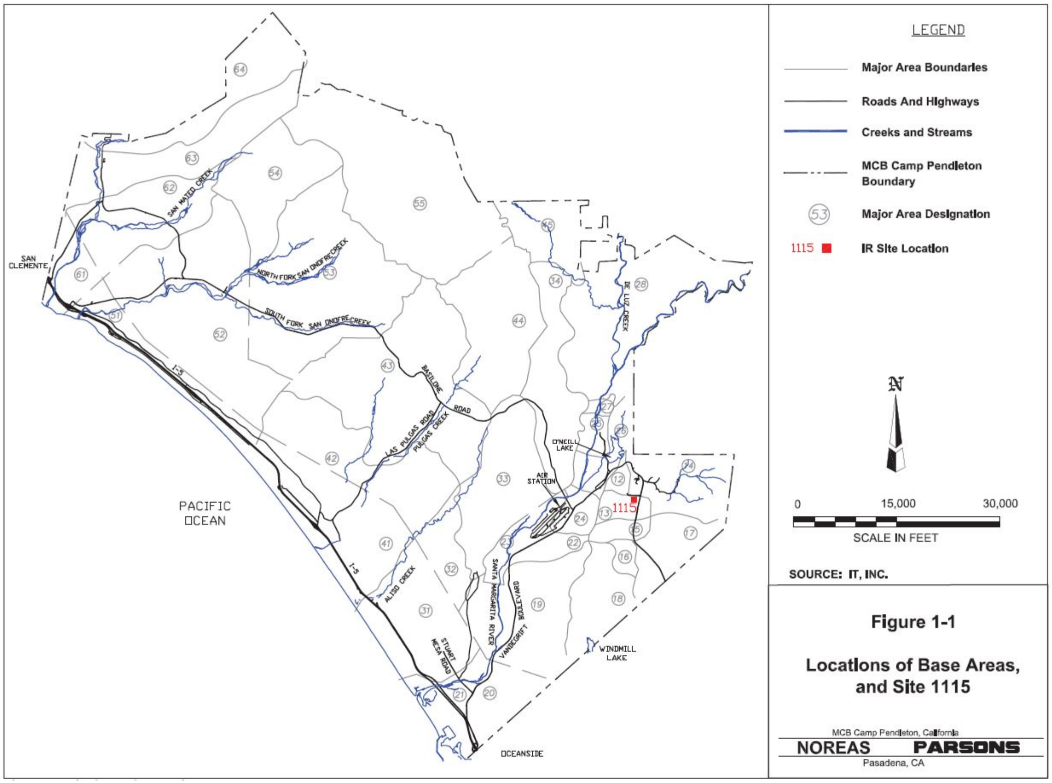

Figure 4.1: **Camp Pendleton Site Map**

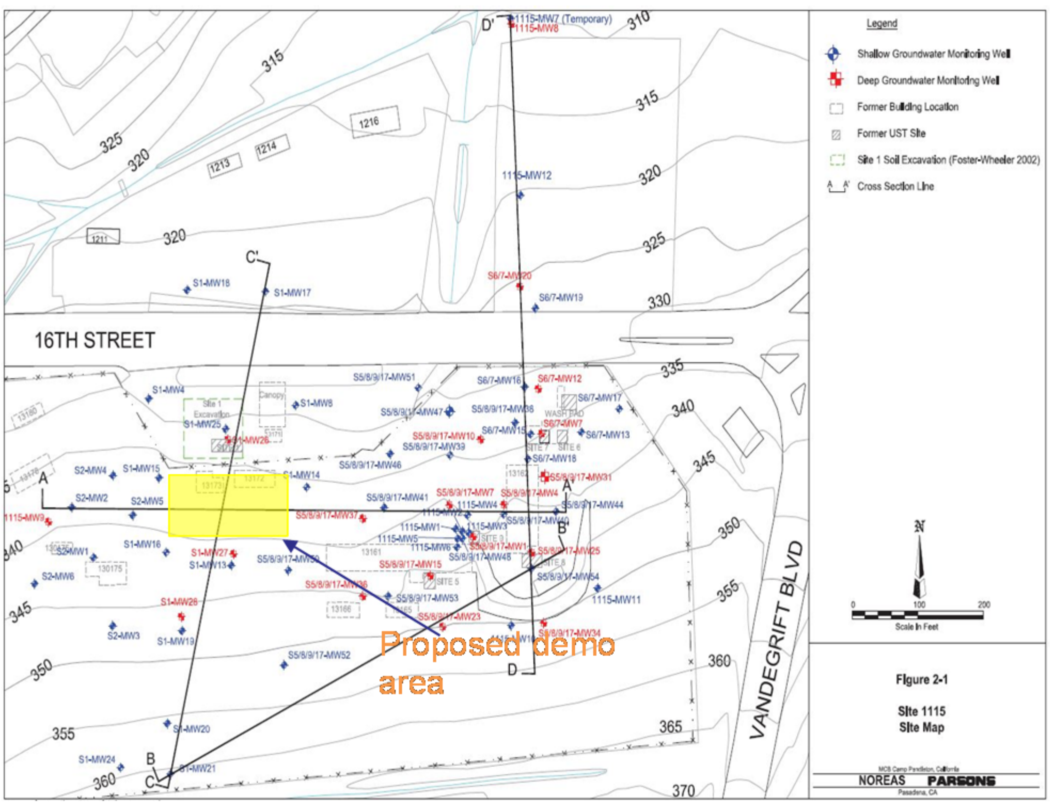

Figure 4.2: **Camp Pendleton Site 115 Building and Well Layout Map**

4.2.1 Site 1115: Hydrogeology and Lithology

Figure 4.3 presents a west to east geologic cross section of Site 1115 soil lithology. The Santiago Formation is ubiquitous throughout the site and consists of mostly interbedded, low-permeability, lightly cemented siltstone, sandstone, and mudstone (Cranham et al.1994). This formation has the characteristic of not being strongly indurated or cemented. The soils in the western part of the site consist of yellowish-brown to very pale brown silty sand, greenish gray lean clay or silty lean clay with sand, light olive brown or olive yellow clayey silt, and dark grayish brown sandy silt. Sand units in this part of the site consist of very fine to coarse-grained, poorly graded sand, silty sand, and clayey sand. Silt and clay beds also contain sand and are very stiff to hard. Shallow soils in this portion of the site consist of a fill material that is a yellow-brown, fine to medium-grained and poorly graded sand. In the eastern part of the site, bedrock consists of clay and silt beds. These clay and silt zones are mostly at depths between 15 and 30 feet below ground surface (bgs). The shallow, low permeability units consist of silt and lean clay, whereas deeper units consist of fat and lean clays with fine laminations with interbedded lenses of unsaturated sand. At approximately 50 to 60 feet bgs, poorly graded sands, silty sands, and clayey sands are present; these are underlain by silt and clay.

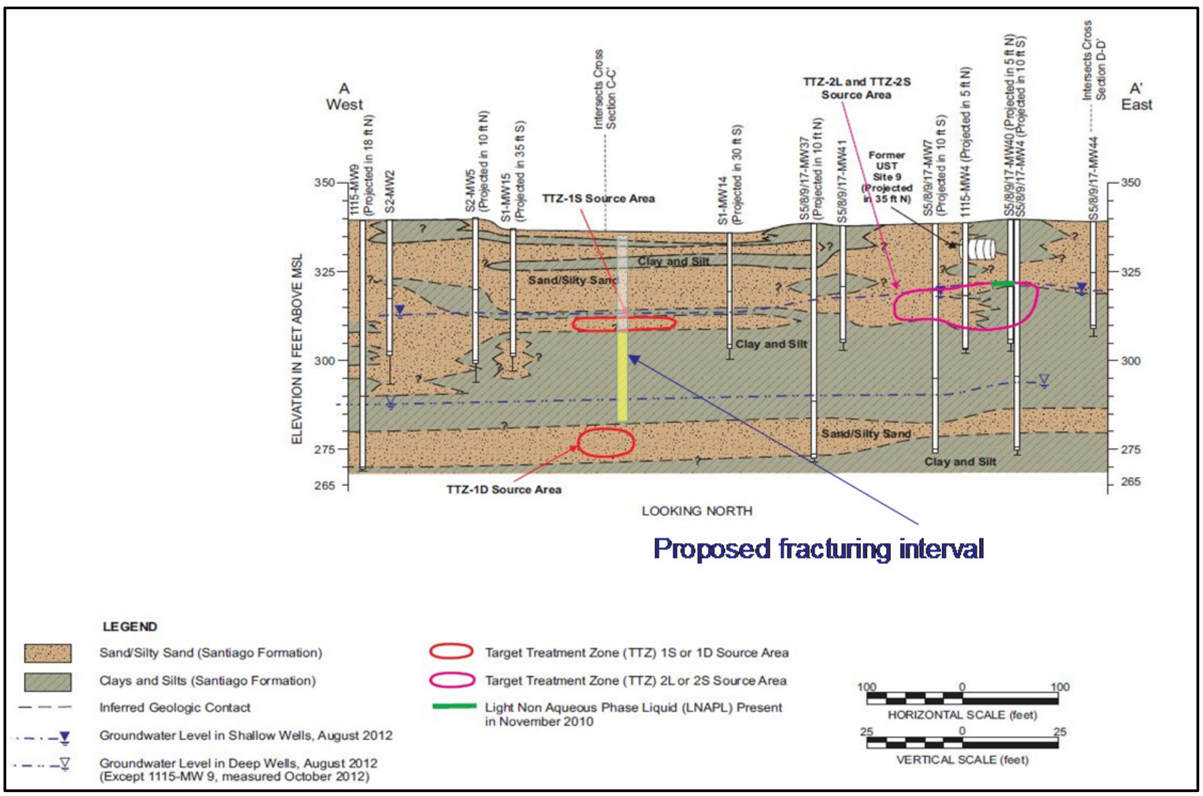

Figure 4.3: **Camp Pendleton Site 1115 Cross Section Lithology**

A shallow groundwater zone exists across the site. It varies considerably in depth due to surface topology, and contains an array of contaminants at roughly an order of magnitude higher in concentration than a deeper groundwater zone (Parsons 2012). On the western portion of the site near monitoring well S1-MW-16 (just south of former UST 1), the shallow and deep groundwater exist at roughly 30 and 52 feet bgs, respectively. At the eastern-central portion of the site, a groundwater mound underlies former Building 13162, which is underneath a nearly flat, depressed area of the site where water collects following rainfall. In this location (near former USTs 5/8/9), the shallow and deep groundwater are at depths of 23 and 49 feet bgs, respectively. The groundwater flow in the shallow zone is multi-directional with a 3-foot mound around monitoring well S5/8/9/17-MW4, but generally flows south and southwest beneath the western and southern portion, west beneath the east-central portion, and north and northeast in the northern portion of the site. Groundwater generally flows to the south and southwest in the lower aquifer. In the eastern portion of the site, the shallow groundwater generally occurs in low-permeability water bearing zones. These zones include silts and clays with thin saturated sand lenses. The western portion of the site has more permeable sand or silty sands. The saturated thickness of the western portion of the shallow aquifer is estimated to be 5 to 20 feet, with an average of 13 feet. The average thickness of the shallow aquifer on the eastern portion of the site is estimated to be 5 feet. The average thickness of the deeper aquifer is estimated to be 5 to 10 feet at a minimum. **Figure 4.3** also depicts the observed depths to the shallow and deeper water tables.

4.2.2 Site 1115: Groundwater Contamination and Chemistry

Contaminant migration from three distinct source areas has resulted in an extensive groundwater

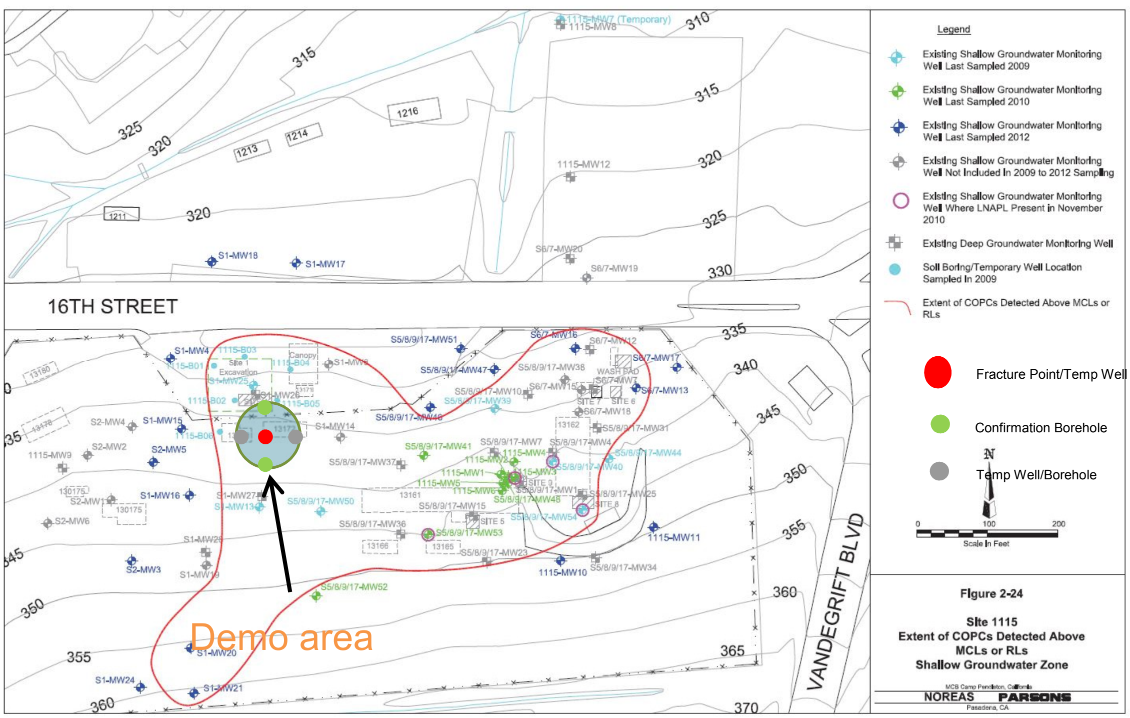

Figure 4.4: **Camp Pendleton Site 1115 Demonstration Layout**

plume as shown in **Figure 4.4**. This plume extends from a northwestern plume associated with UST Site 1 (former fuel service station), and a comingled plume associated with UST Sites 6/7 and 5/8/9, and former pipeline 17 on the eastern side of the site. Presently, the plumes have migrated several hundred feet from these source areas. Approximately 30% (4 acres) of the site is underlain by groundwater with contaminants above their respective maximum contaminant levels (MCLs) or residential soil screening levels (RSSLs).

From a total of 25 previous site investigations dating from 1986 to 2012, commonly detected contaminants in soil and groundwater above RSLs include 1,2-dichloroethane, 1,2-dibromoethane, arsenic, benzene, carbon tetrachloride, cis-1,2-dichloroethene (cis-1,2-DCE), ethylbenzene, methylene chloride, methyl tertiary butyl ether (MTBE), naphthalene, toluene, trichloroethene (TCE), and vinyl chloride (VC). These contaminants are mostly found in the vicinities of the former USTs. Benzene is the primary groundwater contaminant in the northwestern part of the site (area of UST 1), while fuel-related compounds and chlorinated solvents are present on the eastern and central portions of the site. The presence of TCE degradation products including cis-1,2-DCE and VC and low oxidation reduction potential (ORP) indicate potential attenuation of chlorinated solvents within the plume. Total dissolved solids above 5,000 milligrams per liter (mg/L) are also typically encountered in the monitoring wells.

Light non-aqueous phase liquid (LNAPL) has historically been observed in monitoring wells near former UST 1 on the western side of the site and near USTs 5, 6, 7, 8, and 9 on the eastern portion of the site (Parsons 2012). LNAPL has been observed in excess of one foot thick in six monitoring wells next to former USTs 5, 6, 7, 8, and 9 as well as near former buildings 13162 and 13165. In February 1996, 16 feet of LNAPL was observed in the shallow monitoring well MW40, the most observed at Site 1115. As of 2013, most of the visible LNAPL in these wells has been reduced to just sheens, with the exception of MW53 which reported 0.42 feet of LNAPL. Observed LNAPL is thought to exist in isolated pools perched above the shallow groundwater, providing a continued source of contamination to the groundwater. Diesel and gasoline range petroleum hydrocarbons were observed during a series of soil borings in 2009; these ranged in concentrations from non-detect to 14,000 milligrams per kilogram (mg/kg). There are currently 64 monitoring wells at the site that have provided the data showing the contaminant plume extent seen in **Figure 4.4**.

4.2.3 Site 1115: Previous Remedial Work

Previous treatment activities at the 1115 site include UST removals, soil excavations (UST Site 1 in January 2002), pilot study soil-vapor extraction (SVE) investigations, LNAPL recovery, and pilot studies for delivery of organic substrates in 2010 and 2011. Removal of 5,000 cubic yards of soil from the UST 1 area in 2002 resulted in marginal impact to water quality, as leachable concentrations of total petroleum hydrocarbons gasoline range (TPH-G), benzene, toluene, ethylbenzene, and xylene (BTEX), and naphthalene were still found in the sidewalls of the excavation. Performance monitoring following the delivery of organic substrates in 2010 indicate that reductive dechlorination of chlorinated solvents was occurring where substrate was successfully delivered. However, the delivery of treatment amendment was severely restricted due to the site's low permeability and thus minimal remedial success was observed downgradient of the injection sites.

4.2.4 Site 1115: Selected *In Situ* Injection Area

The Camp Pendleton Site 1115 area selected for this technology demonstration is illustrated in **Figures 4.2, 4.3,** and **4.4**. The area's low permeability in the saturated zone and its nearby monitoring network of appropriate screen intervals provide an excellent opportunity to demonstrate the hydraulic permeability enhancement technology as well as pertinent groundwater monitoring. Based on the available site data, including data from monitoring during the summer of 2015, the primary contaminant of concern in the selected test area is benzene. Details regarding the test design are provided in **Section 5.**

4.3 LAKE CITY ARMY AMMUNITION PLANT SITE 17D

The Lake City Army Ammunition Plant (AAP) Site 17D was selected for the demonstration upon review and approval of the Site Screening Memorandum dated February 2015 (**Appendix A**). The site is located in northeastern Independence, Missouri. The site was established in December 1940 for manufacturing and testing of small caliber ammunition for the United States Army (USEPA 2008). The site has been in continuous operation except for a single 5-year period following World War II. On average, the plant has produced almost 1.4 billion rounds of ammunition per year. The site is a government-owned, contractor-operated facility. Remington Arms operated the facility until 1985 when Olin Corporation took over operations, followed by another management change in 2001 to Alliant Techsystems. The site consists of 3,935 acres with 458 buildings as shown in **Figure 4.5**. The small community of Lake City is located adjacent to the northern boundary of LCAAP and relies on private groundwater wells.

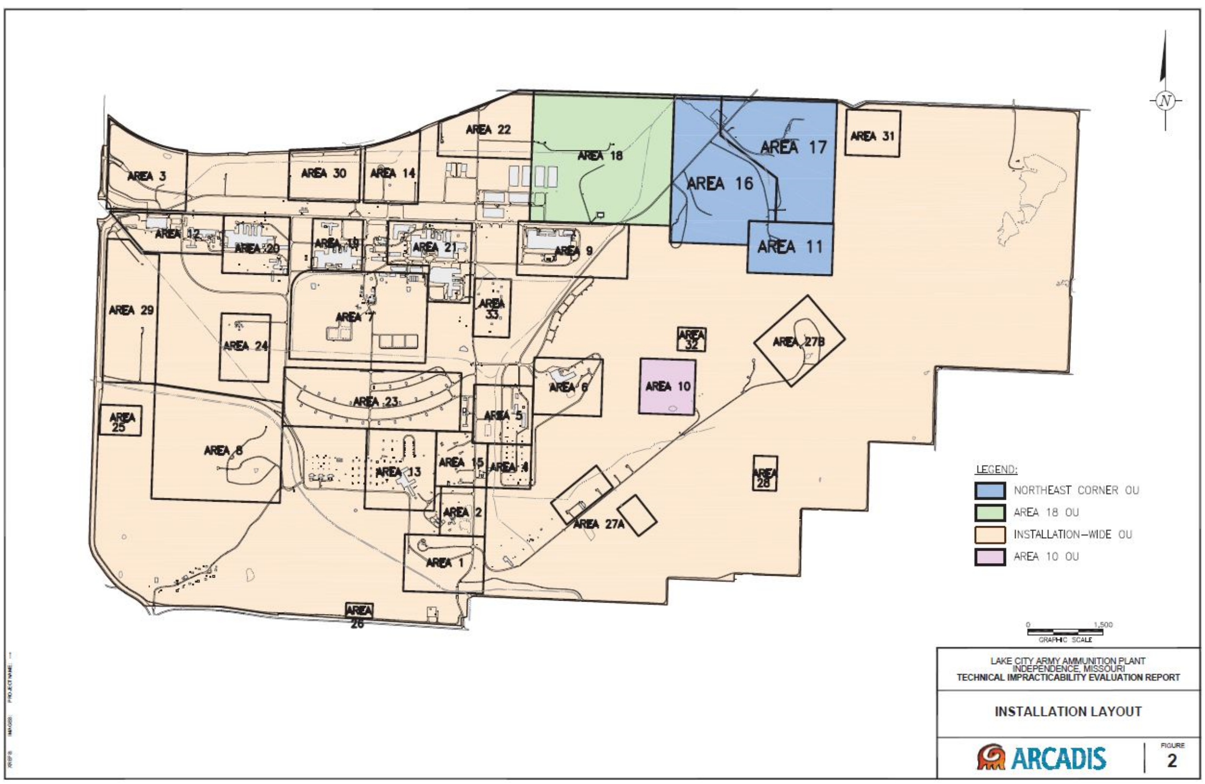

Figure 4.5: **Lake City AAP Site Map**

4.3.1 Site 17D: Hydrogeology and Lithology

Previous investigations indicate that three distinct hydrostratigraphic units exist at the 17D area as shown in **Figure 4.6** (Arcadis 2006). A silty clay overburden consisting of both alluvial silty clays and fine silty sands is approximately 20 to 30 feet thick in this area. Hydraulic conductivity for the silty clay colluvium unit has been measured as 4 x10^{-5} cm/s. Underlying this unit is a silty clay and weathered shale residuum with a thickness of approximately 10 to 15 feet. The water table in the 17D source area is approximately 5 to 10 feet bgs. This water table is most likely influenced by Abshier Creek, which is approximately 400 feet to the north of the source area.

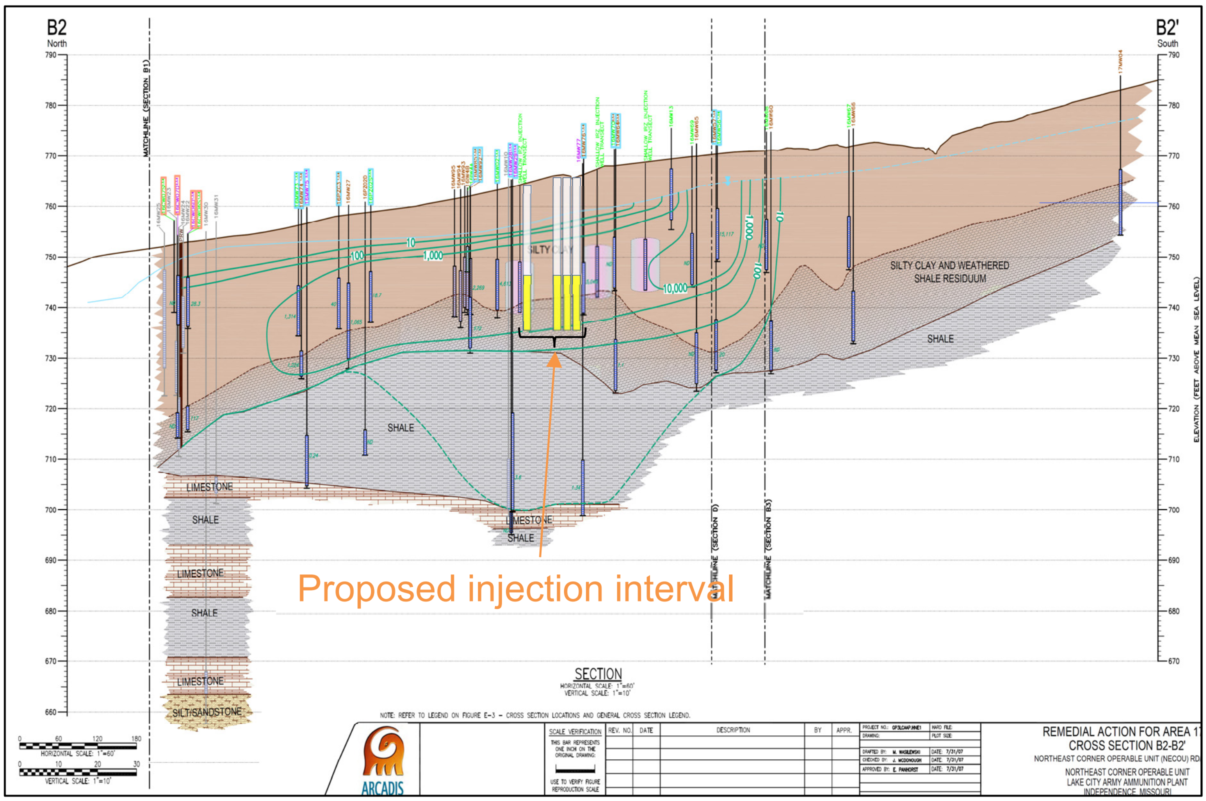

Figure 4.6: Lake City AAP 17D Area Lithology

4.3.2 Site 17D: Groundwater Contamination and Chemistry

Waste treatment and disposal occurred on-site in unlined lagoons, landfills, and burn pits (USEPA 2008a). These disposal processes released solvents, oils, explosives, radionuclides, volatile organic compounds (VOCs), and metals to the local environment. Contaminated groundwater has migrated off-site in the northeastern part of Lake City AAP. A groundwater extraction well is currently used to control further off-site migration of contaminants. As shown in **Figure 4.7**, Area 17D was used for waste storage of glass, paint, and solvents.

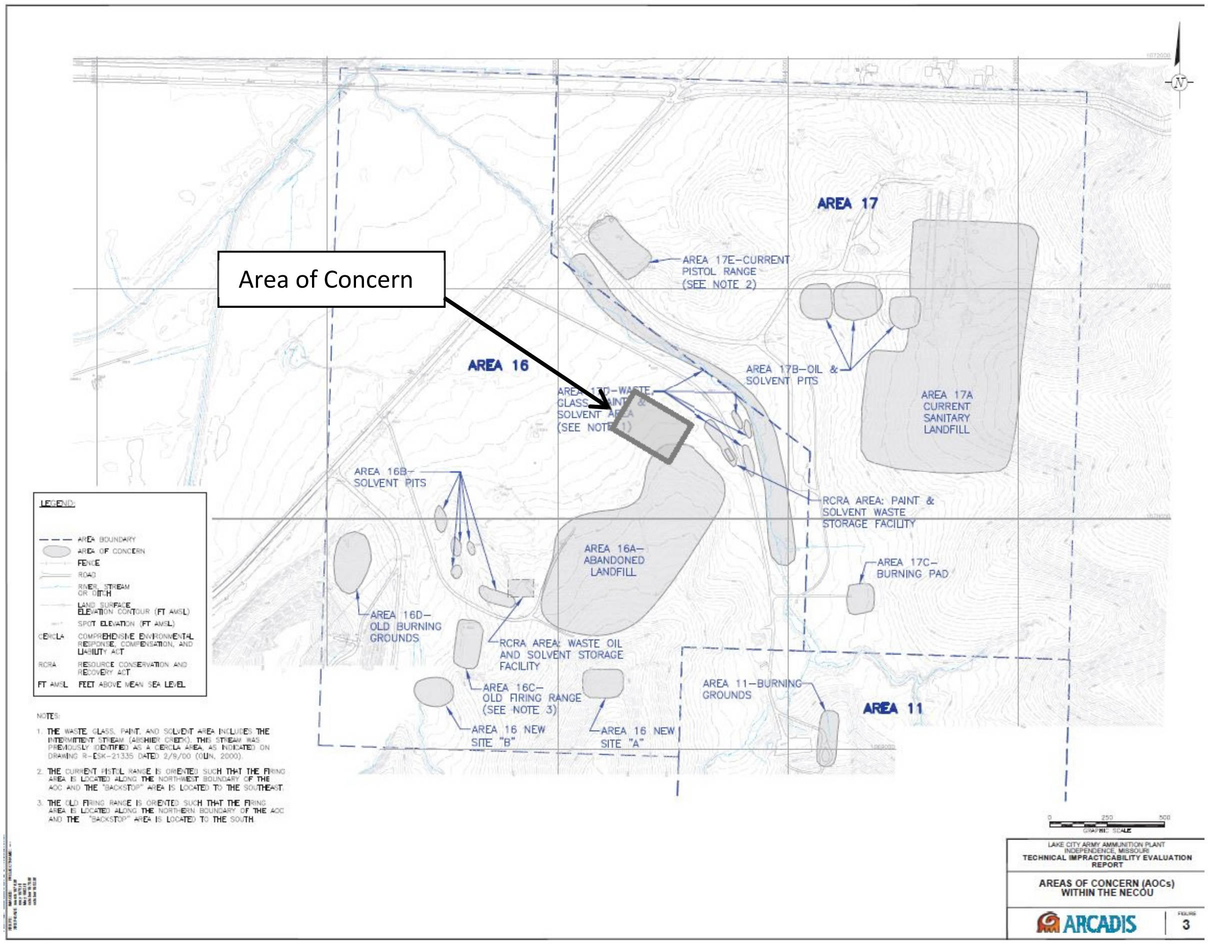

Figure 4.7: **Lake City AAP Area 17 Layout**

Area 17D is long and narrow, located on relatively flat terrain, and has the Abshier Creek (identified as a CERCLA area) running through it (USEPA 2008b). The 17D area was used from 1960 to 1975 for a variety of waste disposal activities. These activities included disposal of fluorescent tubes, oil, grease, bleach cans, ammunition cans, and paint cans.

The area has a chlorinated solvent plume that extends over 2,000 feet from the southeastern source area to the northwest, effectively following the groundwater flow that moves in a west-northwest direction from the source area. Chlorinated solvent concentrations are approximately between 1 and 10 mg/L in the source area near the southeast end of the plume. The area of the 17D plume is estimated to be 7 acres, with an estimated impacted saturated interval of up to 30 feet. In the surficial soil, concentrations of lead exceed cleanup goals. In groundwater, VOCs including TCE, cis-1,2-DCE, and VC are present. Aromatic hydrocarbons are not present in sufficient quantities at the site to feed microbes that would support natural degradation of the contaminants.

4.3.3 Site 17D: Previous Remedial Work

Following an interim 1998 remedial action record of decision, a subsurface permeable reactive wall (PRW) containing ZVI was installed in 2000 to treat dissolved-phase contaminants emanating from the source area (USACE 2013). The PRW is located approximately 500 feet upgradient of the area selected for the permeability enhancement technology demonstration. Concentrations of VOCs are higher on the upgradient side of the PRW than on the downgradient side, indicating that degradation of these compounds is occurring.

In 2007, ARCADIS installed multiple injection wells within an area of the plume with the highest concentrations of VOCs to facilitate injection of an organic carbon substrate and to promote microbially-meditated contaminant attenuation. These injections have been ongoing since the installation and monitoring wells have been installed throughout the 17D area plume to assess the impact of this treatment.

4.3.4 Site 17D: Selected *In Situ* Injection Area

The Lake City AAP area selected for this technology demonstration is illustrated in **Figures 4.7** and **4.8**. The area's lithologic low permeability in the saturated and contaminated zone along with its nearby monitoring network of appropriate screen intervals provide an excellent opportunity for a side-by-side comparison of hydraulic versus pneumatic permeability enhancement. In addition, the demonstration area is located between two rows of biobarriers that have been actively receiving EVO injections and thus will allow for performance comparisons between the permeability enhancement technology and conventional injection technologies. The primary contaminants of concern at this site are the aforementioned chlorinated ethenes. Details regarding the test design for this site are provided in **Section 5.**

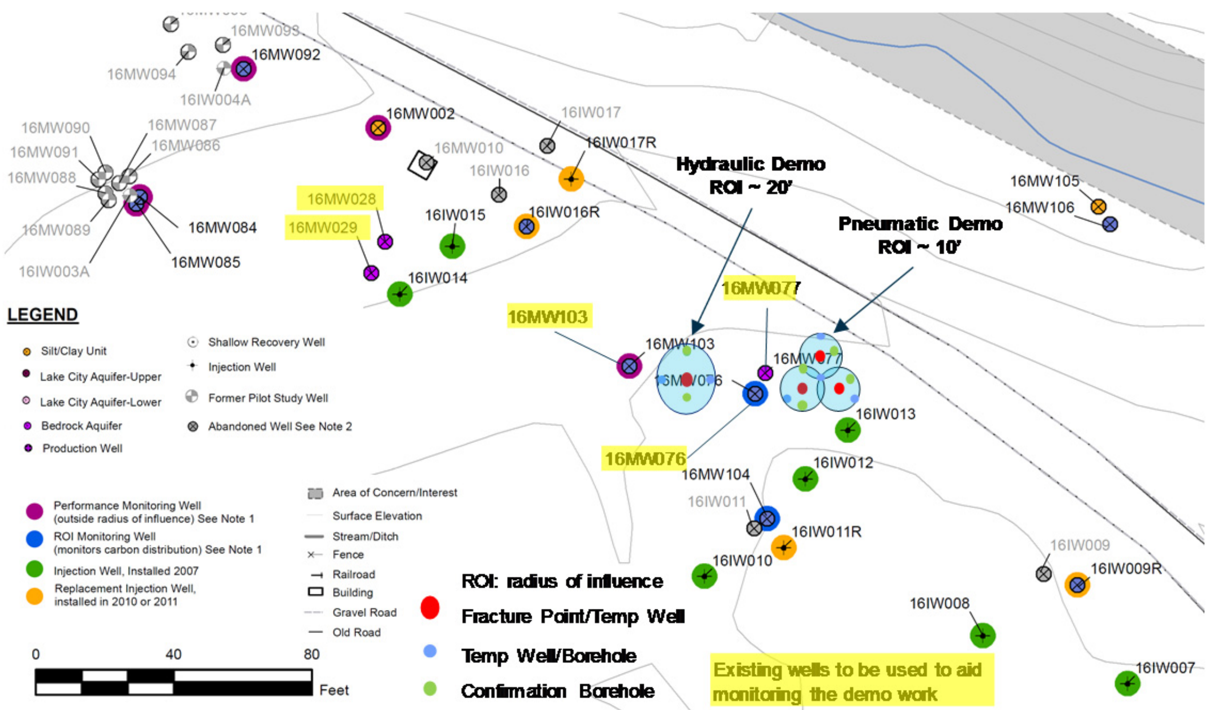

Figure 4.8: **Demonstration Layout at the Lake City APP Site 17D**

4.4 GRAND FORKS AIR FORCE BASE SITE TU504

The Grand Forks Air Force Base (AFB) Site TU504 was selected for the demonstration upon review and approval of the Site Screening Memorandum dated February 2015 (**Appendix A**). Grand Forks AFB is located 12 miles west of Grand Forks, North Dakota, near the state line with Minnesota, as shown in **Figure 4.9**. The site contains 4,830 acres of land, which are partially surrounded by the farming communities of Emerado, Arvilla, and Mekinock (ARGO/LRS JV 2014). The site was historically used as an Air Defense Command Base that housed KC-135 Stratotankers, B-52 bombers, and B-1B bombers. The area selected for this demonstration is TU504, shown in **Figure 4.10**, which is located in the central portion of the base. Building 539 is located within this area, and it was used for jet engine testing from the 1950s through 1992.

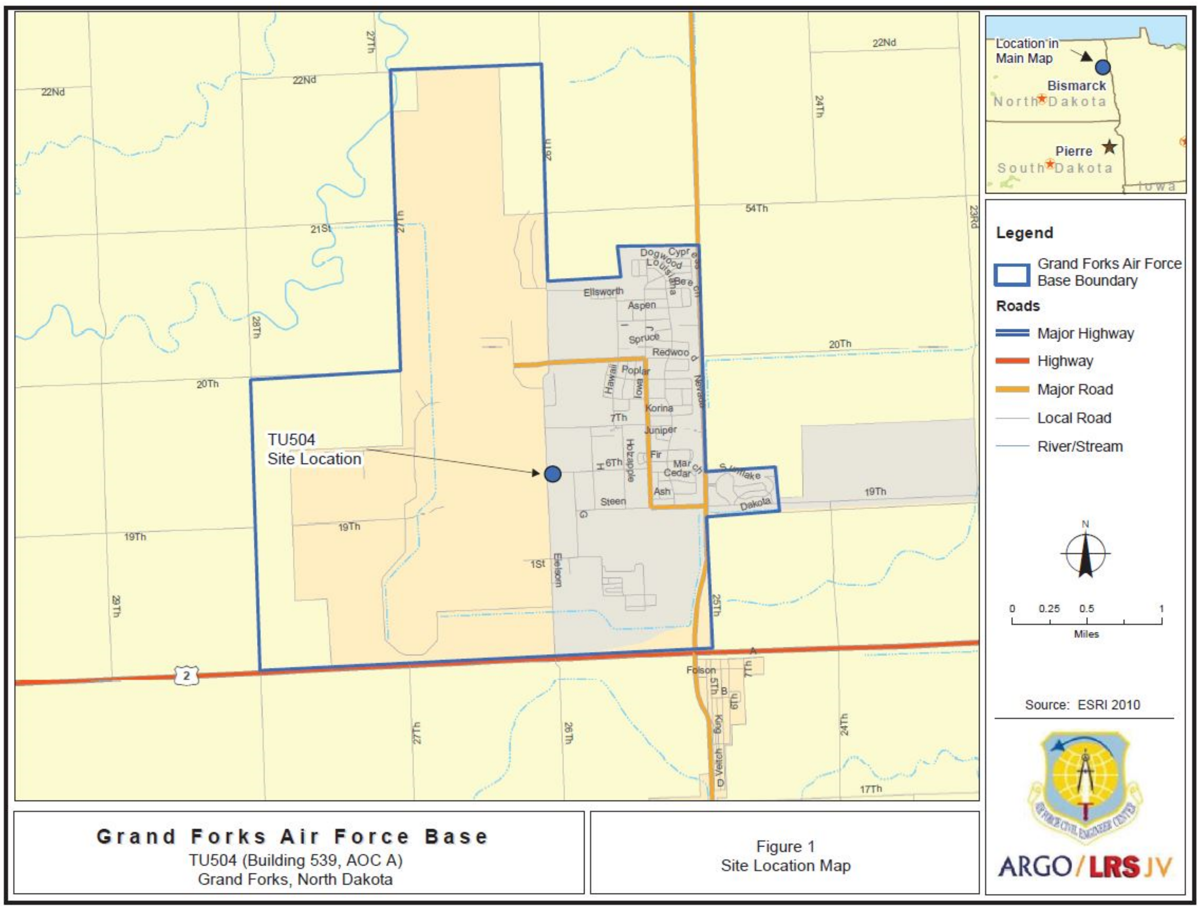

Figure 4.9: **Grand Forks AFB Site Location Map**

4.4.1 Site TU504: Hydrogeology and Lithology

The base lies on interbedded lacustrine and glacial units, which were deposited during interglacial and glacial periods (EA Engineering, Science, and Technologies Inc. 2010). The shallow soil contains a pale brown coarse sand and silty clay fill, which ranges from 2.5 to 6 feet thick. Below this lies a till unit of brown and gray mottled silty clay with decayed vegetation between 15 and 40 feet thick. Below this is a gray clay unit containing gravel and cobbles, which ranges in thickness from 25 to 58 feet. This is followed by a gray silty clay unit approximately 16 to 32 ft thick. Underlying these soils is the Emerado Sand, a gray sand unit approximately 30 feet thick. The interval targeted for the permeability enhancement technology demonstration lies within the clay zone extending from 3 to 30 feet bgs.

A shallow water table observed at the site between 3.68 and 8.26 feet bgs overlies the Emerado Aquifer. A confining unit above such aquifer is present at approximately 60 feet bgs. The potentiometric surface of the Emerado Aquifer is observed to be higher in elevation than the shallow perched water surface. Hydraulic conductivities of the shallow zones of interest for this demonstration have been measured on the order of $2x10^{-5}$ cm/s, but measurements for deeper soils have not been found. A hydraulic gradient of 0.025 is observed on the site, suggesting a groundwater flow velocity of 13 feet per year in the shallow groundwater unit. The lower permeability of the shallow soils suggests that significant migration of contaminants away from the source area is not expected. Unfilled soil fractures have been observed in the shallower portions of the soils, which may contribute to preferential flow.

4.4.2 Site TU504: Groundwater Contamination and Chemistry

In 1996 a petroleum odor was detected in soils removed from an excavated water line. Subsequent analysis of compounds in the site soil and groundwater included detections of JP-4 fuel, hydraulic fluid, engine oil, solvents, TCE, and methyl-ethyl-ketone. A Resource Conservation and Recovery Act Facility Investigation was conducted in 1999 and found VOC and TPH above EPA maximum contaminant levels (MCLs) for soil and groundwater. In 2000 and 2001, a phase II Resource Conservation and Recovery Act Facility Investigation completed the horizontal and vertical delineation of the TU504 area plume. This phase II activity also found other VOCs above MCLs, and determined that the soil contamination extended to a depth of 10 feet.

4.4.3 Site TU504: Previous Remedial Work

In 2002, a phytoremediation project was implemented to hydraulically control and mitigate the plume contamination. The groundwater surface in the vicinity of the plume has been depressed due to limited surface recharge and evapotranspiration. This has caused the groundwater to flow towards the center of TU504. Long-term-monitoring (LTM) of 10 monitoring wells has been conducted on an annual basis since 2003. During the 2014 LTM, tree canopy heights ranged from 7.5 to 62.1 feet, with an average value of 26.9 feet, indicating potentially extensive subsurface root structures (ARGO 2014).Groundwater sampling at this time showed maximum concentrations of TCE and cis-1,2-DCE of 7.54 and 11.1 mg/L, respectively. The maximum benzene concentration was measured at 0.657 mg/L while diesel and gasoline range organics were measured at 0.973 and 6.25 mg/L, respectively. Exceedances of MCLs in the 2014 groundwater sampling results for the 10 monitoring wells are shown in **Figure 4.10**.

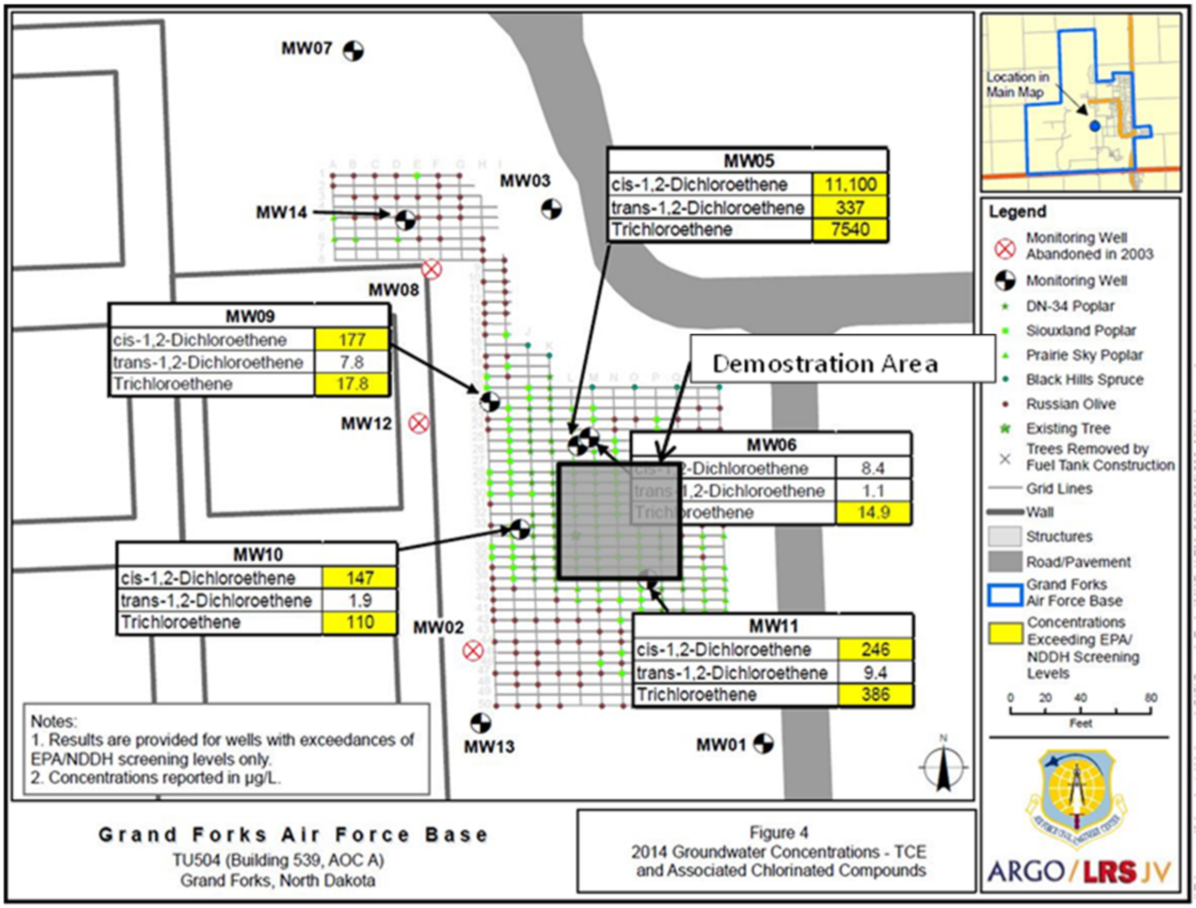

Figure 4.10: Groundwater VOC Results in the Vicinity of the Demonstration Area

In July 2014, 6,625 pounds of LactOil® and 4,323 gallons of a LactOil®/water solution were injected into 30 locations in addition to a bioaugmentation of *Dehalococcoides spp*. The spacing of the trees and the temporary injection well scheme at the TU504 area are shown in **Figure 4.10**. An illustration of the temporary well installation is presented in **Figure 4.11**. Results from the 2014 LTM report indicate that this injection was successful at degrading contaminants in locations where the bioaugmentation and substrate addition had migrated, but exceedances of MCLs in multiple wells for VOCs and TPH still remain. Considerable time may be necessary to fully realize the impact of the bioaugmentation and LactOil® treatment.

Figure 4.11: Temporary Injection Well Installation at the Grand Forks AFB Site TU504

4.4.4 Site TU504: Selected *In Situ* Injection Area

The Grand Forks AFB area selected for this technology demonstration is illustrated in **Figure 4.12**. The area's low permeability in the saturated zone, its nearby monitoring network of appropriate screen intervals, and previous remedial work provide an excellent opportunity for a side-by-side comparison between hydraulic permeability enhancement and standard in-well injection. The primary contaminants of concern at this demonstration site are the aforementioned chlorinated ethenes. Details regarding the test design for this site are provided in **Section 5**.

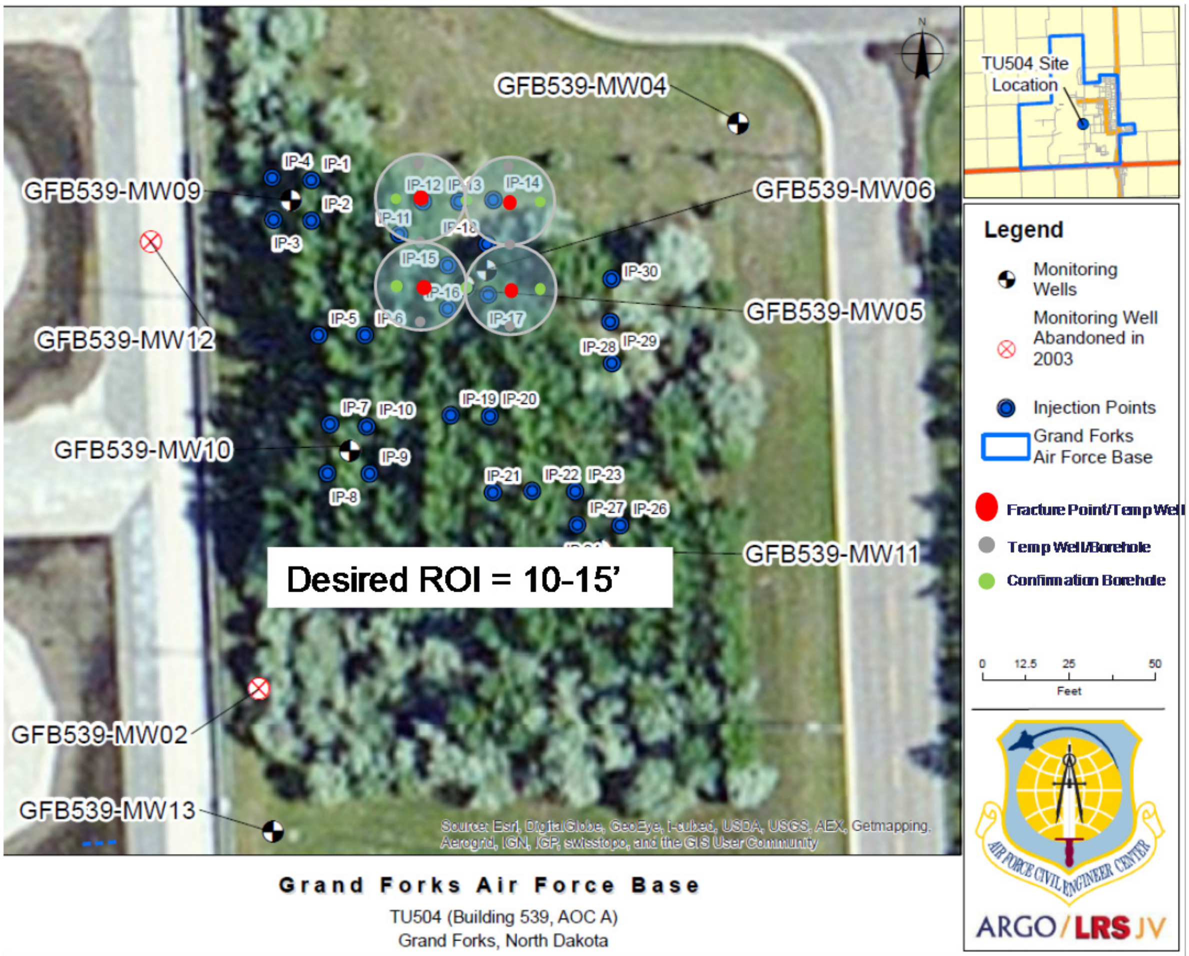

Figure 4.12: Grand Forks AFB Site TU504 Demonstration Layout

5.0 TEST DESIGN

This section provides field demonstration details including conceptual experimental design, baseline characterization activities, demonstration design and layout, sampling plan, and data analysis.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

This demonstration is being performed to demonstrate the efficacy of permeability enhancement techniques to emplace *in situ* treatment amendments in low permeability media. It also provides the opportunity to compare the effectiveness of such techniques to that of conventional injection techniques. This will be accomplished by utilizing the permeability enhancement techniques at three different DoD sites, each of which has a different, low permeability geologic setting. Injections will be monitored using a combination of conventional and innovative techniques to demonstrate amendment distribution using multiple lines of evidence. The sites selected will facilitate the comparison of these results to the previous injection of amendments using conventional approaches. Ultimately, this will allow the advantages and limitations of these injection technologies to be thoroughly documented for a range of low permeability geologies, which will provide the data necessary to establish guidance for DoD project managers and other environmental practitioners to select, procure, and implement effective injections for *in situ* treatment.

The general design layouts of the hydraulic and pneumatic permeability enhancement technologies for the three selected sites are illustrated in **Figures 4.4**, **4.8**, and **4.12**. In general, the injection locations and their fracture initiation depth intervals are in areas of known contamination. Pre-demonstration boreholes located within the expected ROI of the permeability enhancement technologies will be drilled to obtain baseline data applicable for performance evaluation including lithology, total organic compounds (TOC; for Grand Forks AFB Site TU504 and Lake City AAP Site 17D), sulfate (for Camp Pendleton Site 1115), aquifer hydraulic properties, EC, and/or ERT. In addition, baseline groundwater sampling will be conducted at existing and new monitoring wells that are in the vicinity of the injection locations and screened appropriately. High-resolution characterization and monitoring tools coupled with real-time, continuous collection of hydraulic pressure and flow rate will be employed once the permeability enhancement work is in progress. Post-demonstration data will be collected at soil confirmation boreholes and appropriate monitoring wells to evaluate the performance of the permeability enhancement technologies. A summary of these activities is provided in **Table 5.1,** while details are described in the following sections.

5.2 BASELINE CHARACTERIZATION ACTIVITIES

This section provides details regarding available site historical data as well as subsurface clearance and baseline sampling activities that will be performed prior to commencement of the permeability enhancement work at each of the three selected sites.

5.2.1 Historical Data

Significant historical monitoring data are available from each of the three sites, as briefly described in **Section 4**. CDM Smith will work closely with site personnel to obtain and review all relevant data. Following the demonstration, these data will be used to provide one line of evidence in analyzing the efficacy of the *in situ* delivery methods.

5.2.2 Utility and UXO Clearance

Standard underground utility clearance will be performed prior to the start of any intrusive subsurface work at each of the three sites. In addition, clearance of unexploded ordinances (UXOs) will be conducted at the Lake City AAP Site 17D due to the historical UXO presence at the site. A local subcontractor will be used for both the underground utility and UXO clearance at each of the sites.

Table 5.1: **Conceptual Experimental Design**

Site name	Lithology	Depth of interest (ft bgs)	Objectives	Hydraulic permeability enhancement - Geotactical	Pneumatic permeability enhancement - ARS Technologies	Sampling & Analysis
Camp Pendleton Site 1115	Clay stone/silt stone	20-40	Evaluate HPET performance at a claystone/siltstone site	• HPET with persulfate, guar, and sand • 1 permeability enhancement point • 5 depth intervals	• None	• VOCs and water quality parameters in existing MWs • Lithologic data • Pre-demonstration VOCs, sulfate, and water quality parameters in existing and new MWs • Pre-demonstration pumping tests • Tilt-metering during permeability enhancement • Post-demonstration sulfate, persulfate, and visual observation in confirmation boreholes • Post-demonstration VOCs, sulfate, persulfate, and water quality parameters in existing and new MWs • Post-demonstration pumping tests
Lake City AAP Site 17D	Residuum/ weathered shale	15-35	Direct comparison between PPET and HPET at an unconsolidated, low permeability site & comparison between the permeability enhancement technologies and conventional injection techniques previously employed at the site	• HPET with EVO, guar, and sand • 1 permeability enhancement point • 5 depth intervals	• PPET with EVO • 3 permeability enhancement points • 5 depth intervals	• VOCs and water quality parameters in existing and new MWs • Lithologic data and ERT • Pre-demonstration VOCs, MEEA, TOC, and water quality parameters in existing and new MWs • Pre-demonstration pumping tests and ERT • Tilt-metering during permeability enhancement • Post-demonstration TOC, ERT, and visual observation in confirmation boreholes • Post-demonstration VOCs, MEEA, and water quality parameters in existing and new MWs • Post-demonstration pumping tests
Grand Forks AFB Site TU504	Silty clay	10-20	Direct comparison between HPET and conventional injection techniques previously implemented at the site	• HPET with EVO, without guar, and without sand • 4 to 8 permeability enhancement points • Up to 3 depth intervals	• None	• VOCs and water quality parameters in existing MWs • Lithologic data and ERT • Pre-demonstration VOCs, MEEA, TOC, and water quality parameters in existing and new MWs • Pre-demonstration pumping tests and pre-HF EC logging • Tilt-metering during permeability enhancement • Post-demonstration TOC, ERT, and visual observation in confirmation boreholes • Post-demonstration VOCs, MEEA, TOC, and water quality parameters in existing and new MWs • Post-demonstration pumping tests and post-demonstration EC logging

Key:

AFB: Air Force base

AAP: Army Ammunition Plant

bgs: below ground surface

EC: electrical conductivity

ERT: electrical resistivity tomography

ft: feet

HPET: hydraulic permeability enhancement technology

MEEA: methane, ethane, ethene, acetylene

MW: monitoring well

PPET: pneumatic permeability enhancement technology

TOC: total organic carbon

VOC: volatile organic compound
ZVI: zero valent iron

5.2.3 Baseline Sampling

Prior to the *in situ* delivery of amendments at each of the three sites, subsurface conditions will be characterized using existing and installed temporary monitoring wells in the vicinity of the proposed injection areas. The installation and sampling of the new monitoring wells will occur prior to the permeability enhancement mobilization. **Table 5.2** provides a list of existing monitoring wells that will be sampled at each site prior to and after the injections take place, as well as the number of temporary monitoring wells that will be installed prior to site work. The existing monitoring wells were selected because they are located upgradient or downgradient of the demonstration areas, screened approximately within the target permeability enhancement intervals, and in some cases, screened below the confining unit of the deepest permeability enhancement intervals to allow for monitoring of vertical permeability enhancement. The temporary wells will be abandoned once post-injection sampling has been completed. To account for the existing geochemical conditions at each of the sites, baseline analyses for pH, ORP, temperature, dissolved oxygen, alkalinity, ferrous iron, sulfate, methane, ethane, ethene, and acetylene (MEEA), conductivity, and turbidity will be done for each well. In addition, baseline analyses of VOCs will be completed for each monitoring well to determine the contaminant distribution prior to the *in situ* delivery activities. It should be noted that in some cases the sampling of the existing monitoring wells will be done by the onsite staff or subcontractors. The sampling work will be scheduled so that the existing and new sampling wells will be sampled concurrently to the extent practicable.

Table 5.2: Baseline Sampling Locations

Site	Existing Monitoring Wells to be Sampled	Number/Depth of Installed Temporary Wells
Camp Pendleton Site 1115	S1-MW16, S1-MW13, S1-MW27, S5/8/9/17-MW50, S1-MW28, S1-MW19, S2-MW1, and S2-MW5	2/20-40 ft bgs
Lake City AAP Site 17D	16MW076, 16MW077, 16MW103, 16MW028, and 16MW029	6/15-35 ft bgs
Grand Forks AFB Site TU504	3, 4, 5, 6, 9, 10, and 11	6/10-20 ft bgs

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The following sections detail the general design and layout of technology components pertinent to hydraulic and pneumatic permeability enhancement and required site equipment and permeability enhancement activities taking place for each site, as well as the tilt-meter geophysics, ERT, and EC logging confirmation activities. This section also discusses the soil and water management, site restoration, decommissioning, and documentation protocols that will apply across all three sites.

5.3.1 Camp Pendleton Site 1115

Hydraulic permeability enhancement, which uses fluid to cause a tensile parting within a soil or bedrock matrix for the purpose of expediting *in situ* remediation, will be performed at Camp Pendleton Site 1115. The primary objective of the technology demonstration at this site is to evaluate the hydraulic permeability enhancement performance at a site characteristic of a claystone/silt stone lithology. Permeability enhancement at this site will involve a high viscosity fracture fluid consisting of sand and guar to ensure the liquid persulfate amendment is distributed within sand-propped fractures. Details regarding the permeability enhancement equipment, aboveground and underground setup, and monitoring required for hydraulic permeability enhancement at this site are provided in the following sections.

5.3.1.1 Process Description

The EF9300 environmental hydraulic permeability enhancement unit will be used for the technology demonstration at Camp Pendleton Site 1115. The unit is self-contained with power, mixing tanks, and pumps mounted on a single skid. The EF9300 is outfitted with a high-output triplex pump capable of safely and efficiently pumping high solids, slurries, and some reactive agents. A real time data acquisition system is used to display and record permeability enhancement fluid pumping pressure and pump rate.

5.3.1.2 Aboveground Setup

The typical aboveground setup of the EF9300 permeability enhancement unit is illustrated in **Figure 5.1**. The operational area required for the unit is approximately 600 square feet, although it can be adapted to meet site-specific constraints.

Figure 5.1: Typical Setup of the EF9300 Hydraulic Permeability Enhancement Unit

5.3.1.3 Underground Setup

Direct push drilling or open borehole can be used to facilitate the underground setup of hydraulic permeability enhancement. In the former case, standard Geoprobe® 2-¼-inch inner diameter drill rods are used to drive proprietary permeability enhancement tools to the desired fracture initiation depth intervals. The permeability enhancement tools isolate a small vertical zone within the borehole. The top down emplacement method is used to ensure a discrete fracture is initiated at each depth. In areas where direct push drilling is not possible, air rotary, mud rotary, hollow stem auger, and sonic drilling methods can also be used to create an open borehole to facilitate hydraulic permeability enhancement. In this scenario, a straddle packer assembly is used to isolate the zones of interest. A drill rig or a hoist truck is required to help move the packer system in and out of the borehole. Once emplaced at the desired depth interval, the packer assembly is inflated to create an isolated zone within the borehole. Once permeability enhancement is initiated and the target permeability enhancement fluid volume has been pumped into the zone of interest, the packer assembly is deflated and lowered to the next depth as appropriate. CDM Smith understands that sonic drilling with a Geoprobe® 8140 has been successful at the Camp Pendleton Site 1115, thus hydraulic permeability enhancement via sonic drilling and top down fracture emplacement methodology will be utilized.

5.3.1.4 Permeability Enhancement Activities

A summary of relevant permeability enhancement activities to be performed at the Camp Pendleton Site 1115 is presented in **Table 5.3**. Prior to the permeability enhancement work, baseline groundwater sampling described in **Section 5.2.3** and well installation and development activities will be performed in Mobilizations 0 and 1, respectively. Lithologic data will be collected during the first two mobilizations. In Mobilization 2, pre-demonstration data including aquifer pumping test, VOCs, sulfate, and relevant water quality parameters will be collected. ERT will not be completed at Camp Pendleton Site 1115 due to the high background conductivity present in site groundwater. Analytical details are provided in **Section 5.4** and **Appendix B**. Upon completion of these data collection activities, the hydraulic permeability enhancement will commence. One hydraulic permeability enhancement point will be demonstrated at the Camp Pendleton Site 1115 as shown in **Figure 4.2**. Within that borehole, CDM Smith anticipates that up to 5 initiation points with a vertical spacing of approximately 3 ft will be initiated to target the contamination zone of interest between 20 and 40 ft bgs. It is estimated that approximately 585 gallons of the fracture fluid consisting of sand and guar will be introduced to each fracture initiation zone to achieve the desired ROI of approximately 25 ft. Following the sand emplacement, as much of the permeability enhancement fluid will be extracted as attainable, and the borehole will be completed as a 2-inch polyvinyl chloride (PVC) injection well. The screen interval will be determined based on the field results. Once developed, approximately 585 gallons of 5% (by weight) of persulfate will be injected into each enhancement interval.

Table 5.3: Mobilization Activities for Camp Pendleton Site 1115

Mobilization	Mobilization Activities	Data to be Collected
0	• Groundwater monitoring by Camp Pendleton	• VOCs and water quality parameters in existing monitoring wells
1	• Install and develop temporary wells (by Camp Pendleton) • Collect lithology data	• Lithologic data
2	• Collect pre-demonstration VOC data at temporary wells • Perform pumping tests • Perform hydraulic permeability enhancement • Collect permeability enhancement validation data	• Pre-demonstration VOCs, sulfate, and water quality parameters in existing monitoring and temporary wells • Pre-demonstration pumping tests • Tilt-metering during hydraulic permeability enhancement • Post-demonstration sulfate, persulfate, and visual observation in confirmation boreholes
3	• Post-demonstration performance monitoring • Perform post-demonstration tests • Abandon temporary wells	• Post-demonstration VOCs, sulfate, persulfate, and water quality parameters in existing monitoring and temporary wells • Post-demonstration pumping tests

Pressure and flow rate will be continuously monitored during fracture initiation and propagation. Hydraulic fractures are signified by a peak pressure followed by a sharp decrease to the propagation pressure as shown in **Figure 5.2**.

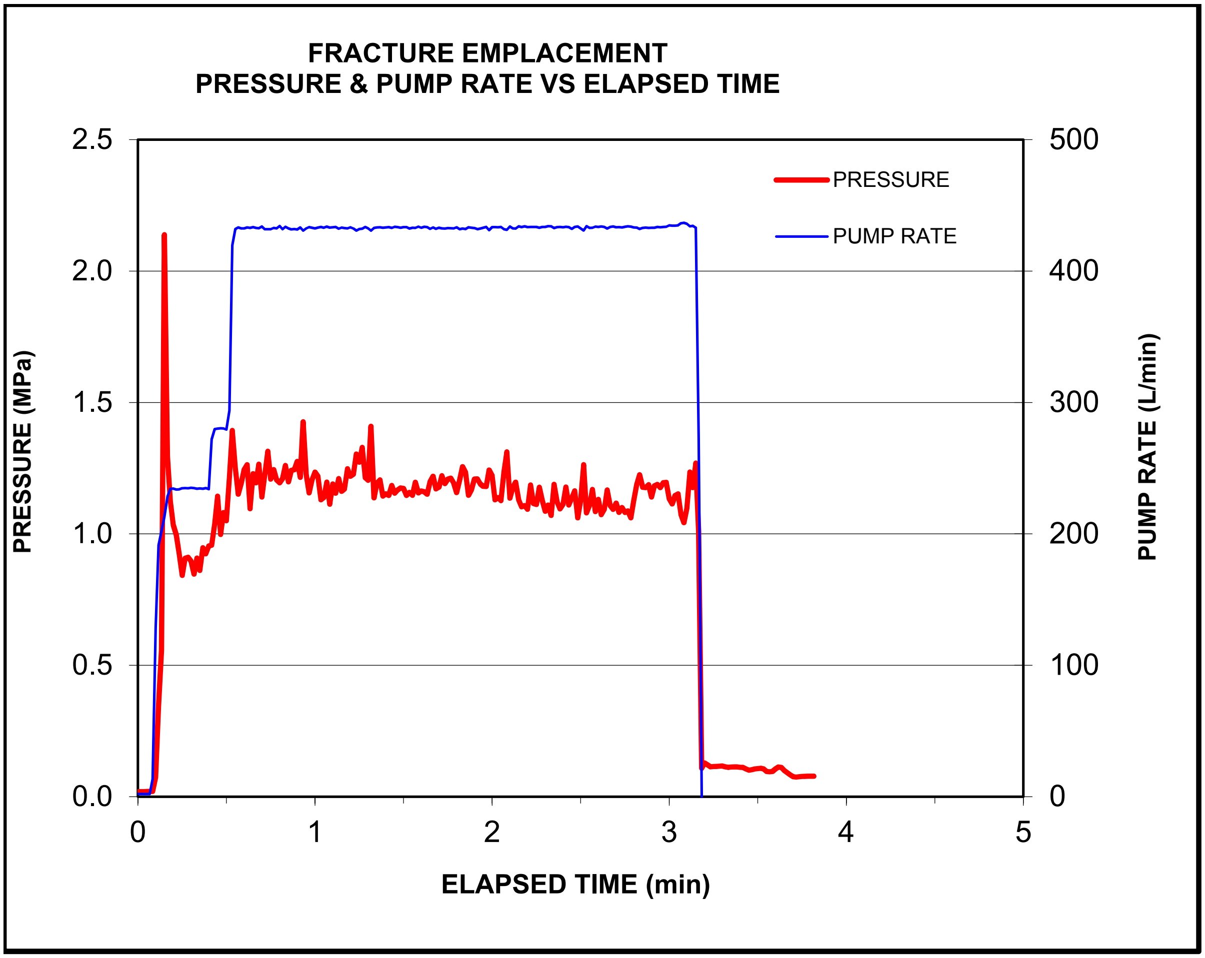

Figure 5.2: **Example Signature of a Fracture on a Pressure vs. Time Curve**

In addition to aforementioned operational parameters, tilt-meter mapping will be performed at the site during fracture initiation and propagation. An array of 10 to 12 surface-mounted tilt-meters will be set up in a concentric configuration surrounding the permeability enhancement borehole. A typical setup of tilt-meters during permeability enhancement is shown in **Figure 5.3**. As permeability enhancement commences, ground surface "tilt" data from each tilt-meter station is collected and stored.

Figure 5.3. Tilt-meter Setup with Dataloggers

Tilt-meter data collected in the field is subsequently analyzed to determine the characteristics of each fracture. Specialized visualization software is used to create an interactive 3-D model of the fracture network in context with the stratigraphy. This software provides a rotatable view of the fracture network as a whole or of individual fractures, and allows the user to create cross sections. A sample software rendering of a fracture network is graphically presented in **Figure 5.4**.

Figure 5.4: **Software Rendering of Fractures**

Following the technology demonstration, post-demonstration soil confirmation sampling will be performed. To minimize costs associated with multiple mobilization efforts, these post-permeability enhancement activities will be scheduled immediately after the permeability enhancement work is completed. Post-demonstration performance monitoring consisting of groundwater sampling for VOCs, sulfate, persulfate, and general water quality parameters will be conducted approximately one month and six months following the permeability enhancement work. Aquifer performance testing will also be performed one month after the permeability enhancement work has been completed.

5.3.2 Lake City AAP Site 17D

The primary objective of the technology demonstration at the Lake City AAP Site 17D is to compare the performance of hydraulic and pneumatic permeability enhancement directly at a contaminated site of low hydraulic conductivity. In both instances, EVO will represent the treatment amendment. Five depth intervals within a single hydraulic permeability enhancement point will be initiated. On the other hand, three pneumatic permeability enhancement points, each consisting of five depth intervals, will be attempted at the Lake City AAP Site 17D. Details regarding the permeability enhancement equipment, aboveground and underground setup, and monitoring requirements for the two permeability enhancement technologies are provided in the following sections.

5.3.2.1 Process Description

The EF9300 unit described in **Section 5.3.1.1** will be used for the hydraulic permeability enhancement technology demonstration at the Lake City AAP Site 17D. Guar and sand will comprise the hydraulic permeability enhancement fluid, followed by injection of approximately 2% EVO (by weight) in water solution. In contrast, a slurry containing EVO and water will be used for the demonstration of the pneumatic permeability enhancement technology at the site. The amendment fluid will be introduced into the subsurface via atomized liquid injection (ALI) (Kelly 2015). ALI is a process whereby a liquid amendment or liquid slurries are injected into a high-velocity, pressurized gas stream to cause the injected materials to be atomized. Using specialized equipment, the atomized permeability enhancement fluid will be introduced into the subsurface at pressures exceeding the natural *in situ* pressures (i.e., overburden pressure, cohesive stress, etc.) and at flow volumes exceeding the natural permeability of the formation. An injection tool consisting of a nozzle and a straddle packer assembly will be lowered into the borehole and permeability enhancement /injection will proceed in a bottom-up manner. Pressurized gas will be introduced to the formation for 10 to 15 seconds to propagate fractures into the formation. Once the fractures are initiated, the packers are deflated and the injection assembly is retracted upward to the next fracture interval of interest. This process is repeated until the entire treatment zone is addressed at that location.

This pneumatic permeability enhancement work results in the propagation of fractures outward at rates of approximately 2 meters per second (m/sec). Fracture propagation distances of 30 to 60 feet have been observed in fractured rock formations. Unconsolidated materials such as silts and clays typically exhibit fracture propagation distances of 20 to 40 feet. Ultimately, these fractures enhance the overall effective bulk permeability of the formation, thus allowing for more effective application of *in situ* treatment technology. A conceptual diagram of pneumatic permeability enhancement is shown in **Figure 5.5**.

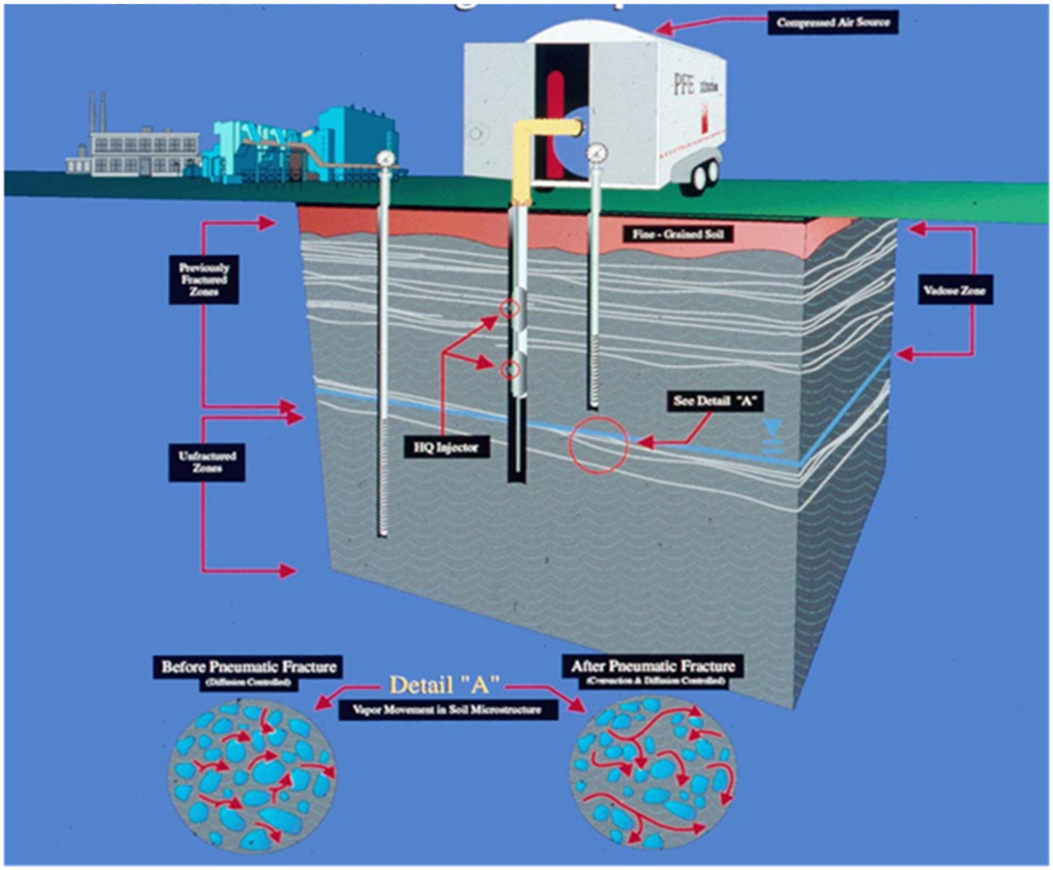

Figure 5.5: Conceptual Diagram of Pneumatic Permeability Enhancement

5.3.2.2 Aboveground Setup

The operational area required for the hydraulic permeability enhancement unit EF9300 is approximately 600 square feet, although it can be adapted to meet site-specific constraints. A pneumatic permeability enhancement unit of similar size will be used for the demonstration of pneumatic permeability enhancement at the site.

5.3.2.3 Underground Setup

A cased borehole approach via hollow-stem auger drilling will be used to facilitate demonstration of both the hydraulic and the pneumatic permeability enhancement technologies. In each scenario, permeability enhancement and injection will proceed in a bottom-up manner using a straddle packer system. Specifically, each permeability enhancement borehole will be drilled to the desired total depth for efficiency. Straddle packers will then be used to isolate and to ensure proper amendment delivery into each of the zones of interest. The permeability enhancement work will begin at the deepest interval and move upwards within the borehole as appropriate, hence the bottom-up notation.

5.3.2.4 Permeability Enhancement Activities

A summary of relevant activities to be performed at the Lake City AAP Site 17D is presented in **Table 5.4**. Prior to the permeability enhancement work, baseline groundwater sampling described in **Section 5.2.3** and well installation and development activities relevant to the hydraulic permeability enhancement will be performed in Mobilizations 0 and 1, respectively. Lithologic data will be obtained during drilling and well installation. In Mobilization 1, pre-demonstration data including ERT, aquifer pumping test, TOC, VOCs, MEEA, and relevant water quality parameters will be collected. Analytical details are provided in **Section 5.4** and **Appendix B**. Upon completion of these data collection activities, the hydraulic and pneumatic permeability enhancement activities will commence. One hydraulic permeability enhancement point and three pneumatic permeability enhancement points will be demonstrated at the Lake City AAP 17D site as shown in **Figure 4.8**. Within each permeability enhancement borehole, CDM Smith anticipates that up to 5 initiation points with a vertical spacing of approximately 3 ft will be initiated to target the contamination zone of interest between 15 and 35 ft bgs. The desired ROIs for pneumatic and hydraulic permeability enhancement are 10 and 20 ft, respectively.

Table 5.4: Mobilization Activities for the Lake City AAP 17D Site

Mobilization	Mobilization Activities	Data to be Collected
0	• Groundwater monitoring by LCAAP	• VOCs and water quality parameters in existing monitoring wells
1a & 1b	• Install and develop temporary wells • Collect lithology data • Collect pre-demonstration VOC data at temporary wells • Perform pumping tests • Perform hydraulic and pneumatic permeability enhancement • Collect permeability enhancement validation data • Install and develop new temporary wells post-demonstration, if necessary	• Lithologic data • Pre-demonstration VOCs, TOC, MEEA, and water quality parameters in existing monitoring and temporary wells • Pre-demonstration pumping tests and ERT • Tilt-metering during hydraulic and pneumatic permeability enhancement • Post-demonstration TOC, MEEA, ERT, and visual observation in confirmation boreholes
2/3	• Perform post-demonstration performance monitoring • Perform post- permeability enhancement pumping tests • Abandon temporary wells	• Post-demonstration VOCs, TOC, MEEA, and water quality parameters in existing monitoring and temporary wells • Post-demonstration pumping tests

Pressure and flow rate will be continuously monitored during both hydraulic and pneumatic fracture initiation and propagation. Hydraulic fractures are signified by a peak pressure followed by a sharp decrease in propagation pressure as shown in **Figure 5.2**. Similarly, an example of the typical pneumatic permeability enhancement pressure curve is illustrated in **Figure 5.6.** Tilt-metering and ERT monitoring and analysis will be performed at the Lake City AAP Site 17D. Post-demonstration ERT and soil confirmation soil sampling will be performed immediately following the technology demonstration. Groundwater performance monitoring will be conducted approximately one and six months following the technology demonstration. Aquifer performance testing will also be performed one month following the permeability enhancement work.

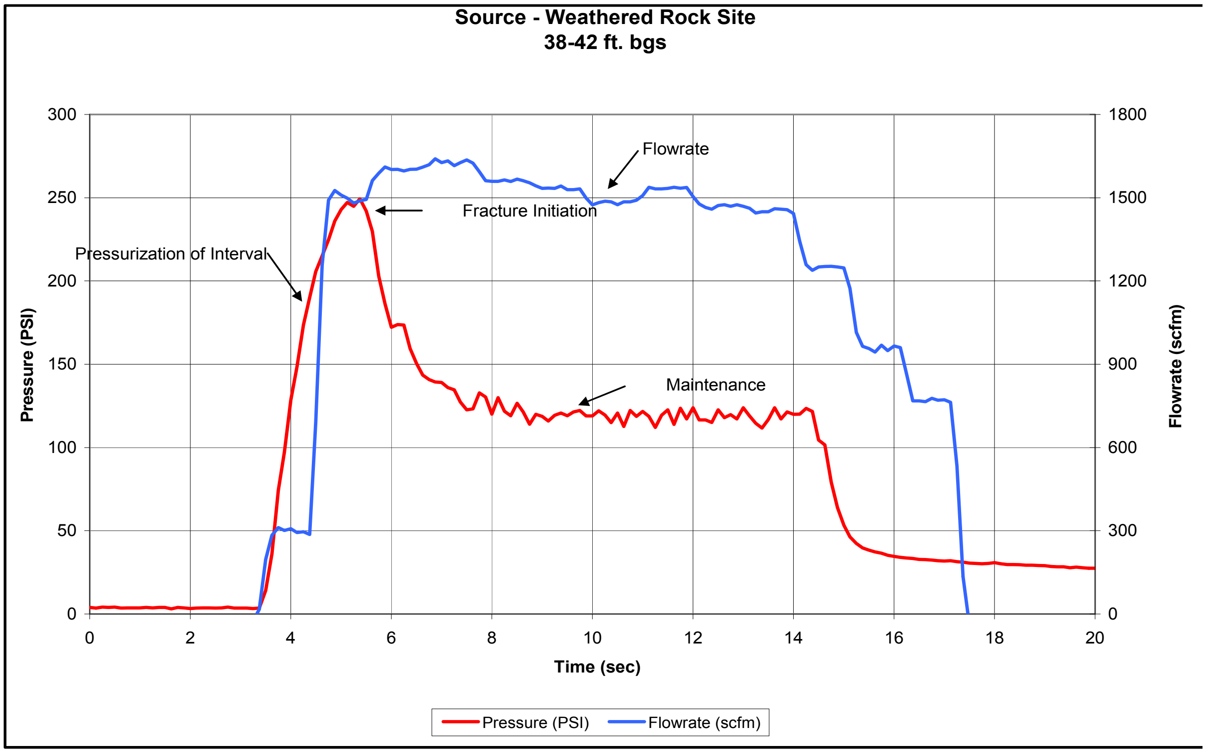

Figure 5.6: **Typical Pneumatic Permeability Enhancement Pressure Curve**

5.3.3 Grand Forks AFB Site TU504

Similar to Camp Pendleton Site 1115, hydraulic permeability enhancement will be performed at the Grand Forks AFB Site TU504. However, the hydraulic permeability enhancement demonstration will involve low-viscosity fracture fluid consisting of EVO alone to allow for a direct comparison between hydraulic permeability enhancement and conventional injection techniques previously implemented at the site. Up to three fracture initiation depth intervals will be implemented at each of the four to eight permeability enhancement points in the area of interest as shown in **Figure 4.10**. Details regarding the permeability enhancement equipment, aboveground and underground setup, and monitoring required for hydraulic permeability enhancement at this site are provided in the following sections.

5.3.3.1 Process Description

The EFI2000 environmental hydraulic permeability enhancement unit will be used for the technology demonstration at the Grand Forks AFB Site TU504. Powered mixing and pumping capabilities are incorporated into a skid platform small enough to fit in the back of a pickup truck. The mixing tanks are separate, although they are powered by and controlled from the skid. This permeability enhancement unit has been fabricated with corrosion-resistant materials to allow for delivery of a variety of chemical reagents. Equipped with two separate progressive cavity pumps and a small triplex used to facilitate permeability enhancement, the EFI2000 is capable of pumping solution amendments as either permeation solutions or generating hydraulic fractures. A real-time data acquisition system also allows for continuous measurement and recording of flow rate and hydraulic pressure.

5.3.3.2 Aboveground Setup

The typical aboveground setup of the EFI2000 permeability enhancement unit is illustrated in **Figure 5.7**. The operational area required for the unit is approximately 200 square feet, although it can be adapted to meet site-specific constraints. The area required for water and amendment storage varies between 100 and 300 square feet.

5.3.3.3 Underground Setup

Direct push drilling will be used to facilitate the underground setup of environmental hydraulic permeability enhancement at the site. Standard Geoprobe® 2-¼-inch inner diameter drill rods are used to drive proprietary permeability enhancement tools to the desired fractured initiation depth intervals. The permeability enhancement tools isolate a small vertical zone within the borehole. Top-down emplacement methodology will be used to ensure a discrete fracture is initiated at each depth.

Figure 5.7: **Typical Setup of the Permeability Enhancement Unit EFI2000**

5.3.3.4 Permeability Enhancement Activities

A summary of relevant activities to be performed at the Grand Forks AFB Site TU504 is presented in **Table 5.5**. Prior to the permeability enhancement work, baseline groundwater sampling described in **Section 5.2.3** and well installation and development activities relevant to the hydraulic permeability enhancement will be performed in Mobilizations 0 and 1, respectively. Lithologic information will be acquired during drilling and well installation. In Mobilization 2, pre- permeability enhancement data including aquifer pumping test, EC logs, TOC, VOCs, MEEA, and relevant water quality parameters will be collected. Analytical details are provided in **Appendix B**. Upon completion of these data collection activities, hydraulic permeability enhancement activities will commence. Between four and eight hydraulic permeability enhancement points will be demonstrated at Site TU504, as shown in **Figure 4.12**. Within each permeability enhancement borehole, CDM Smith anticipates that up to three fracture initiation points with a vertical spacing of at least 2 to 3 feet will be instigated to target the contamination zone of interest between 10 and 20 feet bgs. Assuming an effective porosity of 7.5%, it is estimated that between approximately 265 and 600 gallons of the fracture fluid consisting of 5% (volume/volume) of EVO will be introduced to each fracture initiation zone. The fracture fluid volume calculations are shown in **Appendix C**.

Table 5.5: Mobilization Activities for Grand Forks AFB Site TU504

Mobilization	Mobilization Activities	Data to be Collected
0	• Groundwater sampling by Grand Forks AFB	• VOCs water quality parameters in existing monitoring wells
1	• Install and develop temporary wells • Collect lithology data	• Lithologic data
2	• Collect pre-demonstration data at temporary wells • Perform pumping tests • Perform hydraulic permeability enhancement • Collect permeability enhancement validation data • Install and develop temporary wells post-permeability enhancement	• Pre-demonstration VOCs, TOC, MEEA, and water quality parameters in existing monitoring wells and temporary wells • Pre-demonstration pumping tests • Pre- and post-demonstration EC logging • Tilt-metering during hydraulic permeability enhancement • Post-demonstration TOC, visual observation in confirmation boreholes
3/4	• Post- demonstration performance monitoring • Perform post- demonstration pump test • Abandon temporary wells	• Post-demonstration VOCs, TOC, MEEA, and water quality parameters in existing monitoring wells and temporary wells • Post-demonstration pumping tests

Continuous measurement and recording of hydraulic pressure and flow rate along with tilt-meter monitoring will be performed during hydraulic permeability enhancement at the site similar to Camp Pendleton Site 1115 and Lake City AAP Site 17D. Soil confirmation sampling and ERT will be performed upon completion of the permeability enhancement work. Groundwater performance monitoring will be conducted approximately one and six months following the permeability enhancement work. Aquifer performance testing will also be conducted one month after the permeability enhancement work has been completed.

5.3.4 Soil and Water Management and Site Restoration

Any residuals generated during drilling and during the technology demonstration will be handled and disposed of in an appropriate manner. Residuals expected to be generated from this work include water during drilling, well development, and equipment decontamination; purge water from sampling; drill cuttings; field test kit wastes and sampling equipment decontamination wastes; and personal protective equipment.

Water generated during the demonstration will be stored temporarily in a storage tank or drums and then disposed of in the onsite treatment system, if applicable, or sent to an appropriate disposal facility depending on water characterization results. Soil generated during well installation will be stored in a covered bin on site. Previous soil and groundwater characterization data will be used to facilitate waste profiling and subsequent waste disposal as appropriate. All waste will be disposed of in accordance with local, state, and federal regulations.

5.3.5 Inspections and Documentation

A CDM Smith field representative will supervise all onsite demonstration activities. Field inspections will be performed to verify that all work is in conformance with the approved demonstration plan, Quality Assurance Project Plan (QAPP) (**Appendix B**), and Health and Safety Plan (HASP) (**Appendix D**). Inspection of field activities will include but are not limited to the following:

- All boreholes and wells are properly drilled, constructed, developed, and abandoned in accordance with not only the aforementioned project-governing documents but also with all local, state, and federal regulations
- Leak and pressure testing of the permeability enhancement equipment and accessories as appropriate to ensure safety of all field personnel and integrity of the high-pressure injection system
- Health and safety briefing is held daily and appropriate monitoring is performed
- All field activities including well construction, permeability enhancement, and monitoring are documented

Field documentation will consist of inspection reports, photographic records, observation and testing data sheets, well installation, construction, and development logs, and a brief daily oversight email report. Relevant aspects of the demonstration project will be photographically documented. All photographs will be identified by location, date, time, and a brief description.

The field representative will maintain a field copy of the approved demonstration plan, QAPP, and HASP for the purposes of documenting any deviations. Copies of all change orders, notes, sketches, and memoranda will be available for reference.

A completion summary report will be prepared after the *in situ* amendment delivery system has been implemented at the three sites. This report will include a description of the field activities, copies of field reports, and well boring and construction logs. The report will also include any additional recommendations and lessons learned for successful implementation of these types of *in situ* delivery systems.

5.3.6 Health and Safety

Site personnel are expected to abide by the regulations put forth in the HASP (**Appendix D).**

5.4 SAMPLING PLAN

Details regarding the sampling plan for this demonstration project are provided in **Appendix C**. In summary, up to five mobilizations are planned to encompass all pre- and post-demonstration activities. Mobilization 0 is designed for collection of groundwater data in existing monitoring wells located in close proximity to the demonstration areas. The objective of mobilization 1 is to install temporary wells to support the upcoming permeability enhancement work and to collect lithologic data. The objectives of mobilization 2 are to collect pre-demonstration VOCs and hydraulic data at the temporary wells, to perform the permeability enhancement work, and to collect data to validate the permeability enhancement work. Mobilizations 3 and 4 will focus on collection of post-demonstration data at all three sites approximately one and six months, respectively, following the permeability enhancement work. In some cases mobilizations may be combined, and some pre- and post-enhancement groundwater monitoring will be performed by site representatives.

A sampling program consisting of collection of soil, groundwater, hydraulic, and geophysics data will be implemented as part of this technology demonstration. The rationale for each selected groundwater analyte is presented below:

- VOCs: Collection of pre- and post-demonstration VOC data will be used to evaluate the remedial impacts of permeability enhancement at the contaminated sites.
- MEEA: Accumulation of methane is indicative of strongly reducing and methanogenic conditions, which are conducive to reductive dechlorination. Ethane and ethene are innocuous products of the reductive dechlorination of chlorinated solvents. Acetylene is the by-product of ZVI-mediated *in situ* chemical reduction (ISCR) reactions.
- TOC: Additions of carbon-based amendment (i.e., EVO) into the subsurface will correspond to an increase in TOC concentrations; thus TOC can be used as the direct evidence of EVO delivery.
- Chloride: As chlorine atoms are removed from parent chlorinated compounds, chloride concentrations can noticeably increase; thus chloride can be used to track contaminant degradation depending on site-specific background chloride and chlorinated VOC concentrations.
- Sulfate and nitrate: Sulfate and nitrate are electron acceptors that are consumed when highly reducing conditions are developed in the presence of a carbon-based amendment or an ISCR reagent.
- Sulfate and persulfate: Sulfate and persulfate will be monitored pre- and post-delivery at Camp Pendleton Site 1115 to evaluate distribution of persulfate into the subsurface during injection.

Field parameters including pH and conductivity will be collected concurrently with aforementioned groundwater analytes. The rationale for measuring such parameters is as follows:

- pH: pH is a general groundwater quality parameter that is easy to measure and can be used to evaluate potential adverse impacts of the persulfate oxidant on the aquifer.
- Conductivity: Conductivity can be used to evaluate oxidant and tracer transport and distribution within the aquifer.
- Dissolved oxygen (DO): Similar to nitrate and sulfate, DO is consumed under highly reducing conditions.
- ORP: Additions of an ISCR reagent such as ZVI or an EAB reagent such as EVO will result in changes in the aquifer ORP. Such parameter will be monitored to evaluate amendment transport and geochemical changes.
- Ferrous iron: Ferrous iron is produced under anaerobic conditions and thus will be used to evaluate changes in reduction potential.
- Turbidity: Another general water quality parameter that can be used to assess stability during low-stress, low-flow groundwater sampling as well as to detect presence of an amendment such as EVO.

The rationale for soil analytes is as follows:

- TOC: It may be very difficult to visually detect the presence of diluted EVO in a soil core and therefore composite soil samples will be collected and analyzed for TOC to confirm amendment delivery.
- Sulfate and persulfate: Similar to EVO, visual observation of persulfate may be challenging. Significant elevation in total sulfur concentrations and presence of persulfate is indicative of persulfate delivery.

Collection of all lithologic and analytical data and associated sampling activities will be performed in accordance with CDM Smith's technical standard operating procedures (TSOPs) (**Appendix E**). Specifically, soil samples will be collected using split-spoon or core barrel methodology while a low-stress, low-flow groundwater sampling technique will be used for collection of groundwater samples. CDM Smith will be responsible for collection of soil and groundwater samples at new boreholes or wells installed to support the demonstration project. CDM Smith or onsite staff or subcontractors at each of the three selected sites will perform groundwater sampling at the existing monitoring wells. CDM Smith anticipates the new monitoring wells developed upon completion of all permeability enhancement work will be incorporated into the three sites' existing monitoring programs for the duration of the demonstration project and will be subsequently abandoned if desired. In addition, all tilt-metering, EC logging, and ERT activities will be performed by the appropriate subcontractors using their respective TSOPs. Specifications regarding the sampling and analysis plan for this demonstration project are provided in **Appendix C**.

5.4.1 Quality Assurance and Quality Control (QA/QC)

The container and preservative requirements are shown in **Table 5.6**. Analytical methods and reporting limits are shown in **Tables 5.7** to **5.13**. It should be noted that although specific laboratories are listed in these tables, laboratories to be used for this demonstration project will be procured using federal guidelines. Similar reporting limits and associated quality QA/QC performance criteria are to be expected, however. Quality assurance sampling will include trip blanks, field duplicates, and temperature blanks. Field duplicates will be collected at a frequency of 10 percent. Each cooler will contain a temperature blank and each cooler containing VOC samples will have a trip blank. Calibration of field equipment will be conducted as per manufacturers' or subcontractors' recommendations. Calibration of analytical equipment will follow the analytical laboratory's quality procedures. Details on QA/QC protocols and procedures including sample handling, calibration, sample documentation, and decontamination are described in further detail in **Appendix E**. The specific methods for calibration, decontamination, and sample documentation are also presented in **Appendix E**.

Table 5.6: Analytical Requirements

Analyte	Media	Analytical Methods	Container (number, size, and type)	Preservative Requirements	Holding Time
VOCs	Groundwater	SW 846 EPA 8260B	4 x 40-mL vials with Teflon-lined septum	Preserve with HCl to pH <2; Cool to 4^{o}C; no headspace; no bubbles.	14 days
Sulfate	Groundwater	EPA 300.0	1-250-mL polyethylene bottle	Cool to 4^{o}C	28 days
Chloride	Groundwater				
Nitrate	Groundwater				
Ferrous iron	Groundwater	HACH ferrous iron AccuVac® Ampoules	NA	Analyzed immediately	NA
TOC	Groundwater	EPA 9060/Walkley-Black	2 x 40-mL vial	H_2SO_4 to pH <2; Cool to 4^{o}C	28 days
MEEA	Groundwater	RSK 175	2 x 40-mL vial	Preserve with HCl to pH <2; Cool to 4^{o}C; no headspace; no air bubbles	14 days
Persulfate	Groundwater	Chemetrics persulfate test kits	NA	Analyzed immediately	NA
TOC	Soil	ALS method PSEP	4-oz glass jar	Cool to 4^{o}C	28 days
Sulfate	Soil	Chemetrics sulfate test kits	NA	Analyzed immediately	NA
Persulfate	Soil	Chemetrics persulfate test kits	NA	Analyzed immediately	NA
pH	Groundwater	Multi-parameter water quality meter	NA	Analyzed immediately	NA
DO	Groundwater		NA	Analyzed immediately	NA
Conductivity	Groundwater		NA	Analyzed immediately	NA
Turbidity	Groundwater		NA	Analyzed immediately	NA
Temperature	Groundwater		NA	Analyzed immediately	NA
ORP	Groundwater		NA	Analyzed immediately	NA

Key:

DO: dissolved oxygen
EPA: United States Environmental Protection Agency
HCl: hydrochloric acid
H_2SO_4: sulfuric acid

MEEA: methane, ethane, ethene, acetylene
mL: milliliter
NA: not applicable
^{o}C: degree Celsius
ORP: oxidation-reduction potential
Oz: ounce
TOC: total organic carbon
VOC: volatile organic compound

Table 5.7: Analytical Reference Limits for EPA Method 8260B

VOC	CAS Number	PAL* (µg/L)	Analytical Method		Achievable Laboratory Limits	
			MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
1,1,1-Trichloroethane	71-55-6	200	0.04	NP	0.25	1
1,1,2,2-Tetrachloroethane	79-34-5	1	0.2	NP	0.1	0.5
1,1,2-Trichloroethane	79-00-5	5	0.08	NP	0.25	1
1,1-Dichloroethane	75-34-3	5	0.03	NP	0.25	1
1,1-Dichloroethylene	75-35-4	6	0.2	NP	0.25	1
1,2,4-Trichlorobenzene	120-82-1	5	0.2	NP	0.5	2
1,2-Dichlorobenzene	95-50-1	600	0.05	NP	0.25	1
1,2-Dichloroethane	107-06-2	0.5	0.02	NP	0.25	1
1,2-Dichloropropane	78-87-5	0.5	0.02	NP	0.25	1
1,3-Dichlorobenzene	541-73-1	NA	0.05	NP	0.25	1
1,4-Dichlorobenzene	106-46-7	5	0.04	NP	0.25	1
1,2,4-Trimethylbenzene	95-63-6	NA	0.13	NP	0.25	1
1,3,5-Trimethylbenzene	108-67-8	NA	0.05	NP	0.25	1
2-Butanone	78-93-3	NA	NP	NP	2.5	10
2-Hexanone	591-78-6	NA	NP	NP	1.25	5
4-Methyl-2-Pentanone	108-10-1	NA	NP	NP	0.25	5
Acetone	67-64-1	NA	NP	NP	2.5	10
Benzene	71-43-2	1	0.03	NP	0.25	1
Bromodichloromethane	75-27-4	NA	0.03	NP	0.25	1
Bromoform	75-25-2	NA	0.2	NP	0.25	1
Bromomethane	74-83-9	NA	NP	NP	0.5	2
Carbon disulfide	75-15-0	NA	NP	NP	0.25	1
Carbon tetrachloride	56-23-5	0.5	0.02	NP	0.25	1
Chlorobenzene	108-90-7	NA	0.03	NP	0.25	1
Chloroethane	75-00-3	NA	NP	NP	0.5	2
Chloroform	67-66-3	NA	0.04	NP	0.25	1
Chloromethane	74-87-3	NA	0.05	NP	0.25	1

VOC	CAS Number	PAL* (µg/L)	Analytical Method		Achievable Laboratory Limits	
			MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
cis-1,2-Dichloroethylene	156-59-2	6	0.06	NP	0.25	1
cis-1,3-Dichloropropene	10061015	0.5	NP	NP	0.5	1
Dibromochloromethane	75-25-2	NA	0.07	NP	0.25	1
Ethylbenzene	100-41-4	300	0.03	NP	0.25	1
Naphthalene	91-20-3	NA	0.04	NP	0.5	2
Methylene chloride	75-09-2	NA	NP	NP	0.5	2
m, p-xylene	136777-61-2	NA	0.13	NP	0.5	2
Methyl tertiary butyl ether	1634-04-4	13	0.13	NP	0.25	1
o-xylene	95-47-6	NA	0.11	NP	0.25	1
Styrene	100-42-5	100	0.27	NP	25	1
Tetrachloroethylene	127-18-4	5	0.05	NP	0.25	1
Toluene	108-88-3	150	0.08	NP	0.25	1
trans-1,2-Dichloroethylene	156-60-5	10	NP	NP	0.25	1
trans-1,3-Dichloropropene	10061-02-6	NA	NP	NP	0.25	1
Trichloroethylene	79-01-6	5	NP	NP	0.25	1
Vinyl chloride	75-01-4	0.5	NP	NP	0.15	0.5
Trichlorofluoromethane	75-69-4	5	NP	NP	0.5	2

Key:

*: California MCLs were used to establish PALs as applicable

µg/L: microgram per liter

CAS: chemical abstract service

EQL: estimated quantitation limit
MDL: method detection limit
NP: not published
NA: not available
PAL: project action limit
RL: reporting limit

Table 5.8: **Analytical Reference Limits for EPA Method 300.0**

Analyte	**CAS Number**	**PAL (µg/L)**	**Analytical Method**		**Achievable Laboratory Limits**	
			MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
Sulfate	18785-72-3	NA	2.5	NP	0.330	1.0
Chloride	16887-00-6	NA	0.5	NP	0.170	0.33
Nitrate	14797-55-8	NA	0.25	NP	0.033	0.10

*<u>***Notes***</u>:

- µg/L: microgram per liter
- CAS: chemical abstract service
- EQL: estimated quantitation limit
- MDL: method detection limit
- NA: not available
- NP: not published
- PAL: project action limit

Table 5.9: Analytical Reference Limits for EPA RSK-175

Analyte	CAS Number	PAL (µg/L)	Analytical Method		Achievable Laboratory Limits	
			MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
Methane	98615-667-9	NA	5	NP	0.048	0.12
Ethane	74-84-0	NA	5	NP	0.14	0.21
Ethene	9002-88-4	NA	5	NP	0.15	0.20
Acetylene	74-86-2	NA	5	NP	0.15	0.20

Key:

µg/L: microgram per liter

CAS: chemical abstract service

EQL: estimated quantitation limit

MDL: method detection limit

NA: not available

NP: not published

PAL: project action limit

Table 5.10: Analytical Reference Limits for EPA Method 9060

Analyte	CAS Number	PAL (mg/L)	Analytical Method		Achievable Laboratory Limits	
			MDL (mg/L)	RLs (mg/L)	MDLs (mg/L)	EQLs (mg/L)
TOC	NA	NA	1	NP	0.250	0.680

Key:

CAS: chemical abstract service

EQL: estimated quantitation limit
MDL: method detection limit
mg/L: milligram per liter

NA: not available

NP: not published
PAL: project action limit
TOC: total organic carbon

Table 5.11: **Analytical Reference Limits for ALS Method PSEP**

Analyte	CAS Number	PAL (%)	Analytical Method		Achievable Laboratory Limits	
			MDL (%)	RLs (%)	MDLs (%)	EQLs (%)
TOC	7440-44-0	NA	1	NP	0.05	0.02

Key:
%: percent
CAS: chemical abstract service
EQL: estimated quantitation limit
NA: not available
NP: not published
PAL: project action limit
TOC: total organic compound

5.5 DATA ANALYSIS

Field forms will be stored in the project file and data will be entered into Microsoft® Excel as an electronic database. Analytical results from groundwater sampling will also be stored in the electronic database for tracking and analysis. Statistical analysis using summary statistics such as average, maximum, and minimum values; statistical examinations such as t-tests; linear correlations; and trend analysis of temporal groundwater data using Excel and Minitab® statistical software will be employed to determine correlation among parameters of interest and to evaluate if there exists a statistically significant difference between the pre- and the post-demonstration dataset.

During the technology demonstrations, surface tilt-metering data will be collected to provide a three-dimensional map of the induced fracture planes within the soil. ERT data will then be collected to verify the validity of the fracture maps. Temporary monitoring wells will be sampled at two events following the demonstrations, during which concentrations of relevant VOCs will be measured. All of these data will be evaluated to determine how *in situ* injection schemes reliably and predictably introduce treatment amendments to the subsurface and help reduce contaminant concentrations in groundwater and soils compared to traditional injection schemes. The monitoring data for the injection scheme at Lake City AAP Site 17D will also be used to illustrate the differences between the hydraulic and pneumatic permeability enhancement systems. These data may help determine the optimal operating conditions for the most substantial *in situ* delivery of treatment amendments to a range of soil architectures and hydraulic conductivities. Furthermore, these lines of evidence will be used to determine which of the employed monitoring tools provide meaningful information on the subsurface injections. In addition to these technical data, cost, ease of implementation, and level of effort data will be collected during the demonstration to facilitate development of the permeability enhancement technology selection guidance document.

6.0 COST ASSESSMENT

This section describes the financial parameters that will be acquired from this technology demonstration and how they will be used as cost bases for estimating full-scale implementation.

6.1 COST REPORTING

Table 6.1 presents an outline of costs that will be developed for full-scale implementation of the permeability enhancement technology. The general approach to obtaining these costs will be to first develop a design basis using demonstration data. Specifically, demonstration design and planning, implementation, operations and maintenance, and performance data as well as their associated costs will be used as the basis for estimating full-scale implementation costs.

Table 6.1: **Cost Tracking**

Cost Element	Type
Baseline Characterization	Groundwater sampling and analysis
	Pre-demonstration hydrogeological and geophysical testing
Design	Modeling
	Engineering design
	Permitting
Material Cost	Amendment/sand/guar
Equipment Cost	Equipment mobilization
Installation	Geophysical survey/utility locate
	Surveyor
	Driller/well installation & development
Monitoring	Tilt-metering/EC/ERT setup and analysis
Waste Disposal	IDW disposal
Operations and Maintenance Costs	Well maintenance/repair
	Driller
Long-term Monitoring	Groundwater sampling and analysis

6.2 COST ANALYSIS

This section describes the cost comparison between permeability enhancement technology and conventional *in situ* remediation technologies, development of cost bases for estimating full-scale implementation of the technology, primary cost drivers, and life cycle costs associated with the demonstration technology. Details pertinent to each of the aforementioned topics are provided below.

6.2.1 Cost Comparison

Cost data and parameters controlling cost collected during the demonstration will be applied to full-scale implementation of the technology. These would include factors such as site hydraulic conductivity, permeability enhancement radius of influence, amendment distribution and longevity, contaminant reduction, and secondary impacts of the permeability enhancement technology on groundwater quality of the aquifer. Costs for full-scale application of hydraulic and pneumatic permeability enhancement will be compared to the rough order-of-magnitude cost estimates associated with conventional remedial technologies previously or currently employed at the demonstration sites as appropriate. Example design parameters pertinent for full-scale application of these technologies are shown in **Table 6.1**. It should be noted that some of the parameters may be modified as appropriate to meet the cost basis criteria. The cost assessment will be performed on the different *in situ* technologies assuming similar treatment areas, hydrogeological settings, and aquifer characteristics.

6.2.2 Cost Basis

The following elements will be used in estimating the costs associated with full-scale application of permeability enhancement at a site.

6.2.2.1 Equipment Capital Cost

The equipment capital cost will be estimated assuming a full-scale application of permeability enhancement for treatment of groundwater contamination. CDM Smith will provide a budgetary capital equipment cost upon completion of the demonstration project. The cost associated with other ancillary equipment will be based on budgetary cost from appropriate vendors.

6.2.2.2 Engineering Design Cost

Site-specific hydrogeological data, contaminant type and distribution, remedial timeframe and objectives, and ease of access are among the most important parameters in estimating the preliminary and final design cost of a full-scale application of permeability enhancement technology at a site. The engineering design will be performed in accordance with all applicable local, state, and federal regulations.

6.2.2.3 Construction/Installation Cost

The estimated construction/installation cost associated with a full-scale application of permeability enhancement technology at a site will be prepared by CDM Smith. The construction cost will include acquisition of all necessary permits, installation of full-scale injection and monitoring wells, and installation and construction of support equipment and infrastructure.

6.2.2.4 Operations and Maintenance

The most significant operations and maintenance (O&M) cost is likely associated with periodic amendment injection and performance monitoring on an as-needed basis for a full-scale application of permeability enhancement. Equipment maintenance, repair, and replacement will also contribute to O&M cost. For the purpose of preliminary cost estimating, an assumption will be made upon completion of the demonstration project using the man hours per week required to set up, implement, and monitor the permeability enhancement work.

6.2.3 Cost Drivers

The anticipated cost drivers for implementation of permeability enhancement are construction, equipment mobilization, materials, and O&M. Primary O&M cost drivers are anticipated to include labor and general system maintenance activities.

6.2.4 Life Cycle Cost

The life cycle costs will be based on a five-year operating life of a full-scale remediation system aided by permeability enhancement technlogy. The costs will comprise capital, construction, material, and O&M costs. A five percent interest rate will be assumed in calculating the life cycle costs. Information gathered during the demonstration project including material and labor hour requirements, equipment mobilization costs, and maintenance and monitoring efforts will be used to calculate the expected life cycle costs of the full-scale remediation system.

7.0 SCHEDULE OF ACTIVITIES

The tentative project schedule is illustrated in **Figure 7.1**

ID	Task Name	Start	Finish
1	**Lake City Army Ammunition Plant Site 17D**	**Mon 11/2/15**	**Thu 3/3/16**
2	**Mobilization 1**	**Mon 11/2/15**	**Wed 11/25/15**
3	**Mobilization 1a**	**Mon 11/2/15**	**Wed 11/11/15**
4	Lithologic characterization	Mon 11/2/15	Tue 11/3/15
5	Drilling of permeability enhancement boreholes	Tue 11/3/15	Wed 11/4/15
6	Pre-enhancement soil sampling	Wed 11/4/15	Thu 11/5/15
7	Monitoring well installation & development	Fri 11/6/15	Fri 11/6/15
8	GW sampling at new monitoring wells	Mon 11/9/15	Mon 11/9/15
9	Pre-enhancement ERT	Tue 11/10/15	Tue 11/10/15
10	Pre-enhancement pumping tests	Wed 11/11/15	Wed 11/11/15
11	**Mobilization 1b**	**Thu 11/12/15**	**Wed 11/25/15**
12	Pneumatic permeability enhancement & tilt-meter monitoring	Thu 11/12/15	Mon 11/16/15
13	Post-enhancement soil confirmation sampling for pneumatic	Tue 11/17/15	Wed 11/18/15
14	Hydraulic permeability enhancement & tilt-meter monitoring	Tue 11/17/15	Tue 11/17/15
15	Post-enhancement soil confirmation sampling for hydraulic	Wed 11/18/15	Wed 11/18/15
16	Post-enhancement ERT for pneumatic	Thu 11/19/15	Thu 11/19/15
17	Post-enhancement ERT for hydraulic	Fri 11/20/15	Fri 11/20/15
18	Post-enhancement pumping tests for pneumatic	Mon 11/23/15	Mon 11/23/15
19	Borehole abandonment	Tue 11/24/15	Tue 11/24/15
20	Post-enhancement pumping tests for hydraulic	Wed 11/25/15	Wed 11/25/15
21	**Mobilization 2**	**Mon 12/28/15**	**Tue 12/29/15**
22	Post-enhancement GW sampling round 1	Mon 12/28/15	Tue 12/29/15
23	**Mobilization 3**	**Mon 2/29/16**	**Thu 3/3/16**
24	Post-enhancement GW sampling round 2	Mon 2/29/16	Mon 2/29/16
25	Well abandonment	Tue 3/1/16	Thu 3/3/16
26	**Camp Pendleton Site 1115**	**Mon 12/7/15**	**Wed 4/6/16**
27	**Mobilization 1**	**Mon 12/7/15**	**Mon 12/7/15**
28	Monitoring well installation & sampling (Camp Pendleton)	Mon 12/7/15	Mon 12/7/15
29	**Mobilization 2**	**Mon 1/4/16**	**Fri 1/8/16**
30	Drill permeability enhancement borehole	Mon 1/4/16	Tue 1/5/16
31	Complete pre-enhancement pumping test	Tue 1/5/16	Tue 1/5/16
32	Hydraulic permeability enhancement with sand & guar, with tilt meter monitoring	Wed 1/6/16	Wed 1/6/16
33	Installation and development of well in borehole	Wed 1/6/16	Wed 1/6/16
34	Complete persulfate injections	Thu 1/7/16	Thu 1/7/16
35	Post-enhancement soil confirmation sampling	Thu 1/7/16	Thu 1/7/16
36	Post-enhancement pumping test	Fri 1/8/16	Fri 1/8/16
37	**Mobilization 3**	**Mon 2/1/16**	**Wed 4/6/16**
38	Post-enhancement GW sampling round #1	Mon 2/1/16	Mon 2/1/16
39	**Mobilization 4**	**Mon 4/4/16**	**Wed 4/6/16**
40	Post-enhancement GW sampling round #2 (Camp Pendleton)	Mon 4/4/16	Mon 4/4/16
41	Well abandonment	Mon 4/4/16	Wed 4/6/16
42	**Grand Forks Air Force Base Site TU504**	**Mon 5/2/16**	**Thu 8/11/16**
43	**Mobilization 1**	**Mon 5/2/16**	**Mon 5/2/16**
44	Monitoring well sampling (Grand Forks Air Force Base)	Mon 5/2/16	Mon 5/2/16
45	**Mobilization 2**	**Tue 5/3/16**	**Fri 5/6/16**
46	Lithologic characterization	Tue 5/3/16	Wed 5/4/16
47	Monitoring well installation	Tue 5/3/16	Tue 5/3/16
48	Complete pre-enhancement pumping test	Tue 5/3/16	Tue 5/3/16
49	Hydraulic permeability enhancement with EVO, with tilt meter monitoring	Wed 5/4/16	Wed 5/4/16
50	Post-enhancement soil confirmation sampling	Thu 5/5/16	Thu 5/5/16
51	Post-enhancement pumping test	Fri 5/6/16	Fri 5/6/16
52	**Mobilization 3**	**Mon 6/6/16**	**Thu 8/11/16**
53	Post-enhancement GW sampling round #1	Mon 6/6/16	Mon 6/6/16
54	**Mobilization 4**	**Mon 8/8/16**	**Thu 8/11/16**
55	Post-enhancement GW sampling round #2 (Grand Forks Air Force Base)	Mon 8/8/16	Mon 8/8/16
56	Well abandonment	Tue 8/9/16	Thu 8/11/16

Figure 7.1: **Tentative Project Schedule**

8.0 MANAGEMENT AND STAFFING

The project Principal Investigator is Dr. Kent Sorenson. He will be supported by Michael Lamar for design, planning, installation and commissioning, and reporting. Nathan Smith will serve as the project manager. The permitting engineer and field team lead will be Dung Nguyen, located at CDM Smith's Denver, Colorado office. The organizational chart is presented in **Figure 8.1**. The project's points of contact are provided in **Appendix F**.

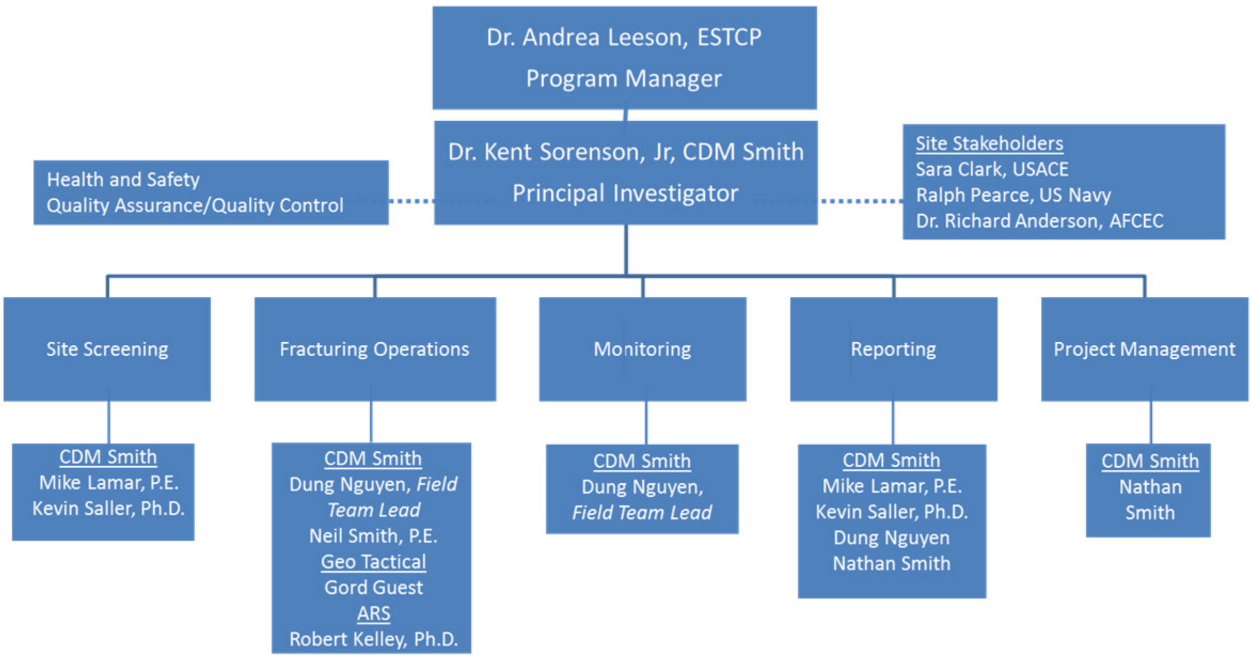

Figure 8.1: **Project Organizational Chart**

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APPENDICES

Appendix A	**Site Selection Memorandum**
Appendix B	**Quality Assurance Project Plan**
Appendix C	**Emplacement Volume Estimates**
Appendix D	**Health and Safety Plan**
Appendix E	**CDM Smith's Technical Standard Operating Procedures**
Appendix F	**Points of Contact**

APPENDIX A

Site Selection Memorandum

SITE SELECTION MEMORANDUM

A Rigorous Demonstration of Environmental Fracturing in Low Permeability Media

ESTCP Project Number ER- 201430

February 2015

1.0 OBJECTIVES OF THE DEMONSTRATION

ESTCP Project Number ER-201430 involves the demonstration and validation of using hydraulic and pneumatic fracturing to enhance the delivery of treatment amendments to low permeability soils. The four technical objectives of this demonstration/validation project are:

1. Demonstrate the amendment distribution capabilities of environmental fracturing techniques in three different low permeability geologic settings. Important parameters to be evaluated include emplaced volume, effective amendment distribution radius, vertical distribution, and architecture of emplaced amendments.
2. Demonstrate a novel, high resolution, non-invasive mapping technique for evaluating the parameters identified in Objective 1. High resolution tiltmeter mapping will be verified by vertical borehole data.
3. Collect sufficient performance and cost data to develop a concise guidance document to help remedial project managers (RPMs) and practitioners select and/or specify the optimal *in situ* delivery technique for a given low permeability site, as well as the monitoring approach to validate its performance quickly.
4. If possible, compare *in situ* delivery performance results using fracturing techniques to results from more conventional injection approaches.

This memorandum provides an evaluation of potential sites to be used for this demonstration and provides a recommendation of sites for this ESTCP demonstration. As a reminder, because this demonstration is intended to evaluate environmental fracturing in three different low permeability geologic settings, up to three sites will be recommended for use in the demonstration.

2.0 TECHNOLOGY DESCRIPTION

At sites with low hydraulic conductivity (approximately 10^{-5} centimeters per second [cm/s] or lower), specialized *in situ* delivery techniques are required to distribute amendments effectively. The three most prevalent methods in use today are pressurized direct-push injection (DPI), hydraulic fracturing, and pneumatic fracturing. Pressurized DPI is commonly used because of its low initial cost. However, distribution of amendments using this technique is often uncontrolled and unverified. Unfortunately, the high life-cycle cost of poor amendment distribution is seldom considered when selecting an appropriate *in situ* delivery strategy, and rapid diagnostic tools for assessing amendment distribution to facilitate real-time optimization of that strategy have not yet been well documented. In recent years, a number of technologies have been developed in an attempt to address the challenge of achieving an effective distribution of treatment amendments in low permeability and fractured media. These advances include hydraulic and pneumatic environmental fracturing, both of which are able to emplace amendments into low permeability media.

Hydraulic fracturing was modified from the oil and gas industry for environmental applications to enhance the remediation of contaminated soil and groundwater starting in the late 1980s. A high viscosity fluid is pumped into a borehole at a rate and pressure high enough to overcome the *in situ* confining stress and the material strength of a geologic formation, resulting in the formation of a fracture. The high viscosity of the fluid allows sand to be injected simultaneously to prop the fracture open for future injections or extractions, typically increasing the bulk hydraulic conductivity by about an order of magnitude. This approach can also be used to inject solid-phase amendments such as zero-valent iron (ZVI) over large areas. Hydraulic fracturing can be performed using almost any drilling technique, including direct-push. It enhances *in situ* remediation in low permeability formations by increasing bulk hydraulic conductivity and the radius of influence (ROI) of amendment delivery and shortening diffusion distances for stored contaminants.

Pneumatic fracturing utilizes a gas at flow volumes exceeding the natural permeability of the formation to generate high enough pressures to overcome the *in situ* confining stress and the material strength of a formation such that fractures are formed. The result is the enhancement of existing fractures and planes of weakness (for example, bedding planes) and the propagation of a dense fracture network surrounding the *in situ* delivery well. Once a geologic zone has been fractured, the injection of the amendment can be performed in an integrated process. For example, the amendment liquid or slurry can be blended into a nitrogen gas stream above ground and become atomized. Relatively low pressures are required to sustain the flow into the formation. The atomization apparatus is a downhole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the interval in between. Using this method and based upon the site formation and depth, the amendment might be distributed to a distance of 10 to 25 radial feet depending on site-specific conditions. As with hydraulic fracturing, this fracture network enhances the overall effective bulk permeability of the formation, extends the ROI for injection, and shortens diffusion distances, thus, enhancing *in situ* treatment.

The nature of fracturing induced by pneumatic techniques is thought to be quite different from hydraulically induced fractures**.** Conventional wisdom suggests that hydraulic fracturing has the advantage of a larger *in situ* delivery radius and propped fractures that can be used for multiple injections or extractions while pneumatic fracturing is expected to produce a more dense fracture network for the same cost but within a smaller zone. However, no studies have been published comparing and documenting the performance of either of these techniques at multiple, low permeability sites.

3.0 SITE SELECTION CRITERIA

The initial solicitation for potential field sites was conducted by emailing Department of Defense (DoD) personnel from the Navy, Air Force, and U.S. Army Corps of Engineers (USACE). Responses from 10 candidate sites were received representing Army, Navy, and Air Force sites.

Site selection was based on two primary criteria sets: threshold criteria and other criteria. Threshold criteria are minimum requirements that need to be met for the demonstration. Threshold criteria include soil hydraulic conductivity, depths to bedrock and water table, site lithology and vertical interval available for demonstration. “Other” criteria include contaminant presence in the groundwater, and site logistical concerns. **Table 3-1** provides a summary of the criteria used to evaluate the sites received for consideration.

3.1 THRESHOLD CRITERIA

In general, threshold criteria were applied for site selection to determine if critical site characteristics would be beneficial to the demonstration. The primary characteristics evaluated were the hydraulic conductivity, depths to bedrock from the injection point, lithology, and the vertical interval for demonstration.

Hydraulic Conductivity
Sites will have low-permeability lithologies (hydraulic conductivity ranging from approximately 10^{-5} to 10^{-7} cm/s) present at varying depths in order to allow for comparison of performance and cost of amendment delivery at varying depths. Sites with hydraulic conductivities greater than 10^{-5} cm/s may be acceptable if previous *in situ* injection activities indicate that effective distribution is limited by subsurface lithology.

Depths to Competent Bedrock
Sites ideally will have competent bedrock (i.e., bedrock not suitable for environmental fracturing technologies) >5 ft deeper than the lowest target injection interval to avoid any interference with drilling and fracturing activities.

Lithology
Each site selected will ideally have different types of low-permeability geologic settings (e.g., glacial till, alluvial or lacustrine deposits, fractured bedrock, or siltstone/sandstone) to provide evaluation of fracturing technologies in a variety of conditions. If two different geologic formations are present at one site, then that site may be used for two demonstrations to reduce overall mobilization costs.

Vertical Interval
The demonstration interval would ideally include a 10-15 ft thick (at minimum) saturated zone. The interval would also not extend within 4-5 ft of ground surface or bedrock.

3.2 OTHER CRITERIA

If threshold criteria were met, then the sites were evaluated further using "other" criteria to determine which sites had the most suitable characteristics for the demonstration. Other criteria included the presence of contaminants and site logistical concerns.

Contamination
Per conversations with ESTCP, expanding the original scope of the work to include contaminated sites is potentially allowable. The project team would prefer contaminated sites so that some treatment can be accomplished at the host site in addition to demonstrating injection parameters. This expansion would include future monitoring of the groundwater surrounding the injection sites to determine the short- and long-term efficacy of the injection events. Additionally, contaminated sites where conventional injection approaches have previously been applied provide the added benefit of a direct comparison of the effectiveness of the different strategies. Lastly, uncontaminated portions of sites typically have far less characterization,

putting more of a burden on this demonstration to generate sufficient data to meet performance objectives. Contaminated sites would therefore be looked upon more favorably.

Site Logistics

Several logistical factors are also considered to evaluate potential sites qualitatively. The work footprint has the potential to impact existing site activities, so areas with less traffic are more desirable. Downgradient receptors, such as drinking water wells and surface waters recharged by groundwater, would limit the ability for this demonstration to be performed because some *in situ* treatments cause adverse water-quality issues. Underground utilities in the area/vertical interval of interest may cause issues with the demonstration, both for fracturing and monitoring techniques. The ease of site access and the ability to schedule the work when necessary is considered as well as regulatory oversight and permitting. Concerns about the ease with which drilling activities can be conducted, and which types of training would be required of the field team, are also considered.

Table 3-1: Site Selection Criteria

	Metric	Preferred Value	Notes
Threshold Criteria	Hydraulic Conductivity	$<10^{-5}$ cm/s	Preference for sites with very fine soils or previous *in situ* injection work indicating poor distribution from previous treatment events
	Depth to Competent Bedrock	>5 ft below injection	Specialized fracturing techniques not available for this demonstration would be necessary to fracture hard rock
	Lithology	Clays and silts	1 site with clay or clay till, 1 siltstone/sandstone, 1 other (not hard rock)
	Vertical Interval	>10 ft saturated interval, >5 ft from ground surface	Needed to demonstrate ROI in saturated, low permeability soils
Other Criteria	Contamination	--	Preference for aged sites with contaminants dissolved into groundwater; i.e., no DNAPL present (for simplicity); preference for sites with data from previous conventional injections
	Previous *in situ* remediation activities	--	Preference for sites with previous *in situ* groundwater remediation activities
	Site Footprint	--	Preference for sites with minimal interaction with existing surface activities
	Downgradient Receptors	--	Minimal groundwater to surface water interactions
	Site Access	--	Few obstacles to scheduling field activities
	Permitting/Regulatory Concerns	--	Preference for states where permitting agency regularly allows injection of ZVI, EHC®, other electron donors, permanganate or persulfate; preference for states where environmental fracturing is expected to be allowed without significant discussion
	Drilling Activities/Training	--	Quick mobilization and training of drilling/field crews is preferred

ft – feet
cm/s – centimeters per second
DNAPL – dense non-aqueous phase liquid
DoD – Department of Defense
bgs – below ground surface
ROI – radius of influence

4.0 PERFORMANCE OBJECTIVES

Preliminary performance objectives are presented in **Table 4-1**. These objectives will be revised as appropriate in the technology demonstration plan. A description of each performance objective, specific data requirements and success criteria are detailed below.

Table 4-1: Preliminary Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantify horizontal and vertical distribution of emplaced fractures within target treatment volume	• At least three soil cores for each fracture initiation boring to a depth equaling the deepest fracture interval	• Visual presence/absence of emplaced materials (e.g., EHC®/ZVI, sand, or dye tracers) in soil cores will constitute success as these data will allow for qualitative assessment of amendment distribution
	• Tiltmeter mapping in a 360° concentric array around fracture borehole	• Successful application of tiltmeters will result in mapped injection planes of emplaced amendment within the target treatment volume. These data provide measurements of fracture orientation, extent, and thickness
	• Continuous downhole electrical conductivity (EC) logging (one site only)	• Successful application of EC will result in statistically different EC results in vertical intervals where fractures are present
	• Electrical Resistance Imaging (ERI) (one site only)	• Successful application of surface ERI will result in a mapping of the aerial distribution of emplaced fractures • Successful application of ERI may also result in observation of vertical distribution of fractures, although this will likely be masked by multiple vertical fractures in each borehole
Perform fracturing (hydraulic and pneumatic) to deliver target amendment dose within the target treatment volume	• Amendment volume emplaced • Soil cores • Tiltmeter mapping • EC logging • ERI	• The target amendment dose is delivered within the treatment area of interest • The majority of emplaced volume is emplaced within the required treatment area
Evaluate increase in aquifer permeability resulting from fracturing	• Aquifer pumping/slug testing conducted in treatment area before and after fracturing	• Successful conductivity enhancement is defined as a statistically significant increase in hydraulic conductivity that allows for improved use of wells for injection and/or extraction

Performance Objective	Data Requirements	Success Criteria
Evaluate effectiveness and accuracy of tiltmeter geophysics monitoring	• Tiltmeter fracture plane maps • Soil coring data • Direct-push EC data (one site only)	• Visual observation and/or EC detection of fractures confirm tiltmeter data within an acceptable range of error (to be determined during demonstration plan development)
Evaluate effectiveness and accuracy of ERI	• Pre-fracture surface ERI • Post-fracture surface ERI	• Observe statistically significant changes in electrical resistivity aerially from the fracture initiation point
Ease of use/implementation of each fracturing technology and performance monitoring strategy	• Level of effort (including availability of equipment) necessary to perform each injection technique • Reporting of problems encountered in the field (including surfacing), and ability to resolve problems quickly	• The relative availability of equipment and access to appropriate expertise, the level of oversight required, and the types of problems encountered and ease of resolution must be evaluated and documented for each fracturing and/or monitoring technique
Cost performance of each fracturing technology	• Costs for equipment, subcontractors, drilling, field oversight, and data evaluation of each fracturing technology	• Costs for equipment, subcontractors, oversight, and data evaluation must be captured and compared for each fracturing technology; the costs will be interpreted in the context of the actual distribution of amendments achieved
Evaluate efficacy of improved amendment delivery for treatment of site contaminants (more detailed performance objective/objectives during demonstration design, once funding allowances for contaminant monitoring are determined)	• Contaminant and geochemistry data from existing groundwater monitoring wells • Previous injection data • Newly installed monitoring wells	• Desired geochemical changes are observed in groundwater consistent with the type of treatment • Contaminant concentrations in groundwater are reduced by at least 50% relative to historical trends and most recent groundwater quality data • Fracturing techniques demonstrated to be more cost-effective over life cycle of remedy than conventional techniques based on site-specific data

4.1 PERFORMANCE OBJECTIVE: QUANTIFY DISTRIBUTION OF EMPLACED FRACTURES

4.1.1 Data Requirements

Data to be collected to quantify the distribution of the emplaced fractures within the target treatment volume include at least three soil cores from each fracture initiation boring to a depth equaling the deepest fracture interval, tiltmeter mapping using a 360° concentric array around fracture borehole, continuous downhole EC logging (one site only), and ERI (one site only).

4.1.2 Success Criteria

Success will be determined based on visual presence/absence of emplaced materials (e.g., EHC®/ZVI, sand, or dye tracers) in soil cores as these data will contribute to quantification of amendment distribution. Successful application of tiltmeters will result in mapped injection planes of emplaced amendment within the target treatment volume to provide measurements of fracture orientation, extent, and thickness. Successful application of EC and ERI activities will further aid in achieving this performance objective.

4.2 PERFORMANCE OBJECTIVE: PERFORM FRACTURING WITHIN THE TARGET TREATMENT VOLUME

4.2.1 Data Requirements

Analysis of the amendment volume emplaced, as well as post-injection sampling of soil cores, tiltmeter mapping, EC logging, and ERI will be completed to determine the extent of the injection fracture networks in the target treatment zone.

4.2.2 Success Criteria

A target amendment dose that is delivered into the intended treatment volume (not into surrounding areas) would be considered a successful *in situ* delivery.

4.3 PERFORMANCE OBJECTIVE: PERMEABILITY ENHANCEMENT FROM FRACTURING

4.3.1 Data Requirements

Data to be collected to evaluate the increase in permeability from the fracturing activities include aquifer pumping or slug tests conducted in the treatment area before and after fracturing.

4.3.2 Success Criteria

A success criterion for the enhancement of aquifer hydraulic conductivity is defined as a statistically significant increase in hydraulic conductivity that allows for improved use of wells for injection and/or extraction.

4.4 PERFORMANCE OBJECTIVE: EVALUATE EFFECTIVENESS AND ACCURACY OF TILMETER GEOPHYSICS MONITORING

4.4.1 Data Requirements

Tiltmeter fracture plane map data will be collected to compare against collected soil cores and direct-push EC data to evaluate the success criteria.

4.4.2 Success Criteria

Success criteria for the tiltmeter geophysics monitoring include visual observation of fracture location within the acceptable range of error (to be determined during demonstration plan development).

4.5 PERFORMANCE OBJECTIVE: EVALUATE EFFECTIVENESS AND ACCURACY OF ERI

4.5.1 Data Requirements

Background ERI values of the native lithology will be collected for comparison to post-fracturing activities.

4.5.2 Success Criteria

Success would be defined as observing a statistically significant increase in ERI results relative to the baseline.

4.6 PERFORMANCE OBJECTIVE: EASE OF USE/IMPLEMENTATION

4.6.1 Data Requirements

Once fracturing activities are completed, data on the level of effort (including the availability of equipment) necessary to perform each injection technique will be collected. These data include reporting of problems encountered in the field, and the ability of field crews to resolve problems quickly.

4.6.2 Success Criteria

The success of this objective requires evaluating and documenting the relative availability of equipment, access to appropriate expertise, the level of oversight required, and the types of problems encountered and ease of resolution for each fracturing and/or monitoring technique.

4.7 PERFORMANCE OBJECTIVE: COST PERFORMANCE OF TECHNOLOGIES

4.7.1 Data Requirements

Data to be collected for evaluating the cost performance of each fracturing technology include costs for equipment, subcontractors, drilling, field oversight, and data evaluation.

4.7.2 Success Criteria

The success of this objective requires that the costs for equipment, subcontractors, oversight, and data evaluation are captured and compared for each fracturing technology. The costs will be interpreted in the context of the actual distribution of amendments achieved.

4.8 PERFORMANCE OBJECTIVE: ENHANCED TREATMENT OF SITE CONTAMINANTS

4.8.1 Data Requirements

Data to be gathered for evaluating the efficacy of improved amendment delivery for the removal of site contaminants includes the post-injection collection and analysis of groundwater samples for geochemistry and contaminants from onsite monitoring wells. Where possible, data from previous conventional amendment injections will also be obtained and analyzed for site-specific comparison to fracturing techniques.

4.8.2 Success Criteria

Preliminary success criteria for this objective are that the geochemical conditions change as desired for the intended treatment, and the historically known contaminants in the groundwater within the vicinity of the fracturing emplacement are reduced by at least 50% in future sampling events. This could be modified based on site-specific conditions. Additionally, for sites with previous *in situ* injection data, cost comparisons should show that *in situ* delivery via fracturing is demonstrably more cost effective (over life-cycle) than conventional injections.

5.0 SITE SELECTION

As described in Section 3, evaluation of sites began with a screening step that considered certain threshold selection criteria. A total of 10 candidate sites were received for consideration from USACE, Air Force, and Navy personnel. Five sites passed the initial threshold criteria, and a tabulation of relevant information on these sites is provided in **Tables 5-1** and **5-2** in Section 5.1. A detailed description of the history, hydrogeology, contamination, and any previous remedial activities for the three retained sites is provided in Section 5.2. In the case of unforeseen circumstances, a backup site is discussed in detail in Section 5.3. The five sites that were considered but did not pass the initial threshold criteria are listed in **Attachment A**.

5.1 SITES EVALUATED

Using the criteria described in Section 3, five sites (out of 10) that passed the threshold criteria are evaluated in detail below: Camp Pendleton Site 1115, Camp Pendleton Site 1119, Lake City Army Ammunition Plant (LCAAP), Nike SL-10, and Grand Forks Air Force Base (AFB). The lithology and the depth to groundwater, which were used in the site screening process, are summarized in **Table 5-1**, and a summary of the screening criteria are presented in **Table 5-2**.

Table 5-1: Site-specific lithology and water-table data.

Site	Lithology	Anticipated Vertical Interval for Demonstration	Depth to Shallow GW
Camp Pendleton Site 1115	In the western part of the site: yellowish-brown to very pale brown silty sand to 30 ft bgs, greenish gray lean clay or silty lean clay with sand, light olive brown or olive yellow clayey silt, and dark grayish brown sandy silt from 30 ft to 60 ft bgs. Silt and clay beds also contain sand and are very stiff to hard.	30-45 ft bgs	10-30 ft bgs
Camp Pendleton Site 1119	Extending to 160 ft bgs, Holocene alluvium consists of fine and coarse-grained deposits (sands), moderately well consolidated, poorly sorted, permeable flood plain sediment, which contains some clays. Below, bedrock consists of interbedded sandstone, siltstone, and mudstone.	20-50 ft bgs	10-15 ft bgs
Lake City AAP, Area 17D	A silty clay overburden consists of both alluvial silty clays and fine silty sands, with a transitional weathered bedrock and residuum for 20 to 30 ft, followed by a silty clay and weathered shale residuum for 5 to 10 ft, followed by a bedrock unit consisting of massive to thin-bedded claystones and interbedded shales.	10-30 ft bgs	5-10 ft bgs
Nike SL-10	Clay and silt to 20 ft bgs, sandy silt from 20 to 30 ft bgs, and clayey silt to silty clay from 30 to 92 ft bgs.	20-40 ft bgs	5 ft bgs
Grand Forks AFB	Interbedded lacustrine and glacial units, boring logs indicate an initial shallow soil containing a dark brown sand to 2 ft bgs, followed by a medium stiff silty clay with potential sand lenses to approximately 22.5 ft bgs, followed by a gray clay unit with gravel and cobbles from 25-30 ft bgs.	5-20 ft bgs	3.7 to 8.3 ft bgs

Table 5-2: Summary of site-specific screening results.
Y indicates criteria were met, N were not met. Blank cells indicate data that was unavailable.

	Metric	Camp Pendleton Site 1115	Camp Pendleton Site 1119	Lake City AAP	Nike SL-10, IL	Grand Forks AFB
Threshold Criteria	**Hydraulic Cond. <10E-5 cm/s**	Y	**N**	Y	Y	Y
	Deep Bedrock		Y	Y	Y	Y
	Low K Lithology	Y	**N**	Y	Y	Y
	Needed Vertical Interval	Y	Y	Y	Y	Y
Other Criteria	**Contaminated**	Y	Y	Y	Y	Y
	Previous *in situ* remediation work	Y		Y		Y
	Site Footprint	Y	Y	Y		Y
	Downgradient Receptors	Y	N	Y		Y
	Easy Site Access	Y	Y	Y		Y
	Permitting Concerns	Y	Y	N		Y
	Training/Drilling Concerns	Y	Y	Y	Y	Y

5.2 RECOMMENDED SITES

Camp Pendleton Site 1115, Lake City AAP site 17D, and Grand Forks AFB site TU504 are recommended for this demonstration project as a majority of threshold and other criteria requirements were met. These sites have the desired low permeability soil architecture, saturated zone thicknesses, diverse soil lithology, and provide opportunities to test the fracturing technologies on a range of contaminated soils where other remediation techniques have previously been attempted.

Camp Pendleton Site 1115

The Camp Pendleton site map is provided in **Figure 5-1**, and the building and well layouts for Site 1115 are shown in **Figure 5-2**. Site 1115 is located on the eastern portion of Camp Pendleton, southwest of the intersection of Vandegrift Boulevard and 16th Street, and is approximately 14.5 acres in size. The site once served as a motor pool for vehicle maintenance and repair, painting, washing, and fuel service station for the base. A total of nine USTs were used at the site for these activities, which stored a range of fuels and solvents. All buildings and USTs have been removed or closed in place. The site is currently paved with asphalt and is used for vehicle and equipment staging.

Site 1115 is relatively flat and mostly slopes at a 5 to 7% grade toward the north. Elevations of the site range from 325 to 365 feet above mean sea level (amsl). There is no permanent surface water present at Site 1115, and rainfall drains to the west and also to the swales along 16th Street, which lies north of the site.

Figure 5-3 presents a west to east geologic cross section of Site 1115 soil lithology. The Santiago Formation is ubiquitous throughout the site and consists of mostly interbedded, low-permeability lightly cemented siltstone, sandstone, and mudstone. This formation has the characteristic of not being strongly indurated or cemented. The soils in the western part of the site consist of yellowish-brown to very pale brown silty sand, greenish gray lean clay or silty lean clay with sand, light olive brown or olive yellow clayey silt, and dark grayish brown sandy silt. Sand units in this part of the site consist of very fine to coarse-grained, poorly graded sand, silty sand, and clayey sand. Silt and clay beds also contain sand and are very stiff to hard. Shallow soils in this portion of the site consist of a fill material that is a yellow-brown, fine to medium-grained and poorly graded sand. In the eastern part of the site, bedrock consists of clay and silt beds. These clay and silt zones are mostly at depths between 15 and 30 ft bgs. The shallow low permeability units consist of silt and lean clay, whereas deeper units consist of fat and lean clays with fine laminations with interbedded lenses of unsaturated sand. At approximately 50 to 60 ft bgs, poorly graded sands, silty sands, and clayey sands are present, which are underlain by silt and clay.

A shallow groundwater zone exists across the site that varies in depth considerably due to surface topology, and contains an array of contaminants at roughly an order of magnitude higher in concentration than a deeper groundwater zone. On the western portion of the site near monitoring well S1-MW-16 (just south of former UST 1), the shallow and deep groundwater exist at roughly 30 and 52 ft bgs, respectively. At the eastern-central portion of the site, a groundwater mound underlies former Building 13162, which is underneath a nearly flat, depressed area of the site where water collects following rainfall. In this location (near former USTs 5/8/9), the shallow and deep groundwater are at depths of 23 and 49 ft bgs, respectively. The groundwater flow in the shallow zone is multi-directional with a 3-foot mound around monitoring well S5/8/9/17-MW4, but generally flows south and southwest beneath the western and southern portion, west beneath the east-central portion, and north and northeast in the northern portion of the site. Groundwater generally flows to the south and southwest in the lower aquifer. In the eastern portion of the site, the shallow groundwater generally occurs in low-permeability water bearing zones. These zones include silts and clays with thin saturated sand lenses. The western portion of the site has more permeable sand or silty sands. The saturated thickness of the western portion of the shallow aquifer is estimated to be 5 to 20 ft, with an average of 13 ft. The average thickness of the shallow aquifer on the eastern portion of the site is estimated to be 5 ft. The average thickness of the deeper aquifer is estimated to be 5 to 10 ft at a minimum. **Figure 5-3** also depicts the observed depths to the shallow and deeper water tables.

Contaminant migration from three distinct source areas has resulted in an extensive groundwater plume (**Figure 5-4**). This plume extends from a northwestern plume associated with UST Site 1 (former fuel service station), and a comingled plume associated with UST Sites 6/7 and 5/8/9, and former pipeline 17 on the eastern side of the site (see **Figure 5-2** for UST locations). Presently, the plumes have migrated several hundred feet from these source areas.

Approximately 30% (4 acres) of the site is underlain by groundwater with contaminants above MCLs or Residential Soil Screening Levels (RSLs).

From a total of 25 previous site investigations dating from 1986 to 2012, commonly detected contaminants in soil and groundwater above RSLs include 1,2-dichloroethane, 1,2-dibromoethane, arsenic, benzene, carbon tetrachloride, cis-DCE, ethylbenzene, methylene chloride, methyl tertiary butyl ether (MTBE), naphthalene, toluene, TCE, and VC. These contaminants are mostly found in the vicinities of the former USTs. Benzene is the primary groundwater contaminant in the northwestern part of the site (area of UST 1), while fuel-related compounds and chlorinated solvents are present on the eastern and central portions of the site. The presence of cis-DCE, VC, low oxidation reduction potential (ORP), and very high chloride concentrations indicate attenuation of chlorinated solvents within the plume. Geochemical conditions within the central parts of the plumes are predominantly anaerobic, which facilitate the attenuation of chlorinated species but reduce the degradation rates of petroleum constituents that degrade more quickly under aerobic conditions. Conversely, geochemical conditions at the plume edge are predominantly aerobic, which provide the conditions necessary for degradation of petroleum constituents but not for chlorinated compounds. Overall, these conditions likely maintain a steady-state for the plume extent, which will likely not migrate significantly farther than its current extent but will also not be reduced in size and/or concentration through only natural attenuation processes in a short timeframe. Total dissolved solids above 5,000 mg/L are also typically encountered in the monitoring wells.

LNAPL has historically been observed in monitoring wells near former UST 1 on the western side of the site and near USTs 5, 6, 7, 8, and 9 (**Figure 5-4**) on the eastern portion of the site. LNAPL has been observed in excess of 1 foot thick in 6 monitoring wells next to former USTs 5, 6, 7, 8, and 9 as well as near former buildings 13162 and 13165. In February 1996, 16 feet of LNAPL was observed in the shallow monitoring well MW40, the most observed at Site 1115. As of 2013, most of the visible LNAPL in these wells has been reduced to just sheens, with the exception of MW53 which reported 0.42 feet of LNAPL. Observed LNAPL is thought to exist in isolated pools perched above the shallow groundwater, providing a continued source of contamination to the groundwater. Diesel and gasoline range petroleum hydrocarbons were observed during a series of soil borings in 2009, which ranged in concentrations from non-detect to 14,000 milligrams per kilogram (mg/kg). There are currently 64 monitoring wells at the site that have provided the data showing the contaminant plume extent seen in **Figure 5-4**.

Previous treatment activities at the 1115 site include UST removals, soil excavations (UST Site 1 in January 2002), pilot-study SVE investigations, LNAPL recovery, and pilot-studies for delivery of organic substrates in 2010 and 2011. Results from removing 5,000 cubic yards of soil from the UST 1 area in 2002 suggest marginal impact to water quality, as leachable concentrations of total petroleum hydrocarbons gasoline range (TPH-G), BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), and naphthalene were still found in the sidewalls of the excavation. Monitoring well sampling following the delivery of organic substrates in 2010 indicate that reductive dechlorination was occurring where substrate was successfully delivered, but low permeability soils at the site were severely restricting downgradient migration of the injected substrate.

The target injection area for this demonstration is shown in **Figures 5-2, 5-3,** and **5-4**. The hydraulic fracturing activity will have five fracture initiation points delivered at a vertical spacing of 3 ft between the initiated fractures. The expected radius of influence of these hydraulic fractures is 15-25 ft. The fractures will be emplaced using direct-push fracturing tools using a top-down approach within each borehole. These procedures for the hydraulic fracturing activities apply for each of the three selected sites, and are subject to slight modifications depending on specific site conditions. The section of the Site 1115 subsurface highlighted in **Figures 5-2, 5-3, and 5-4** was selected for this demonstration because it has the required low permeability lithology and saturated zone interval, provides an opportunity to test this technology on contaminated soils, and provides an acceptable distance from the screened intervals of nearby wells.

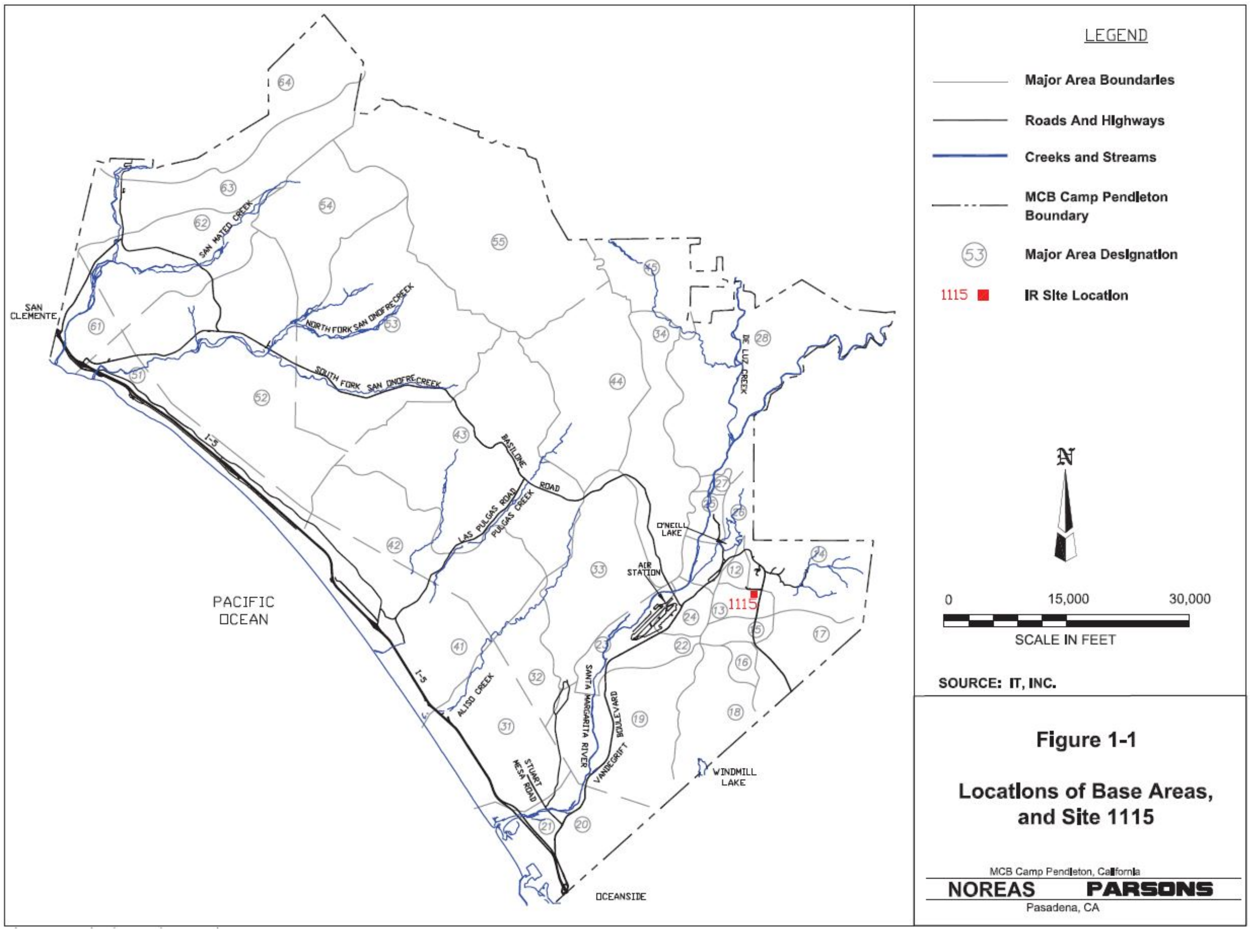

Figure 5-1: Camp Pendleton site map with Site 1115 in red.

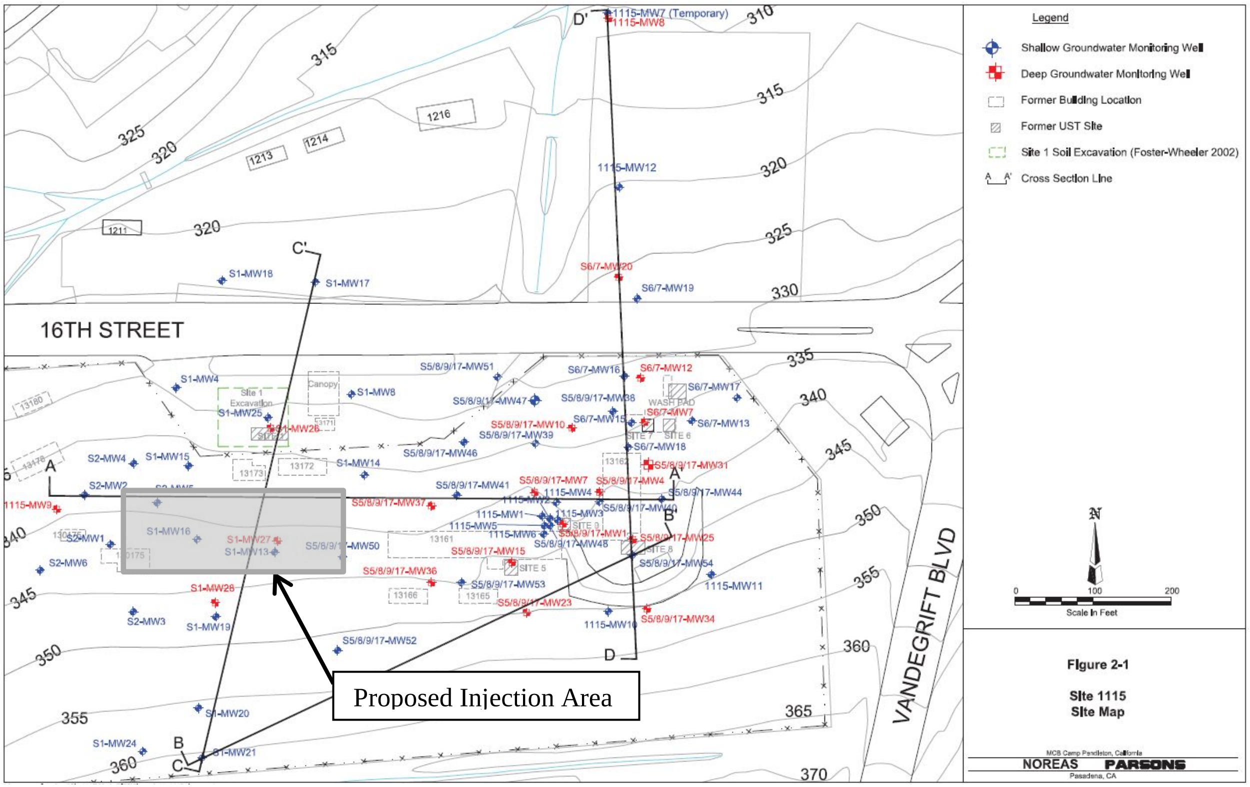

Figure 5-2: Camp Pendleton Site 1115 building and well layouts with ground elevations.

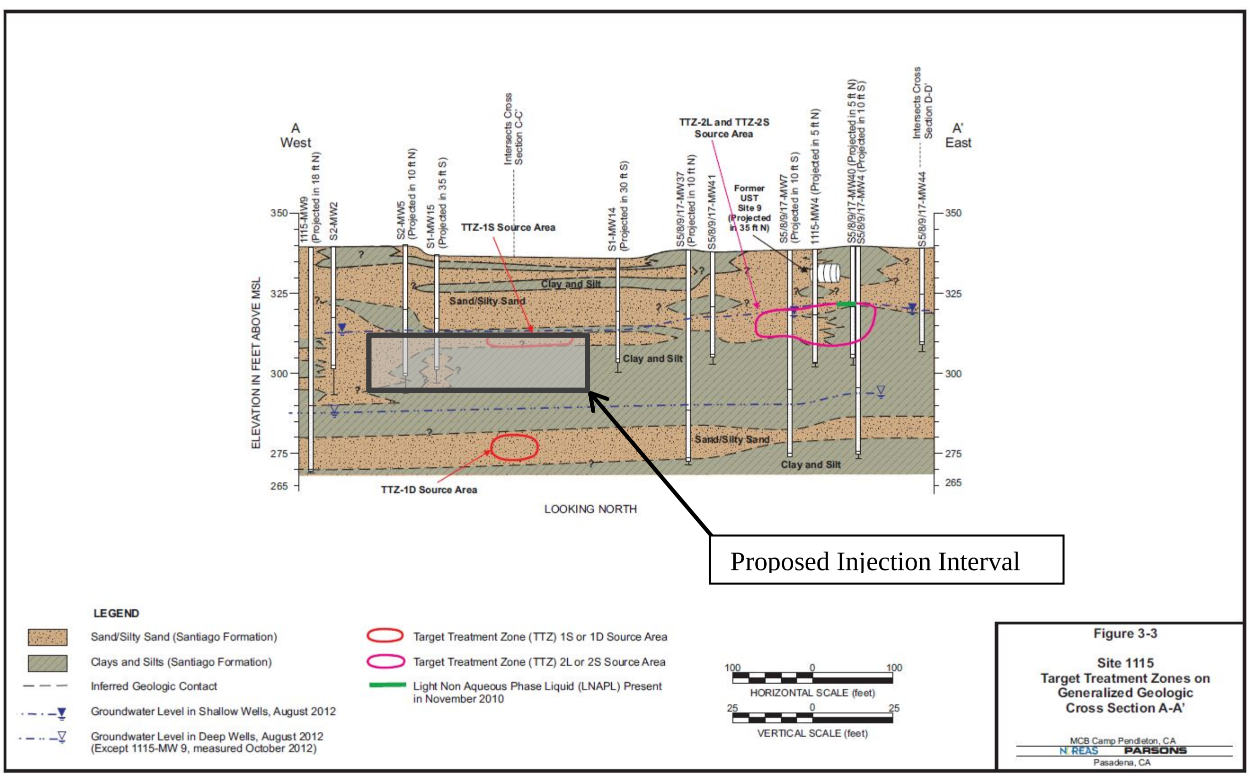

Figure 5-3: Camp Pendleton Site 1115 cross-section A-A lithology (west-east).

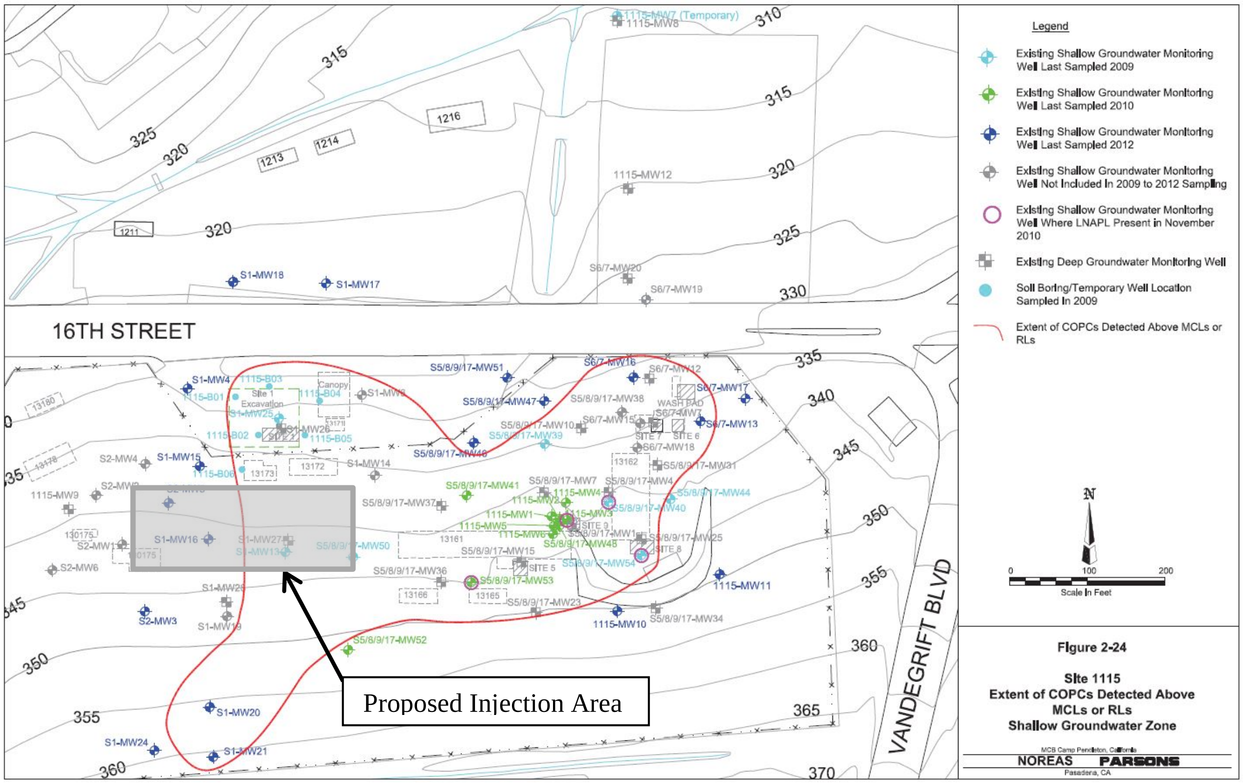

Figure 5-4: Camp Pendleton Site 1115 contaminant plume extent in shallow wells (2012).

Lake City AAP site 17D

LCAAP is located in northeastern Independence, Missouri. The site was established in December 1940 for manufacturing and testing of small caliber ammunition for the U.S. Army. LCAAP has been in continuous operation except for a single 5 year period following World War II. On average, the plant has produced almost 1.4 billion rounds of ammunition per year. The site is a government-owned, contractor-operated facility. Remington Arms operated the facility until 1985 when Olin Corporation took over operations, followed by another management change in 2001 to Alliant Techsystems. LCAAP consists of 3,935 acres with 458 buildings (**Figure 5-5**). The small community of Lake City is located adjacent to the northern boundary of LCAAP and relies on private groundwater wells.

Waste treatment and disposal occurred on site in unlined lagoons, landfills, and burn pits. These disposal processes released solvents, oils, explosives, radionuclides, VOCs, and metals to the local environment. Contaminated groundwater has migrated off site in the northeastern part of LCAAP. A groundwater extraction well is currently used to control further off-site migration of contaminants. The site is listed on the U.S. EPA National Priorities List as of July 1987. Area 17D (**Figure 5-6**), which was used for waste of glass, paint, and solvents, is the focus of this site selection.

Three distinct hydrostratigraphic units exist at the 17D area. First, a silty clay overburden consists of both alluvial silty clays and fine silty sands. Hydraulic conductivity for the silty clay colluvium unit has been measured as $4.6*10^{-5}$ cm/s. Underlying this silty clay colluvium is a silty clay and weathered shale residuum for approximately 10 to 15 ft. Lastly, a bedrock unit consisting of massive to thin-bedded claystones and interbedded shales is found. Both of these two soil units currently have monitoring and injection wells installed. These shales range in thickness from inches to tens of feet and are very weathered in some areas (**Figure 5-7**). Weathered bedding plane partings and fractures are not apparent in this shale formation, and the unit acts as an aquitard.

Area 17D is long and narrow, located on relatively flat terrain, and has the Abshier Creek (identified as a CERCLA area) running through it. The 17D area was used from 1960 to 1975 for a variety of waste disposal activities. These activities included disposal of fluorescent tubes, oil, grease, bleach cans, ammunition cans, and paint cans. The area has a chlorinated solvent plume that extends over 2,000 ft from the southeastern source area to the northwest, which is effectively following the groundwater flow that moves in a west-northwest direction from the source area. Chlorinated solvent concentrations are approximately between 1 and 10 mg/L in the source area near the southeast end of the plume (**Figure 5-8**). Following a 1998 remedial action ROD, a subsurface permeable reactive wall was installed to treat dissolved-phase contaminants emanating from the 17D source area (seen in **Figure 5-8)**. The area of the 17D plume is estimated to be 7 acres, with an estimated impacted saturated interval of up to 30 ft. Monitoring wells have been installed throughout the 17D area plume. The water table in the 17D source area is approximately 5 to 10 ft bgs. This water table is most likely influenced by Abshier Creek, which is approximately 400 ft to the north of the source area.

The target injection area for this demonstration is shown in **Figures 5-7** and **5-8**. This part of the 17D area subsurface was selected because it has the required low permeability lithology, has a large vertically saturated interval, allows a demonstration of this technology for treating contaminated groundwater with VOC concentrations above 1 mg/L, and provides an acceptable distance from the screened intervals of nearby wells. The Lake City AAP site is proposed to be the one site for testing all of the technologies described in the project proposal, which include pneumatic fracturing and ERI. The pneumatic fracturing demonstration involves three fracture borings (in a triangle configuration) with a target radius of influence of approximately 10 ft at each borehole.

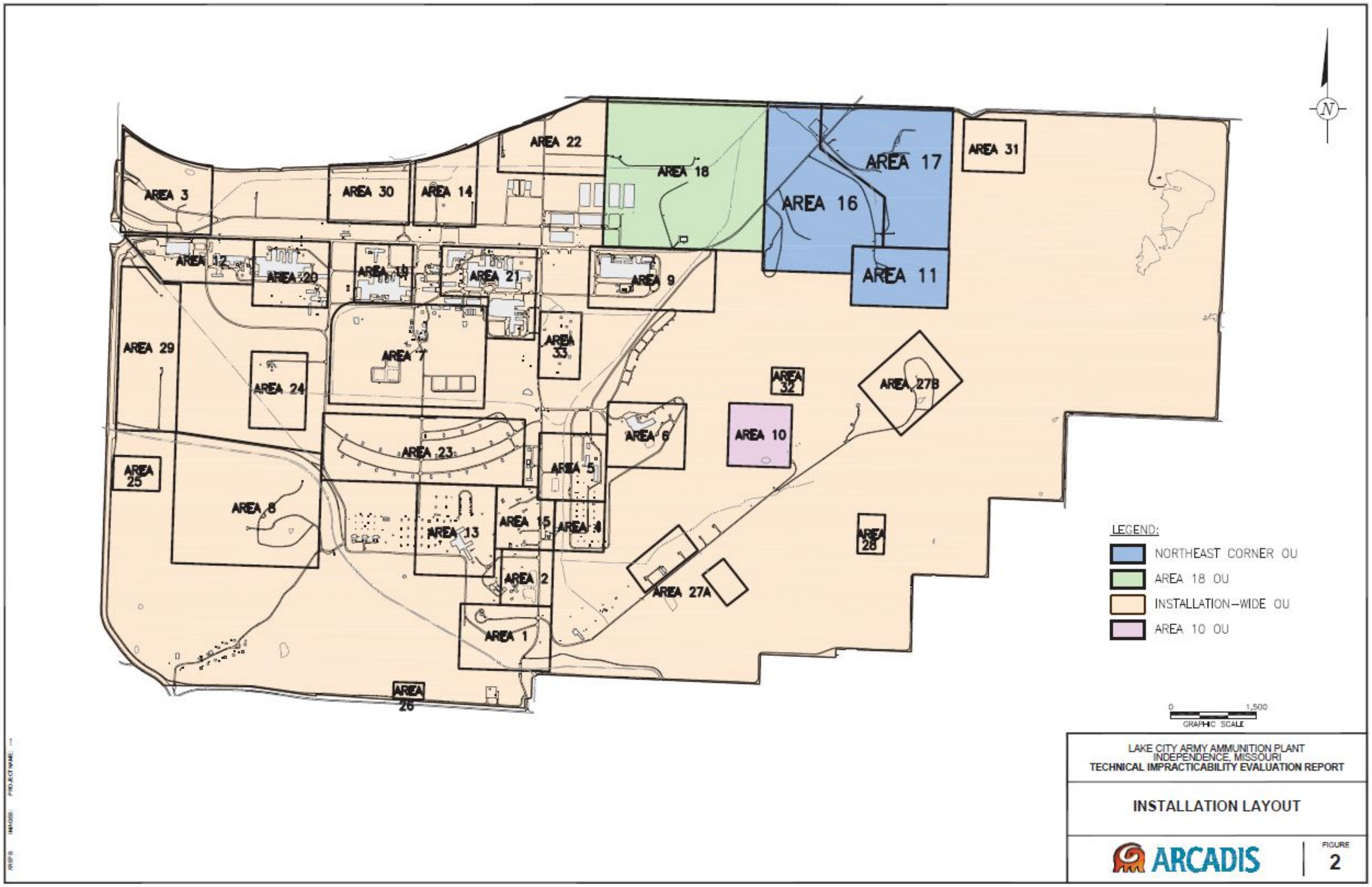

Figure 5-5: Lake City AAP site map showing Area 17 (highlighted).

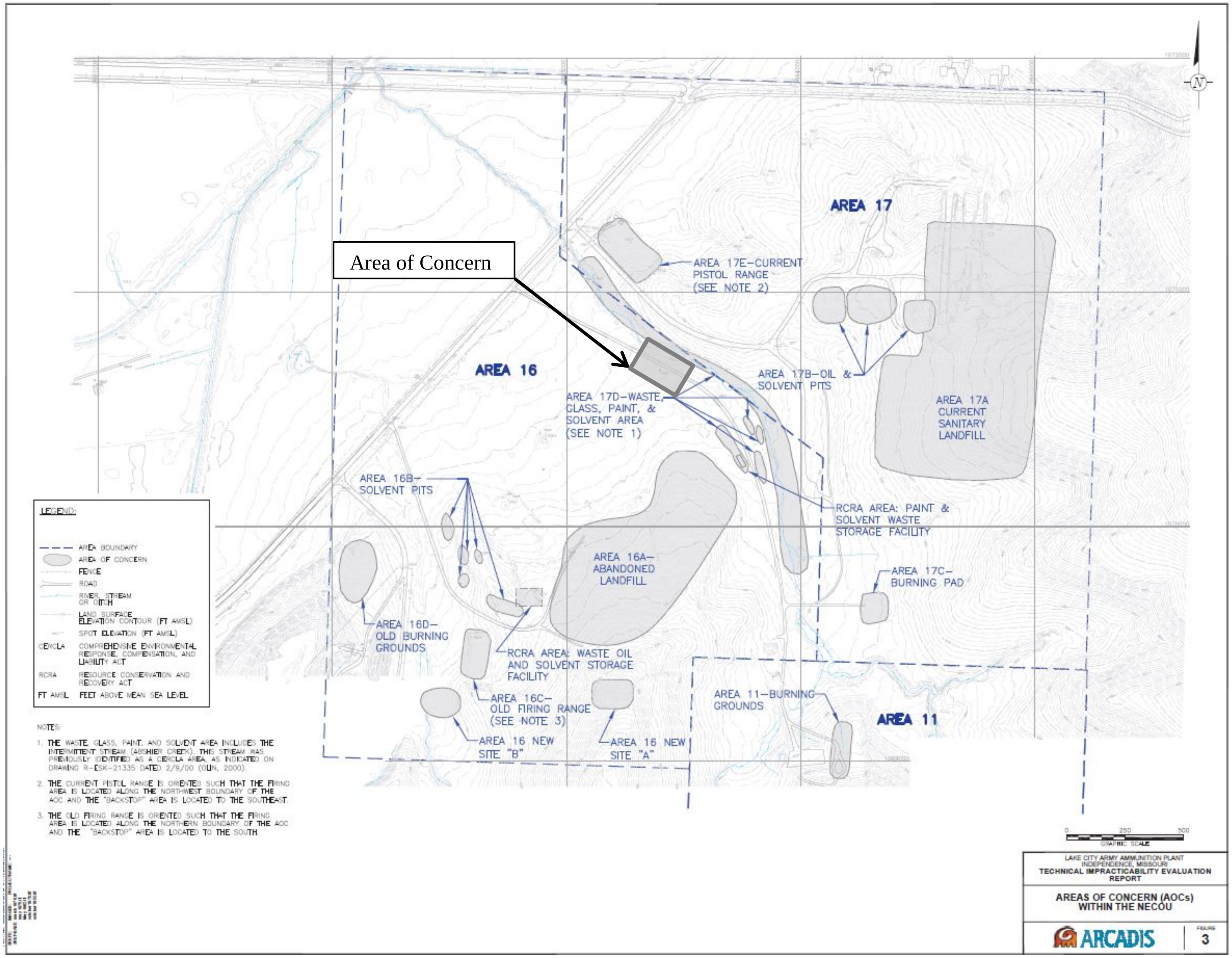

Figure 5-6: Lake City AAP Area 17 layouts and descriptions. The proposed injection area within the 17D area is highlighted.

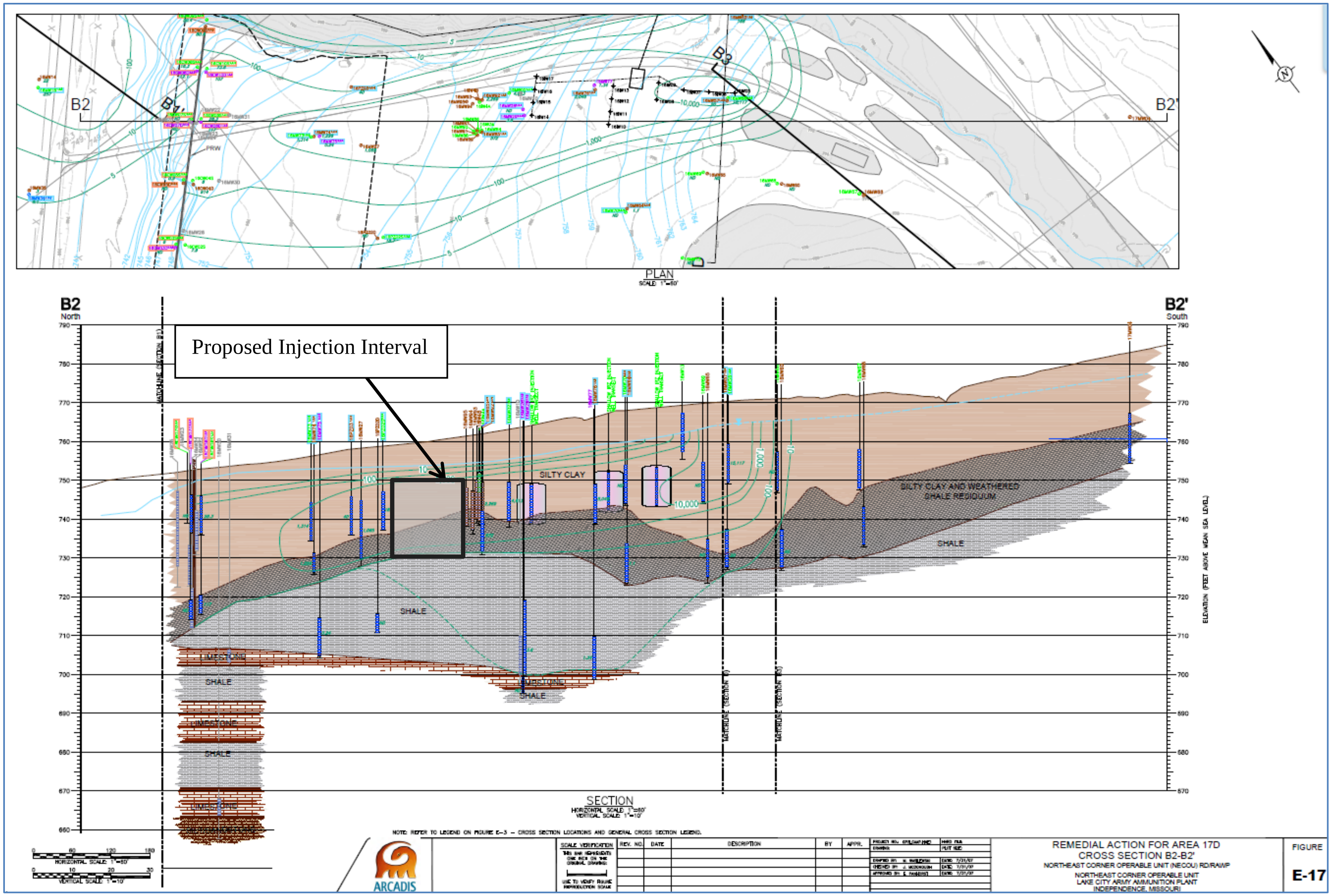

Figure 5-7: Lake City AAP 17D Area lithology (ARCADIS Remedial Action Plan, 2007). Note that the TCE plume extent shown in this 2007 figure is different from the plume shown in Figure 5-8 which is from a 2009 investigation.

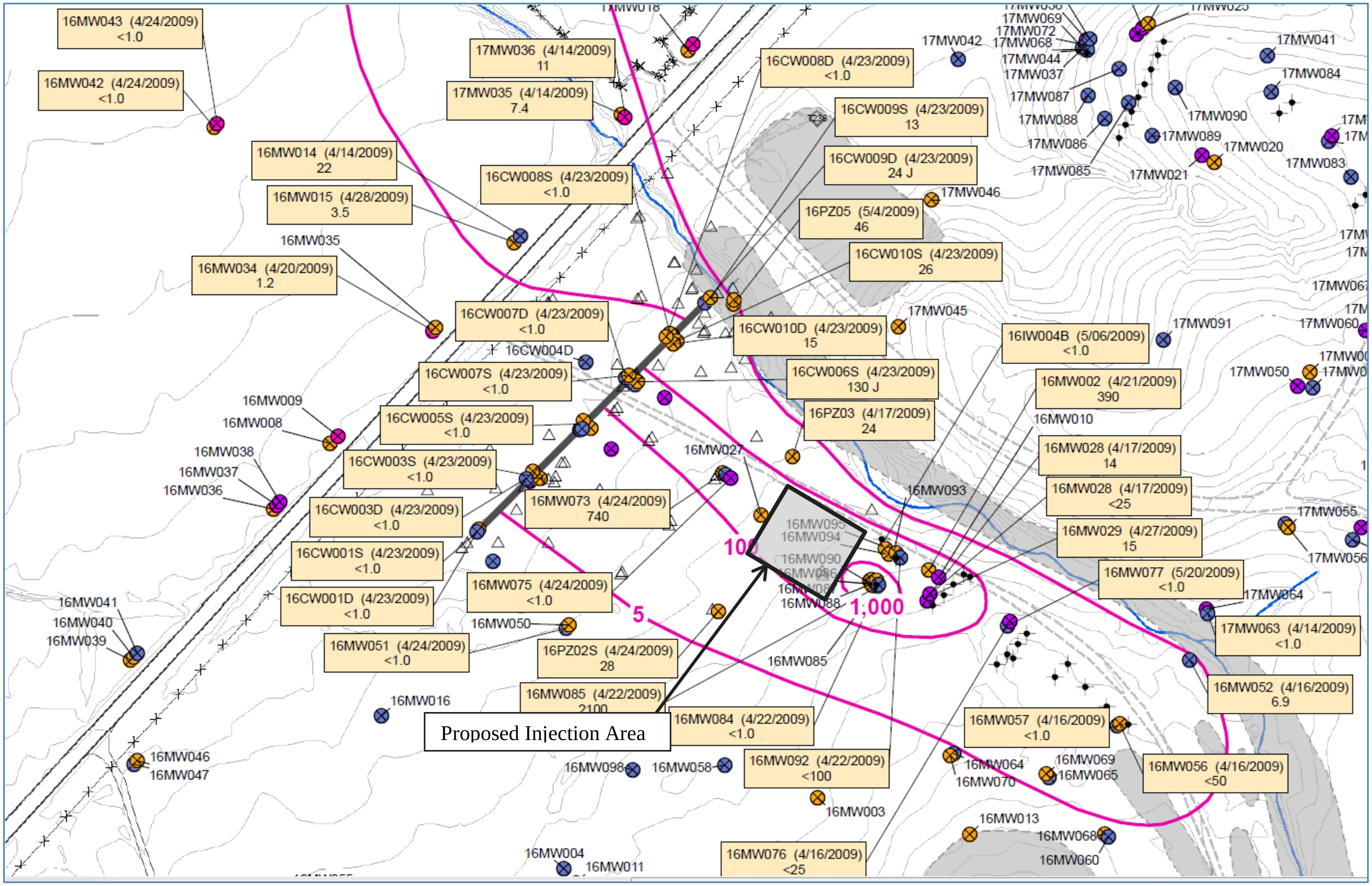

Figure 5-8: Lake City AAP Area 17D TCE plume map from the 2009 groundwater monitoring event (ARCADIS, 2009). Captions show the well name, date sampled, and TCE concentration, respectively. The proposed injection area is seen downgradient of the source area and injections done by ARCADIS. The permeable reactive wall is seen as the dark line oriented southwest to northeast.

Grand Forks AFB Site TU504

Grand Forks AFB is located 12 miles west of Grand Forks, North Dakota, near the state line with Minnesota (**Figure 5-9**). The site contains 4,830 acres of land, which are partially surrounded by the farming communities of Emerado, Arvilla, and Mekinock. The site was historically used as an Air Defense command Base that housed KC-135 Stratotankers, B-52 bombers, and B-1B bombers. The area of concern for this demonstration is named TU504 (**Figure 5-10**), which is located in the central portion of the base. Building 539 is located within this area and was used historically for jet engine testing from the 1950s through 1992.

The base lies on interbedded lacustrine and glacial units, which were deposited during interglacial and glacial periods. The shallow soil contains a pale brown coarse sand and silty clay fill, which ranges from 2.5 to 6 ft thick. Below this, a till unit of brown and gray mottled silty clay with decayed vegetation between 15 and 40 ft thick is encountered. Next, a gray clay unit containing gravel and cobbles is found, which ranges in thickness from 25 to 58 ft. Next is a gray silty clay unit, which is approximately 16 to 32 ft thick. Underlying these soils is the Emerado Sand, which is a gray sand unit, approximately 30 ft thick.

Site-specific geology consists of silts or sandy silts from ground to 3 ft bgs, and then clays from approximately 3 to 30 ft bgs. The silty clays of the ancestral Glacial Lake Agassiz are the confining unit above the Emerado Aquifer, which is encountered at approximately 60 ft bgs. A shallow water table is observed between 3.68 and 8.26 ft bgs, which overlies the Emerado Aquifer. The potentiometric surface of the Emerado Aquifer is observed to be higher in elevation than the shallow perched water surface. Hydraulic conductivities of the shallow soils have been measured to be on the order of $2*10^{-5}$ cm/s, but the same measurements of deeper soils have not been found. A hydraulic gradient of 0.025 is observed on the site, suggesting a groundwater flow velocity of 13 ft/year in the shallow groundwater unit. The lower permeability of the shallow soils suggests that significant migration of contaminants away from the source area is not expected. Unfilled soil fractures have been observed in the shallower portions of the soils, which may contribute to preferential flow.

In 1996, a petroleum odor was detected in soils removed from an excavated water line. Subsequent analysis of compounds in the site soil and groundwater included detections of JP-4 fuel, hydraulic fluid, engine oil, solvents, TCE, and methyl-ethyl-ketone. A Resource Conservation and Recovery Act Facility Investigation (RFI) was conducted in 1999 and found VOC and TPH above EPA MCLs for soil and groundwater. In 2000 and 2001, a phase II RFI completed the horizontal and vertical delineation of the TU504 area plume. This phase II activity also found other VOCs above MCLs, and determined that the soil contamination extended to a depth of 10 ft.

In 2002, a phytoremediation scheme (trees) was implemented to hydraulically control and mitigate the contaminant concentrations of the plume. The groundwater surface in the vicinity of the plume has been depressed due to limited surface recharge and evapotranspiration. This has caused the groundwater to flow towards the center of TU504. Long-term-monitoring (LTM) of 10 monitoring wells has been conducted on an annual basis since 2003. During the 2014 LTM, tree canopy heights ranged from 7.5 to 62.1 ft, with an average value of 26.9 ft, indicating potentially extensive subsurface root structures. Groundwater sampling at this time showed maximum concentrations of TCE and cis-DCE of 7.54 and 11.1 mg/L, respectively. The maximum benzene concentration was measured at 0.657 mg/L while diesel and gasoline range organics were measured at 0.973 and 6.25 mg/L, respectively. Exceedances of MCLs in the 2014 groundwater sampling results for the 10 monitoring wells are shown in **Figure 5-11**.

In July 2014, 6,625 pounds of LactOil and 4,323 gallons of a LactOil/water solution were injected into 30 locations in addition to a bioaugmentation of *Dehalococcoides spp*. The spacing of the trees and the temporary injection well scheme at the TU504 area are shown in **Figure 5-12**. Results from the 2014 LTM report indicate that this injection was successful at degrading contaminants in locations where the bioaugmentation and substrate addition had migrated but exceedances of MCLs in multiple wells for VOCs and TPH still remain (**Figure 5-11**). Considerable time may be necessary to fully realize the impact of the bioaugmentation and LactOil treatment.

The target injection area for this demonstration is highlighted in **Figure 5-10**. This section of the TU504 area was selected because it has the required low permeability lithology and vertically saturated thickness, is located within the hot-spot of the plume to demonstrate the efficacy of this technology on treating VOC contaminated soils, and further provides the opportunity to compare the technologies to more commonly encountered heterogeneous soils and field conditions. Two monitoring wells that are located in the vicinity of the proposed injection location are MW05 and MW06, which are screened from 4.8 to 14.8 ft bgs, and 19.8 to 29.8 ft bgs, respectively. Although well MW05 is screened within the injection zone of this demonstration, it is located beyond the expected injection radius and will most likely not influence the injection event. Well MW06 is screened below the injection range for this demonstration and is not an area of concern.

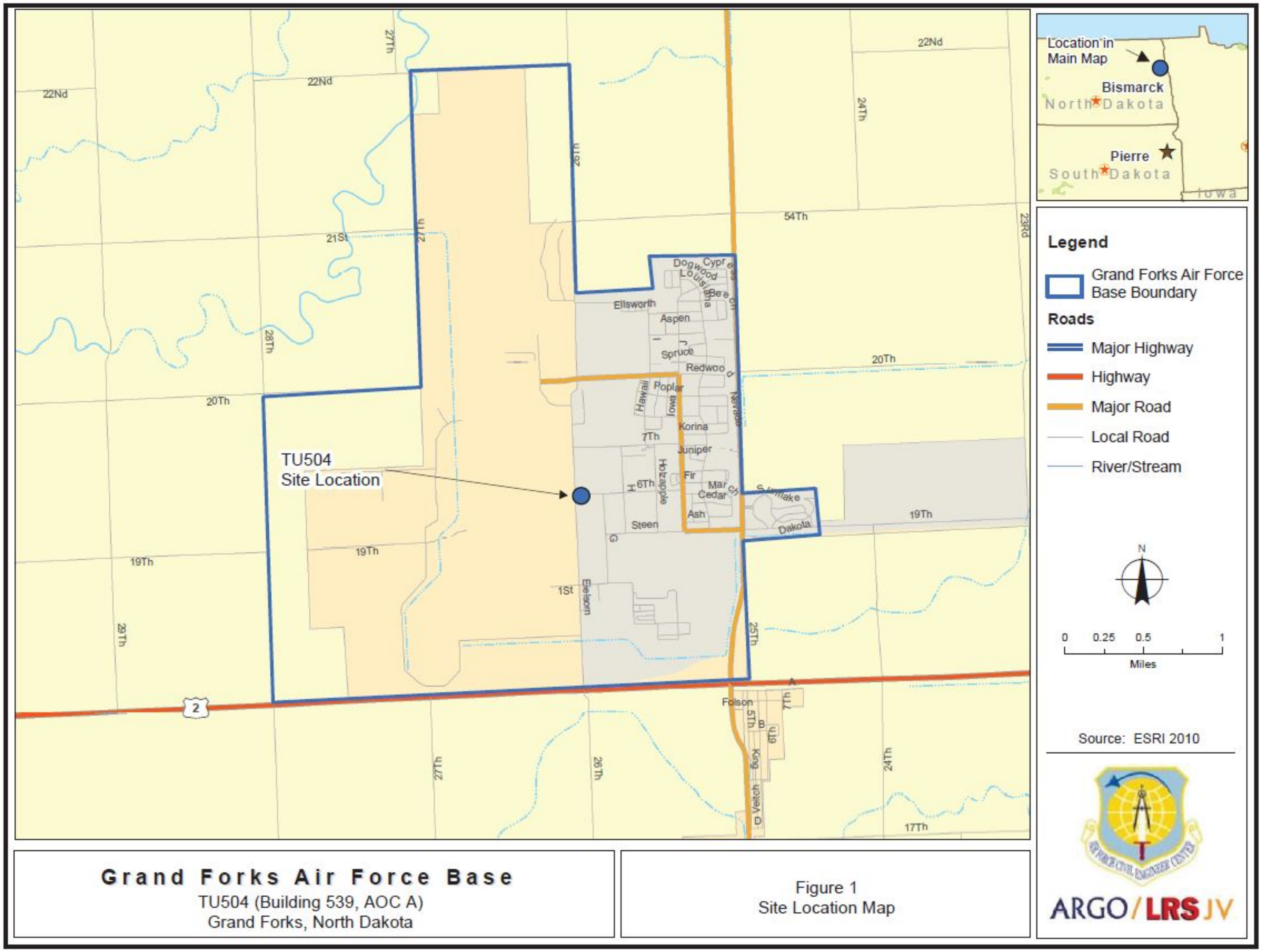

Figure 5-9: Grand Forks AFB site map.

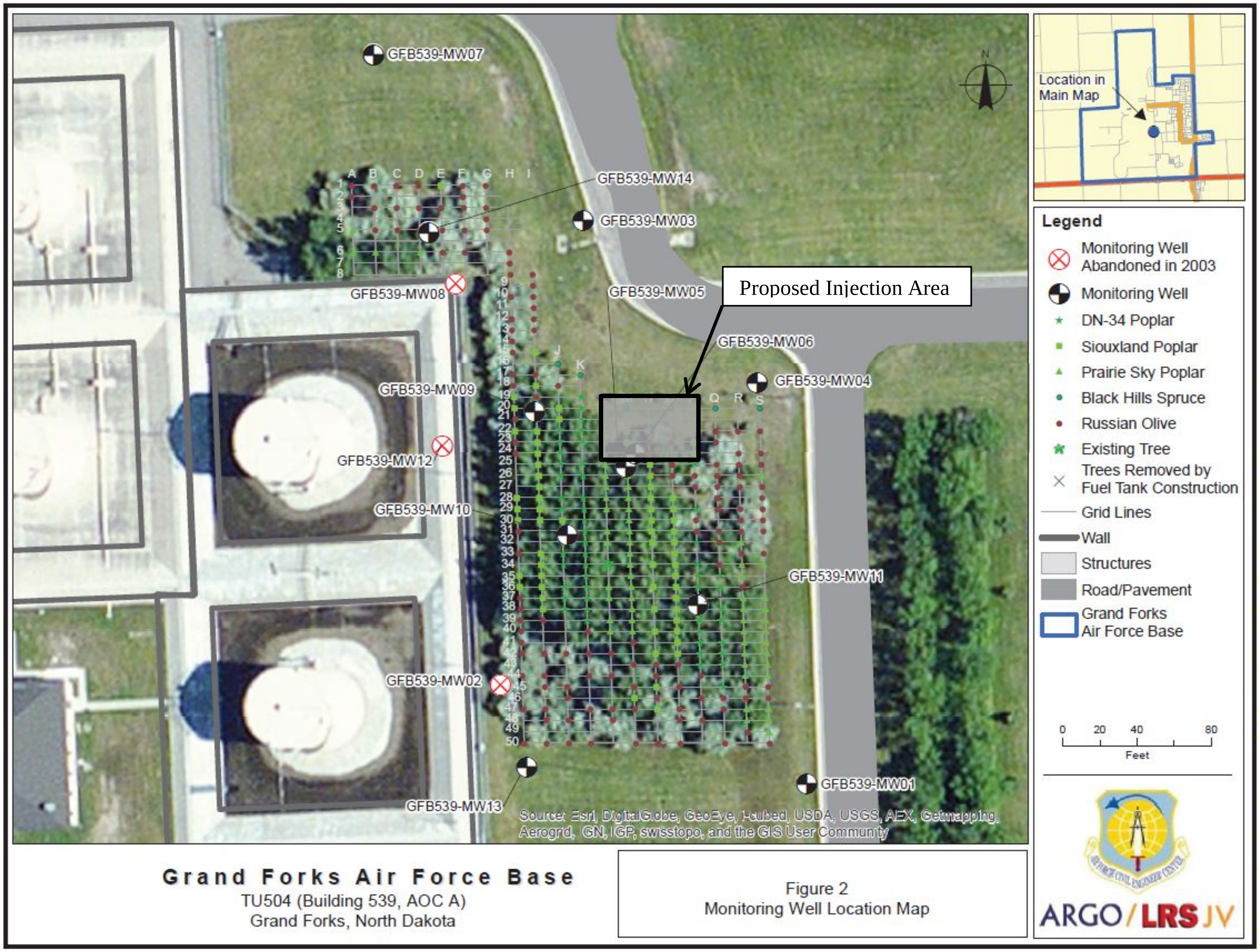

Figure 5-10: Grand Forks AFB site TU504 layout. The proposed injection area is highlighted.

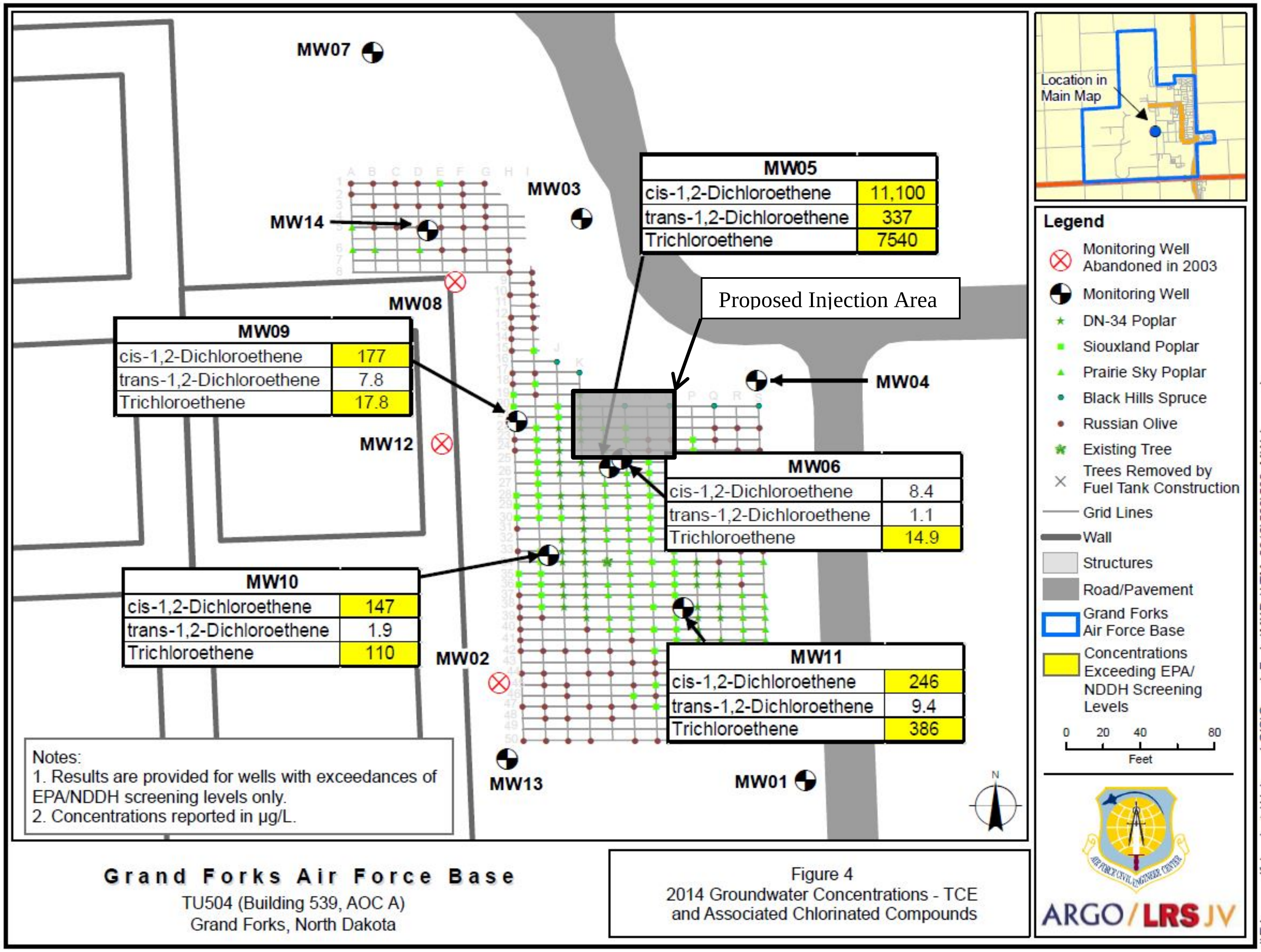

Figure 5-11: Grand Forks AFB TU504 VOC concentrations in groundwater. Wells with no data indicate no violations of MCLs detected. The proposed injection area is downgradient of MW05.

Figure 5-12: Temporary injection well installation and tree spacing at Grand Forks AFB TU504.

5.3 ALTERNATE SITE

Nike SL-10

If unforeseen problems are encountered during the planning or field activities of this demonstration, the Nike SL-10 site located in Madison County, Illinois, will be used as an alternative site. Starting in 1959, the Nike SL-10 site was acquired by the DoD and used for the operation of Nike Hercules surface-to-air guided missiles. The site is 19.87 acres, which includes missile assembly, a generator and warheading building, an acid fueling station, and support buildings. The site was deactivated in August 1968.

A flat-lying, glacial till covers the extent of the site, estimated to be between 50 and 100 ft thick. The site soil consists of three soil units. First, an uppermost till that consists of clay and silt mixtures from the surface to approximately 20 ft bgs is found. Second, an intermediate zone of sandy silt with up to 20% sand and gravel extends from 20 to 30 ft bgs. Lastly, a clayey silt to silty clay extends from 30 to 92 ft bgs. The silt/clay layer below 30 ft bgs has the properties of an aquitard or aquiclude. Some soil logs have the uppermost clay/silt soils extend to as deep as 24 to 28 ft bgs. Lenses of silt and clay have been observed within the middle sandy silt layer between 20 and 30 ft bgs.

The groundwater gradient has been observed to be relatively flat and has been estimated at 0.003 ft/ft, with a flow direction of south to southeast. The vadose zone at the site is relatively thin, with the saturated zone typically within 3 ft of ground surface. The vadose zone consists of dark brown to gray, mottled, fine-grained materials, silt and clay. The water table is considered to be around 5 ft bgs, with parts of the site at lower elevations typically presenting with pooling water.

The intermediate layer of sandy silt from 20-30 ft bgs contains the majority of the VOC groundwater contamination at the site. The hydraulic conductivity of the upper silt/clay zone has been measured between $6.54*10^{-6}$ and $6.3*10^{-4}$ cm/s. The middle silty sand layer has a measured K value between $1.4*10^{-3}$ and $7*10^{-3}$ cm/s. Soil taken from between 45 to 47 ft bgs had a measured vertical K value of $2.3*10^{-8}$ cm/s, which is typical of an aquitard. Bedrock was not encountered in borings that extended to 92 ft bgs, but is likely Pennsylvanian in age and part of the Modesto or Bond Formation.

6.0 REFERENCES

Antigo Final Groundwater Pilot Study Report, Prepared by Bay West, August 2014

Area 17D ERD Performance Monitoring and Injection Well Operation Memorandum, Lake City Army Ammunition Plant, Prepared by ARCADIS, April 2011

Final Corrective Measures Implementation Report, Grand Forks Air Force Base, Prepared by ARGO/LRS JV, September 2014

Internal Draft 2014 Annual Long Term Monitoring Report, Grand Forks Air Force Base, Prepared by ARGO/LRS JV, November 2014

Remedial Design/Action Work Plan, Lake City Army Ammunition Plant, Prepared by ARCADIS, April 2011

Site 1115 Remedial Investigation Report and Feasibility Study, Marine Corps Base Camp Pendleton, Prepared by NOREAS and Parsons, February 2014

Site 1119 Remedial Investigation Report and Feasibility Study, Marine Corps Base Camp Pendleton, Prepared by Parsons, May 2014

Charles G. Coyle, personal communications, October 2014.

Attachment A

Table A. Sites that were screened from further analysis based on preliminary screening criteria.

Contact	Site
Charles Coyle	Lowry AFB 1C
Charles Coyle	Lowry AFB 2C
Charles Coyle	Lowry AFB 1B
Charles Coyle	Antigo AFS
Charles Coyle	F.E. Warren AFB Atlas D Site

APPENDIX B

Quality Assurance Project Plan

Final Quality Assurance Project Plan for a Rigorous Demonstration of Permeability Enhancement Technology for *In Situ* Remediation of Low Permeability Media
ESTCP Project Number ER-201430

October 2015

Revision 1

Prepared by: Zoom Nguyen — Date: 10/01/2015
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Reviewed by: [signature] for Janelle Amador — Date: 10/01/2015
Janelle Amador
Quality Assurance Coordinator

Contents

List of Tables

Acronyms

AAP	Army Ammunition Plant
AFB	Air Force Base
DO	dissolved oxygen
DQO	data quality objective
EAB	enhanced anaerobic bioremediation
EC	electrical conductivity
EPA	United States Environmental Protection Agency
ERT	electrical resistivity tomography
ESTCP	Environmental Security Technology Certification Program
IDW	investigation derived waste
ISCR	*in situ* chemical reduction
MEEA	methane, ethane, ethene, and acetylene
mg/kg	milligram per kilogram
mg/L	milligram per liter
mg-N/L	milligram nitrogen per liter
mV	millivolt
NA	not applicable
NTU	nephelometric turbidity units
ORP	oxidation-reduction potential
PQL	practical quantitation limit
QAPP	Quality Assurance Project Plan
QA	quality assurance
QC	quality control
RPD	relative percent difference
SOP	standard operating procedure
VOC	volatile organic compound
TOC	total organic carbon
µg/L	microgram per liter
%	percent
%R	percent recovery

1.0 Purpose and Scope of the Plan

The purpose of this Quality Assurance Project Plan (QAPP) is to collect data of known and defensible quality as determined by adherence to quality assurance (QA) and quality control (QC) requirements detailed herein. The QAPP presents the organization, functional activities, and specific QA/QC activities associated with the implementation of the Demonstration Plan. All QA/QC procedures will be in accordance with applicable professional technical standards.

This QAPP is pertinent to the rigorous demonstration of the environmental hydraulic and pneumatic permeability enhancement technologies that will be performed at three low-permeability sites. The three sites are the Camp Pendleton Site 1115, the Lake City Army Ammunition Plant (AAP) Site 17D, and the Grand Forks Air Force Base (AFB) Site TU504. This QAPP was developed in accordance with United States Environmental Protection Agency (EPA) Guidance for Quality Assurance Project Plans EPA QA/G5 (EPA 2002), Environmental Security Technology Certification Program (ESTCP) Demonstration Plan Guidance for Environmental Restoration Projects July, 2010, and CDM Smith's Quality Assurance Manual, Revision 20 (CDM Smith 2012). A discussion of the regulatory drivers associated with the project is presented in **Section 1.3** of the Demonstration Plan. Details of the objectives of the demonstration are presented in **Section 3** of the Demonstration Plan. Background and historical information associated with the demonstration are provided in **Section 4** of the Demonstration Plan. At each of the three sites, multiple mobilizations will be conducted to facilitate completion of all permeability enhancement activities as described in the following sections. Depending on sequencing of activities, some mobilizations as described below may be combined into one field event.

1.1 Mobilization 0

The objective of this mobilization is to perform pre-enhancement groundwater sampling at existing monitoring wells that are screened appropriately and located in close proximity to the selected demonstration areas. At Grand Forks AFB Site TU504 and Camp Pendleton Site 1115, groundwater sampling using low-stress, low-flow sampling techniques or an equivalent technique previously employed at the demonstration sites will be performed by onsite personnel/subcontractors as part of the sites' ongoing performance monitoring programs. While such programs will dictate which analytes will be collected, CDM Smith anticipates that volatile organic compounds (VOCs) and general water quality parameters will be collected during this mobilization. Sampling of existing monitoring wells at Lake City AAP Site 17D is included with Mobilization 2, as described below.

1.2 Mobilization 1

The objective of this mobilization is to collect pre-enhancement soil lithology. Pre-enhancement lithologic data will be collected during well installation. Total organic carbon (TOC) samples will be collected from soil cores at Lake City AAP Site 17D and Grand Forks AFB Site TU504, and sulfate samples at Camp Pendleton Site 1115. These samples will be collected for comparison of pre-enhancement concentrations versus post-enhancement concentrations. Two existing wells will be installed at Camp Pendleton Site 1115 and six wells that will be installed at Lake City AAP Site 17D (two wells for the hydraulic point, and four wells total for the three pneumatic points) and Grand Forks AFB Site TU504 (three wells to monitor at least four fracture points).

1.3 Mobilization 2

The objectives of this mobilization are to collect pre-enhancement VOCs and hydraulic data at the temporary wells, to perform the enhancement work, and to collect data to validate the enhancement work.

At Camp Pendleton Site 1115, this mobilization will include collection of pre-enhancement data for VOCs, sulfate and persulfate, and general water quality parameters from nearby existing monitoring wells and temporary wells. In addition, baseline hydraulic data will also be collected prior to the permeability enhancement work. Tilt-metering data collection will be performed throughout the permeability enhancement demonstration at this site. It should be noted that sand emplacement will first be performed followed by amendment injection at the Camp Pendleton Site 1115 and the Lake City AAP Site 17D. Following completion of all enhancement work, post-enhancement confirmation sampling in two boreholes located within the expected radius of influence of the environmental hydraulic permeability enhancement demonstration will be conducted. Visual evidence of permeability enhancement fluid within the collected soil cores will be documented. Soil samples will also be collected for sulfate and persulfate analysis.

Many of the aforementioned activities will be performed during this mobilization at the Lake City AAP Site 17D. However, TOC analysis will be performed instead of sulfate and persulfate analysis to facilitate detection of the aqueous organic amendment that will be used at this site. In addition, methane, ethane, ethene, and acetylene (MEEA) will be monitored to aid bioremediation performance evaluation. Electrical Resistivity Tomography (ERT) and tilt-meter geophysics will be performed in association with permeability enhancement activities.

Similar to the Lake City AAP Site 17D, VOCs, TOC, MEEA, water quality parameters, and hydraulic data will be collected prior to the start of the enhancement work at the Grand Forks AFB Site TU504. Tilt-metering and ERT will be completed, and electrical conductivity (EC) logging will be performed prior to and during environmental permeability enhancement to monitor fracture propagation.

1.4 Mobilization 3

The objective of this mobilization is to collect post-enhancement data at all three sites approximately one month following the enhancement work. VOCs, TOC, MEEA, water quality parameters, and hydraulic data will be collected at the Lake City AAP Site 17D and the Grand Forks AFB Site TU504 while VOCs, sulfate and persulfate, water quality parameters, and hydraulic data will be collected at the Camp Pendleton Site 1115.

CDM Smith will perform the field testing and reporting in accordance with the schedule presented in **Section 7** of the Demonstration Plan. A brief summary of the sample collection activities and associated methods and procedures is provided **Section 5** of the Demonstration Plan. More details are provided in subsequent sections of this document. Offsite laboratory analytical work will be performed. Each laboratory will perform analyses following the procedures specified in their Quality Assurance Manual, which will be obtained and provided in **Appendix F** of the Demonstration Plan once laboratory subcontracts are in place.

2.0 Quality Assurance Responsibilities

The specific individuals participating in the project and their roles are presented in **Section 8** of the Demonstration Plan. The specific QA and management responsibilities of key project personnel are described below.

2.1 CDM Smith Principal Investigator

Kent Sorenson, Jr., CDM Smith's Principal Investigator, will have the ultimate responsibility for all aspects of this project, including implementation of the QA program as defined in this QAPP and in the Demonstration Plan. He will ensure proper adherence to the Demonstration Plan and QA program. He is also responsible for managing and executing the technical aspects of this project.

2.2 CDM Smith Project Manager

Nathan Smith, CDM Smith's Project Manager, is responsible for scheduling, budgeting, and procurement. He has overall responsibility for implementation of the QA program. He has final responsibility to make sure the requirements of the contract are disseminated to the project team and into project plans, and ultimately implemented. This includes Planning, Work Planning, Contracting, Implementation, Monitoring, and Project Closeout. The project manager will be responsible for the overall performance of field operations and testing and will ensure they are conducted in accordance with approved work plans and procedures, including this QAPP. The project manager is responsible for ensuring proper reviews are performed on reports and documents in accordance with the CDM Smith QA program.

2.3 CDM Smith Quality Assurance Coordinator

The CDM Smith QA Coordinator is Janelle Amador. The QA Coordinator is responsible for establishing the QA policy and practices for the project. This includes reviewing this QAPP and procedures, ensuring management and independent assessments are scheduled and performed, and ensuring acceptance testing is performed and equipment is calibrated on a routine basis. The QA Coordinator will remain independent of the data generating activities.

2.4 CDM Smith Technical Team

CDM Smith technical staff will be used to perform field activities, gather and analyze data, and prepare various task reports and support materials. The designated technical team members are experienced professionals who possess the degree of specialization and technical competence necessary to perform the required work effectively and efficiently. The field team lead will coordinate field activities for adherence to procedures outlined in this QAPP on a routine basis. The technical task lead for data analysis and interpretation will coordinate data acquisition and validation and check that data quality indicators are met. The technical team will adhere to QA requirements under direction of the project manager.

2.5 Laboratory Project Manager/Project Chemist

The responsibilities of the subcontracted Laboratory Project Manager are to initiate and maintain the services of the contract, to ensure all resources of the laboratory are available on an as-required basis, and to review final analytical data and reports.

2.6 Laboratory Operations Manager

The subcontracted Laboratory Operations Manager shall have complete authority for the production capabilities of the laboratory. Each laboratory under subcontract to CDM Smith that performs work for this project will have its own Operations Manager. The responsibilities of the Laboratory Operations Manager are to:

- Coordinate laboratory analyses
- Supervise in-house chain-of-custody procedures
- Schedule sample analyses
- Oversee data review
- Oversee preparation of analytical reports
- Approve final analytical reports

2.7 Laboratory Quality Assurance Coordinator

The Laboratory QA Coordinator is responsible for the laboratory QA/QC in accordance with the requirements of this QAPP and in conjunction with the laboratory's established QA Program. The responsibilities of the Laboratory QA Coordinator are to:

- Implement the lab QA/QC program
- Supervise laboratory quality assurance
- Supervise QA/QC documentation
- Conduct detailed data review
- Decide laboratory corrective actions, if required
- Process laboratory non-conformance reports
- Provide technical representation of laboratory QA procedures
- Prepare laboratory Standard Operation Procedures

2.8 Laboratory Sample Custodian

The responsibilities of the Laboratory Sample Custodian are to:

- Receive and inspect the incoming sample containers
- Record the condition of the incoming sample containers
- Sign appropriate documents
- Verify chain-of-custody and its correctness
- Notify the laboratory manager and laboratory supervisor of sample receipt and inspection
- Ensure control and safekeeping of all samples received by the laboratory
- Assign a unique identification number and customer number, and enter each number into the sample receiving log

2.9 Laboratory Data Manager

The responsibilities of the Laboratory Data Manager are to:

- Support and maintain the laboratory database
- Initiate and create compatible electronic data
- Serve as the single point-of-contact for transmission of electronic data deliverables and corrections of versions with problems

The Principal Investigator and Project Manager have primary responsibility for project quality and will interface with the analytical laboratory. Independent quality assurance will be provided by the Laboratory Project Manager and Laboratory QA Coordinator prior to the release of the data to CDM Smith.

3.0 Data Quality Objectives

The data quality objective (DQO) process is a series of planning steps designed to ensure data of known and appropriate quality are obtained to support decisions. The process uses qualitative and quantitative statements intended to clarify study objectives; define appropriate data types; determine appropriate conditions from which to collect the data; and specify acceptable levels of decision errors. The outputs of each step are then used as inputs in designing the sampling plan.

EPA DQO guidance recommends a seven-step process be used to implement the process to design both qualitative and quantitative sampling and analysis plans. This demonstration will use both qualitative and quantitative analysis of influent and effluent groundwater monitoring results to determine progress toward the performance objectives identified in **Table 3-1** of the Demonstration Plan. The steps of the DQO process are listed below, and are described further in the following sections.

Step 1: State the problem, including identifying the data users, the planning team, the primary decision maker, resources, and deadlines.

Step 2: Identify the decision to be made, including the principal study question(s) and alternative actions that could result from resolution of the principal study questions, and formulate and prioritize decision statements.

Step 3: Identify inputs to the decision, including required data types and sources, action levels, and analytical methods.

Step 4: Define study boundaries, including spatial and temporal aspects.

Step 5: Develop a decision rule, including (where appropriate) specifying the statistical parameter that characterizes the population and (where appropriate) action levels for the statistical tests.

Step 6: Specify limits on decision errors.

Step 7: Design the data collection program, which will be implemented through this demonstration project.

3.1 State the Problem

This level of the analysis summarizes the problem requiring new data and identifies resources available to resolve the problem.

In recent years, a number of technologies have been developed in an attempt to address the challenge of achieving a uniform and effective distribution of treatment amendments in low permeability and fractured media. These advances include environmental hydraulic and pneumatic permeability enhancement, both of which are able to emplace amendments into low permeability media. The importance of this technology is that emplacing treatment amendments via environmental permeability enhancement can help overcome the aforementioned challenges of traditional amendment injection systems where low permeability soils can impede delivery. Significant confusion currently exists in the industry as to the differences among hydraulic permeability enhancement, hydro-fracking, and permeation injections. While one technology may be more warranted for a particular application, practitioners often do not have the information required to make good decisions regarding which delivery technique to use. Definitive guidance on selecting the most appropriate technique is needed. In addition, significant advances have been made in technologies that can provide high resolution mapping of the subsurface distribution of amendments. However, a rigorous comparison of such methods in different geologies of low hydraulic conductivity has never been made, in part because the high resolution mapping and data processing tools are proprietary and have not been widely available. Consequently, no guidance is available for practitioners or Remedial Project Managers to assist in the selection or specification of amendment distribution and monitoring techniques for assessing amendment delivery within low permeability media. Therefore, the overall problem to be investigated is to demonstrate the performance and cost of environmental permeability enhancement and associated high-resolution monitoring tools at low-permeability sites.

The resources available to resolve the problem include CDM Smith scientists and engineers and the ESTCP funding for this demonstration. The schedule is presented in **Section 7** of the Demonstration Plan, and project management and staffing are described in **Section 2** of this QAPP.

3.2 Identify the Decision

This step identifies the decisions that must be made based on the results of permeability enhancement and associated monitoring as well as who will use the data. The immediate data users will be CDM Smith scientists and engineers analyzing the data to assess overall performance. Ultimate data users include site owners and other scientists and engineers who will apply the technology at other sites, and regulatory agency personnel who must evaluate site-specific applicability of the technology. Additional data users include Department of Defense Remedial Project Managers, Department of Defense contractors, private industry, and the general public.

The decisions relevant to this demonstration are:

1. Quantify horizontal and vertical distribution of emplaced fractures within the target treatment volume (performance objective 1).
2. Deliver the target amendment dose within the target treatment volume (performance objective 2).
3. Evaluate the increase in aquifer permeability resulting from permeability enhancement (performance objective 3).
4. Evaluate the effectiveness and accuracy of tilt-meter geophysics monitoring (performance objective 4).
5. Evaluate the effectiveness and accuracy of electrical conductivity (EC) (performance objective 5).
6. Evaluate the effectiveness and accuracy of ERT (performance objective 6).

7. Evaluate the efficacy of improved amendment delivery for treatment of site contaminants (performance objective 7).
8. Evaluate the ease of use/implementation of each permeability enhancement technology and performance monitoring strategy (performance objective 8).
9. Evaluate the cost performance of each permeability enhancement technology (performance objective 9).

3.3 Identify Inputs to the Decisions

This step identifies information required to make the decision including the specific types, quality, and quantity needed to support decisions. This stage of analysis must ensure that sufficient data of the required types, and of a quality appropriate for the data uses, are obtained. Results of this stage are typically used to define quality levels to be applied to the entire data collection effort, from sampling through analysis and data validation. Specifying unnecessarily stringent data quality costs the project time and money, while specifying insufficiently stringent data quality may result in failure to meet project objectives.

The EPA defines data quality levels as “screening” or “definitive.” Screening data are generated using rapid, less precise analytical methods with less rigorous sample preparation. Screening data both identify and quantify analytes, although quantification may be relatively imprecise. Screening data are adequate for some performance monitoring of groundwater. Monitoring of groundwater will be completed via the use of calibrated instruments (for example pH, temperature, conductivity, turbidity, and oxidation-reduction potential [ORP] probes) and field test kits such as dissolved oxygen.

Definitive data are generated using rigorous analytical methods such as approved EPA or other well-established and documented test methods. Definitive data both identify and quantify analytes with relatively high precision and accuracy, and are typically used for compliance monitoring and to confirm screening data. Definitive data will be generated for groundwater and soil samples. Definitive analytical methods produce tangible, hard copy or electronic format, raw data (e.g., chromatograms, spectra, and digital readout values). Data not obtained and/or reported in these formats are documented in logbooks.

Inputs to the decisions stated previously, including data required, data uses, and minimum data quality levels, are summarized in **Table 3.1.** Requirements for decision input data, including analytical methods and practical quantitation limits, are summarized in **Table 3.2**.

Table 3.1: Decision Inputs

Decision	Data Required	Data Use	Minimum Data Quality Level Required
Quantify horizontal and vertical distribution of emplaced fractures within target treatment volume	• Two soil cores for each fracture initiation boring to a depth equaling the deepest fracture interval • Tilt-meter mapping in a 360-degree concentric array around fracture borehole • Continuous down-hole EC logging (one site) • ERT (two sites)	Visual and analytical confirmation sampling will aid validation of amendment delivery via environmental permeability enhancement at the depth intervals of interest. Tilt-metering, EC, and ERT further support such validation by providing multiple lines of evidence of amendment delivery	Definitive for TOC/sulfate analyses. Screening for tilt-metering, EC, and ERT
Deliver target amendment dose within the target treatment volume	• Amendment volume emplaced • Soil cores • Tilt-meter mapping • EC logging • ERT	Visual and analytical confirmation sampling will aid validation of amendment delivery via environmental permeability enhancement at the depth intervals of interest. Tilt-metering, EC, and ERT further support such validation by providing multiple lines of evidence of amendment delivery	Definitive for TOC/sulfate analyses. Screening for tilt-metering, EC, and ERT
Evaluate increase in aquifer permeability resulting from permeability enhancement	• Aquifer pumping/slug testing conducted in treatment area before and after permeability enhancement	A statistical analysis of the pre- and post- permeability enhancement hydraulic data will be performed to determine if there is a statistically significant difference, which is defined as an increase of approximately one order of magnitude, in hydraulic conductivity induced by environmental permeability enhancement.	Definitive
Evaluate effectiveness and accuracy of tilt-meter geophysics monitoring	• Tilt-meter fracture plane maps • Soil coring data (including TOC and sulfate) • Direct-push EC data	Confirmation soil sampling data will be used to determine if tilt-metering is capable of reliably predicting fractured zones.	Definitive for TOC/sulfate analyses. Screening for visual analysis and EC
Evaluate effectiveness and accuracy of EC	• Pre-fracture EC values • Post-fracture EC values • Soil coring data (including TOC and sulfate)	EC values for adjacent borings will be compared to determine if changes in EC from pre to post-enhancement can be used to confirm fracture depths. Confirmation soil sampling data will also be used to	Definitive for TOC/sulfate analyses. Screening for visual analysis and EC

Decision	Data Required	Data Use	Minimum Data Quality Level Required
		determine if EC is capable of reliably predicting fractured zones.	
Evaluate effectiveness and accuracy of ERT	• Pre-enhancement ERT values • Post- enhancement ERT values • Soil coring data (including TOC and sulfate)	ERT collected pre and post-enhancement will be compared to determine if changes in ERT from pre to post- enhancement can be used to confirm fracture depths and extent. Confirmation soil sampling data will also be used to determine if ERT is capable of reliably predicting fractured zones.	Definitive for TOC/sulfate analyss. Screening for visual analysis and EC
Evaluate efficacy of improved amendment delivery for treatment of site contaminants	• Contaminant and geochemistry data from existing groundwater monitoring wells • Previous injection data • Data from newly installed monitoring wells	Changes in VOCs and other geochemical parameters will be used to determine effects of environmental permeability enhancement on treatment of site contaminants.	Definitive for VOCs, TOC, sulfate and persulfate, and MEEA. Screening for general water quality parameters
Evaluate the ease of use/implementation of each enhancement technology and performance monitoring strategy	• Level of effort (including availability of equipment) necessary to perform each injection technique • Reporting of problems encountered in the field (including surfacing), and ability to resolve problems quickly	Documented work-planning efforts and in-the-field issues will be used to determine the ease of implementation of the enhancement technologies.	Screening

Table 3.2: Acceptable Practical Quantitation Limits for Field and Laboratory Analyses

Analyte	Analytical Method	Practical Quantitation Limit
Offsite Laboratory Analysis		
TOC (solid)	Walkley-Black	0.01%
VOCs	EPA 8260B	Varies; e.g., trichloroethene, cis-1,2-dichloroethene, and vinyl chloride are 2 µg/L
MEEA	RSK 175	10 µg/L, 20 µg/L, 20 µg/L, 1 µg/L respectively

Analyte	Analytical Method	Practical Quantitation Limit
TOC (aqueous)	EPA 9060	0.25 mg/L
Chloride, sulfate, and nitrate	EPA 300.0	0.5 mg/L for chloride and sulfate, 0.10 mg N/L for nitrate
Field/Test Kit Measurements		
pH	Multi-parameter water quality meter	0.1 standard unit
Temperature		NA
ORP		10 mV
Conductivity		NA
Turbidity		0.1 NTU
Dissolved oxygen		0.1 mg/L
Ferrous Iron	HACH ferrous iron AccuVac® Ampoules	0.1 mg/L
Sulfate	Chemetrics sulfate test kit	0.1 mg/L
Persulfate	Chemetrics persulfate test kit	0.35 mg/L

Key:
NA – not applicable
mV - millivolts
µg/kg – micrograms per kilogram
µg/L – micrograms per liter
mg/kg - milligrams per kilogram
mg/L – milligrams per liter
mg-N/L – milligrams of nitrogen per liter
NTU – nephelometric turbidity units

3.4 Define Study Boundaries

The demonstration will be conducted at the three selected demonstration sites. The demonstration duration is estimated to be two years, beginning in 2015.

3.5 Develop a Decision Rule

Decision rules should contain four main elements, including:

- The *parameter of interest* (e.g., a descriptive measure that specifies the characteristic or attribute the decision maker would like to know about a statistical population)
- The *scale of decision making* (i.e., the smallest, most appropriate subset of the data for which separate decisions will be made)
- The *action level*, a measurement threshold value of the parameter of interest that provides the criterion for choosing among alternative actions (e.g., a regulatory standard or other risk-based level)
- The *alternative actions*, which are the actions the decision maker would take depending on the true value of the parameter of interest.

Decision rules by performance objective include the following:

- Determine whether environmental permeability enhancement is capable of delivering amendment within the target treatment interval (performance objective 1, decision rule 1).
- Determine whether environmental permeability enhancement is capable of delivering the target amendment volume within the target treatment interval (performance objective 2, decision rule 2).
- Determine whether environmental permeability enhancement results in an increase in aquifer permeability (performance objective 3, decision rule 3).
- Determine whether tilt-metering can be used as an effective and accurate geophysics monitoring tool (performance objective 4, decision rule 4).
- Determine whether EC can be used as an effective and accurate monitoring tool (performance objective 5, decision rule 5).
- Determine whether ERT can be used as an effective and accurate geophysics monitoring tool (performance objective 6, decision rule 6).
- Determine whether environmental permeability enhancement positively impacts treatment of site contaminants (performance objective 7, decision rule 7).
- Determine whether the environmental permeability enhancement technology is easy to implement (performance objective 8, decision rule 8).
- There is no decision rule associated with performance objective 9.

Decision Rule 1: If soil confirmation data show elevated concentrations of TOC relative to baseline results at each target enhancement interval, then the enhancement demonstration is considered successful. Otherwise, the demonstration is considered a failure.

Decision Rule 2: If 75% of the target amendment volume is successfully injected into each fracture interval, then the permeability enhancement technology is considered successful in delivering the target amount of amendment into the zone of interest. Otherwise, the technology is considered incompetent in amendment delivery.

Decision Rule 3: If approximately an order of magnitude increase in hydraulic conductivity is observed post-enhancement, then the technology is considered successful in increasing the aquifer's permeability.

Decision Rule 4: Post-permeability enhancement soil confirmation sampling will be used to evaluate the effectiveness and accuracy of tilt-meter technology. Two evaluation criteria will be considered including the vertical and horizontal extent of the initiated fracture networks. Preliminary tilt-meter results as well as available data associated with implemented mapping techniques such as ERT will first be used to determine the soil confirmation sampling locations. Visual observations and analytical sampling of post-enhancement soil cores will allow for determination of actual depth intervals of fracture initiation as well as the horizontal extent of the fracture networks. Subsequently, the estimated horizontal extent of the fracture network based on tilt-meter analysis will be compared against that observed during soil confirmation sampling. A relative percent difference (RPD) between these values will be calculated. An average RPD, calculated for all permeability enhancement intervals and boreholes, equal to or less than 40 percent (%) will be considered acceptable.

The accuracy of tilt-meter in predicting the depth intervals where permeability enhancement occurs will be evaluated similarly; the depth at which individual fractures are expected to be encountered in the soil cores will be compared against that where fractures are visually observed or confirmed analytically during post-permeability enhancement soil confirmation sampling. An average RPD for all initiated fracture intervals will be calculated and is considered acceptable if it is equal to or less than 30 percent.

Decision Rule 5: Similar to the aforementioned evaluation of tilt-meter, the effectiveness and accuracy of EC will be determined by comparing the estimated fracture depth interval and extent against the actual values obtained during post-enhancement soil confirmation sampling. Again, soil confirmation sampling locations will first be determined using available mapping data such as tilt-meter. Subsequently, RPDs between the estimated and the actual fracture depth and fracture extent will be calculated. RPD values comparisons between EC and visual observations and/or analytical results collected during post-enhancement soil confirmation sampling will be used to evaluate the accuracy of these monitoring tools. Specifically, the depths at which significant differences (50% or greater) in pre- and post-permeability enhancement EC measurements are observed will be compared against those where visual and/or analytical detections of initiated fractures. An average RPD value equal to or less than 50% between these depths for all tested intervals and boreholes will be considered acceptable. The acceptable RPD value for EC is somewhat higher than for the tilt-meters because those parameters are not measuring the actual fracture, but rather the impact of injected amendment on water properties, which can extend beyond the primary fractures both horizontally and vertically.

Decision Rule 6: The effectiveness and accuracy of ERT will be determined by comparing the estimated fracture depth interval and extent against the actual values obtained during post-enhancement soil confirmation sampling. Soil confirmation sampling locations will first be guided using available mapping data such as tilt-meter. Subsequently, RPDs between the estimated and the actual fracture depth and fracture extent will be calculated. RPD values comparisons between EC and ERT and visual observations and/or analytical results collected during post-enhancement soil confirmation sampling will be used to evaluate the accuracy of these monitoring tools. Specifically, the depths at which significant differences (50% or greater) in pre- and post-permeability enhancement ERT measurements are observed will be compared against those where visual and/or analytical detections of initiated fractures are observed. An average RPD value equal to or less than 50% between these depths for all tested intervals and boreholes will be considered acceptable. The success criteria for ERT will be evaluated similarly to tilt-meter where both the modeled depth interval of fracture initiation and the horizontal extent of the fracture networks will be compared against those obtained during guided soil confirmation sampling. The acceptable RPD value for ERT is somewhat higher than for the tilt-meters because those parameters are not measuring the actual fracture, but rather the impact of injected amendment on water properties, which can extend beyond the primary fractures both horizontally and vertically.

Decision Rule 7: If significant changes in geochemical conditions or a 50% in reduction in concentrations of the contaminants of concern are observed at nearby monitoring wells post-enhancement relative to the historical data, then the technology is considered successful in enhancing contaminant treatment. Significant changes in geochemical conditions are defined here as development and/or enhancement of highly reducing conditions as often observed during *in situ* chemical reduction and enhanced anaerobic bioremediation implementation. It should be noted that since remediation has already been implemented at the selected demonstration sites, changes in geochemical conditions induced by environmental permeability enhancement may not be apparent and multiple lines of evidence will be used to determine the effects of the demonstrated technology.

Decision Rule 8: If the field demonstration is performed with relative ease and at a reasonable cost from the work-planning to the implementation stages, then the technology is considered easy to implement.

3.6 Specify Limits on Decision Errors

Because this is a research demonstration, an explicit definition of limits on decision errors is not necessary or appropriate. The weight of evidence of several groups of parameters will be considered as described in the previous section.

3.7 Design Data Collection Program

The final step in the DQO process is to design a program to cost-effectively collect data that will meet the DQOs. This program is described in **Section 5.0** of the Technology Demonstration Plan.

4.0 Calibration Procedures, Quality Control Checks, and Corrective Action

The purpose of this section is threefold:

- Provide the specific maintenance/calibration procedures for equipment related to the collection of data either in the field or through laboratory analysis of samples.
- Provide specific quality control checks to determine if an analytical operation is in control or if the sample matrix has an effect on the data being generated.
- Provide a corrective action process for general field issues and laboratory analyses.

4.1 Calibration Procedures

4.1.1 Laboratory Equipment Calibration

Initial and continuing calibration procedures for laboratory instruments are found in each laboratory's QA Manual. Calibration for analyses performed by offsite laboratories are defined by the analytical methods. Data reduction and validation for the laboratory data and for the final reporting are described in the laboratory's QA Manual. A subcontract laboratory has not yet been selected for this demonstration; the laboratory's QA Manual will be provided with the final document.

4.1.2 Field Instrumentation and Test Kits

Field instrumentation will be used to provide data concerning health and safety considerations and as a method for field screening samples. Field instrumentation will be calibrated in accordance with manufacturers' recommendations. Documentation of the results from each calibration will be maintained in the field manager's logbook and on equipment calibration log forms. Any equipment maintenance that is performed as well as field calibrations will also be recorded on this form.

Test kits will be used to measure concentrations of specific parameters in the field. Vendor instructions for use of these kits will be followed and documented.

4.2 Quality Control Checks

4.2.1 Field Sample Collection

QA/QC samples are analyzed to provide site-specific, field-originated information regarding the homogeneity of the sample matrix and the consistency of the sampling effort. These samples are collected concurrently with the primary environmental samples and will equally represent the medium at a given time and location. QA/QC samples to be collected and used for the demonstration are:

- Temperature blanks
- Trip blanks
- Field duplicates
- Matrix spike/matrix spike duplicates

<u>Temperature blanks</u>

One laboratory-provided temperature blank sample will be included in each sample cooler submitted for analysis to facilitate temperature monitoring by the laboratory.

Trip blanks

One sample consisting of laboratory-grade water will be included in each sample cooler submitted for VOC analysis to evaluate the potential for cross-contamination during sampling and shipping.

Field Duplicates

These samples will be collected by the sampling team for analysis by the off-site laboratory. The purpose of these samples is to provide site-specific, field-originated information regarding the homogeneity of the sample matrix and the consistency of the sampling effort. Additionally, field duplicates provide an assessment of precision including sampling and handling error. Field duplicates will be collected at a frequency of 10 percent of the total field samples (i.e., 1 QC sample per 10 field samples).These samples are collected concurrently with the primary environmental samples and will equally represent the medium at a given time and location.

Matrix Spike/Matrix Spike Duplicates

Matrix spike/matrix spike duplicate samples assess the laboratory accuracy and the matrix effects (if any) on the outcome of laboratory analysis. Matrix spike and matrix spike duplicates will be collected at a frequency of 5 percent (i.e., 1 matrix spike/matrix spike duplicate per 20 field samples) for VOCs.

4.2.2 Laboratory Analysis

To ensure the production of analytical data of known and documented quality, laboratories associated with this demonstration will implement method required QA and QC checks. Subcontracted laboratories will have a written QA program that provides rules and guidelines to ensure the reliability and validity of work conducted at the laboratory. Compliance with the QA program is coordinated and monitored by the laboratory's QA department, which is independent of the operating departments. All laboratory procedures will be documented in writing as standard operating procedures (SOPs), which will be edited and controlled by the QA department. Internal QC measures for analysis will be conducted with their SOPs and the individual method requirements specified.

4.3 Corrective Action

4.3.1 General Field Issues

All nonconformance situations noted during the two phases of the demonstration will be documented and acted upon. The person identifying the nonconformance is responsible for notifying the CDM Smith Principal Investigator and Project Manager and initiating a corrective action request. The corrective action request is submitted to the QA Coordinator, who determines if the nonconformance is a significant condition adverse to quality and assigns personnel responsible for developing and implementing the corrective action plan. Implementation of corrective action will be confirmed in writing and noted in generated reports describing the demonstration results.

For unexpected situations encountered during field activities where changes to operating systems must be implemented, a field change request will be completed by personnel that will make the change and will be approved by the project manager. All variances from existing operating procedures, field sampling, quality assurance requirements, and/or health and safety plans will be documented on a field change request form.

4.3.2 Laboratory Analyses

Each laboratory QA plan shall provide systematic procedures to identify laboratory related out-of-control situations and corrective actions. Corrective actions shall be implemented to resolve problems and restore malfunctioning analytical systems. Laboratory personnel shall have received QA training and will be aware that corrective actions are necessary when QC data are outside warning or control windows for precision and accuracy, blanks contain target analytes above acceptable levels and must be investigated, undesirable trends are detected in spike recoveries or relative percent difference (RPD) between duplicates, there are unusual changes in practical quantitation limits, or deficiencies are detected by internal audits, external audits, or from performance evaluation sample results.

Corrective action procedures are generally handled by the analyst who reviews the preparation or extraction procedure for possible errors and checks instrument calibration, spike, and calibration mixes, instrument sensitivity, etc. If the problem persists or cannot be identified, the matter is referred to the Laboratory Supervisor, Manager, and/or QA Department. Once resolved, full documentation of the corrective action procedure is filed with project records and the QA Department, and the information is summarized within case narratives.

5.0 Demonstration Procedures

Demonstration startup and each successive phase are discussed in **Section 1** of this QAPP and also **Section 5** of the Demonstration Plan.

5.1 Field Equipment

The various subcontractors to be procured for this demonstration project will provide the appropriate equipment to perform the drilling, environmental permeability enhancement, and high-resolution monitoring activities. Other field equipment needed for this project includes a multi-parameter water quality meter for measurement of pH, ORP, temperature, turbidity, DO, and conductivity and a four-gas meter for health and safety monitoring. Specific preventive maintenance procedures to be followed for field equipment are those recommended by the manufacturer. Where appropriate, new batteries will be purchased and kept with the field equipment to facilitate immediate replacement in the field as necessary.

5.2 Equipment Maintenance

Instruments required for CDM Smith's monitoring activities, such as the aforementioned four-gas meter and multi-parameter water quality meter, will be calibrated on a daily basis. Periodic maintenance on these instruments will be performed per manufacturer-provided specifications or as needed. Field equipment used by subcontractors to perform the permeability enhancement work will be calibrated and maintained per their SOPs or vendor-provided recommendations.

5.3 Laboratory Instruments

Laboratory instruments will be maintained according to laboratory SOPs. Preventive maintenance procedures are described in the laboratory QA manuals.

5.4 Sampling and Analysis

The sampling and analysis program for this demonstration was developed based on the objectives discussed in **Section 3** and the design discussed in **Section 5** of the Technology Demonstration Plan. A summary of the process monitoring parameters including a sampling and analysis schedule is provided in **Section 5** of the Technology Demonstration Plan.

Samples of soil and groundwater will be collected by CDM Smith during multiple mobilizations. CDM Smith SOPs to be implemented during sample collection such as 1-2 Sample Custody, 1-4 Subsurface Sampling, 1-6 Groundwater Level Measurement, 1-12 Low-Stress Low-Flow Groundwater Sampling, 1-13 Drum Sampling (for investigation derived waste [IDW] management), 2-1 Packaging and Shipping Environmental Samples, 2-2 Guide to Handling of IDW, 3-1 Geoprobe Sampling, 3-5 Lithologic Logging, 3-6 Underground Facility Location, 4-1 Field Logbook Content and Control, 4-2 Photographic Documentation of Field Activities, 4-3 Well Development and Purging, 4-4 Design and Installation of Monitoring Wells in Aquifers, 4-5 Field Equipment Decontamination, 4-6 Hydraulic Conductivity Testing, 4-10 Borehole Well Decommissioning, and 5-1 Control of Measurement and Test Equipment are provided in **Appendix E** of the Demonstration Plan.

Groundwater Sampling

The following general procedure will be used to collect groundwater samples for field and on-site analysis.

- Groundwater samples will be collected using low-stress, low-flow sampling techniques shown in **Appendix E** of the Demonstration Plan.
- The number of groundwater samples to be collected at each of the three demonstration sites by CDM Smith and the associated list of analytes are shown in **Tables 5.1** through **5.3** below. Note that CDM Smith anticipates installing two temporary monitoring wells surrounding each hydraulic permeability enhancement point at Lake City AAP Site 17D and Camp Pendleton Site 1115, a total of six temporary monitoring wells at Grand Forks AFB Site TU504, and a total of four temporary monitoring wells in the vicinity of the pneumatic permeability enhancement points at Lake City AAP Site 17D.Existing onsite monitoring wells will also be sampled as part of the demonstration.
- Sample container and preservation requirements are presented in **Table 5.6** of the Demonstration Plan. Sample containers will be completely filled with groundwater.
- Each sample will be labeled with the appropriate sample identification and other information discussed in **Section 9** of this QAPP.
- The sample containers will then be placed on ice or inside a refrigerator to maintain the temperature at 4±2 degrees Celsius prior to being analyzed in the field and/or shipped to the laboratory on ice.

Table 5.1: **Groundwater Sampling and Analysis Plan for Camp Pendleton Site 1115**

Event	Number of samples to be collected		
	VOCs	Sulfate/Persulfate	Anions
Pre-enhancement	13	13	13
Post- enhancement (1 month)	13	13	13
Pre- enhancement (6-month)	13	13	13

Note: Samples will be collected from 11 existing monitoring wells and 2 temporary wells.

Table 5.2: **Groundwater Sampling and Analysis Plan for Lake City AAP Site 17D**

Event	Number of samples to be collected			
	VOCs	MEEA	TOC	Anions
Pre- enhancement	12	12	12	12
Post- enhancement (1 month)	12	12	12	12
Pre- enhancement (6-month)	12	12	12	12

Note: Samples will be collected from 6 existing monitoring wells and 6 temporary wells (2 near hydraulic and 4 near pneumatic enhancement points).

Table 5.3: **Groundwater Sampling and Analysis Plan for Grand Forks AFB Site TU504**

Event	Number of samples to be collected			
	VOCs	MEEA	TOC	Anions
Pre- enhancement	13	13	13	13
Post- enhancement (1 month)	13	13	13	13
Pre- enhancement (6-month)	13	13	13	13

Note: Samples will be collected from 7 existing monitoring wells and 6 temporary wells.

<u>Soil Sampling</u>

The following general procedure will be used to collect soil samples for off-site analyses. CDM Smith SOPs shown in **Appendix E** will also be followed.

- Soil samples will be collected for TOC analysis at the Lake City AAP Site 17D and the Grand Forks AFB Site TU504 while sulfate and persulfate analyses will be conducted at the Camp Pendleton Site 1115.
- Three composite soil samples from the entire fracture interval (20-foot interval for Lake City and Camp Pendleton; 10-foot interval for Grand Forks) will be collected at each of the pre enhancement boreholes (which will be completed as temporary wells) while at least two composite soil samples from each target fracture interval (4-foot interval for Lake City and Camp Pendleton; 5-foot interval for Grand Forks) will be collected at each of the two post-enhancement confirmation boreholes as shown in **Tables 5.4** and **5.5**.
- Sample container and preservation requirements are presented in **Table 5.6** of the Demonstration Plan. Sample containers will be completely filled with soil.
- Each sample will be labeled with the appropriate sample identification and other information discussed in **Section 9** of this QAPP.
- The sample containers will then be placed on ice or inside a refrigerator to maintain the temperature at 4±2 degrees Celsius prior to being shipped to the laboratory on ice.

Table 5.4: **Pre-Enhancement Soil Sampling and Analysis Plan for Three Demonstration Sites**

Site	Depth interval (feet below ground surface)	Number of samples to be collected	
		Sulfate/Persulfate	TOC
Camp Pendleton Site 1115	20-40	6	-
Lake City AAP Site 17D	15-35	-	18
Grand Forks AFB Site TU504	10-20	-	18

Table 5.5: **Post-Enhancement Soil Sampling and Analysis Plan for Three Demonstration Sites**

Site	Depth interval (feet below ground surface)	Number of samples to be collected	
		Sulfate/Persulfate	TOC
Camp Pendleton Site 1115 (2 borings; 2 composite samples per interval)	20-24	4	-
	24-28	4	-
	28-32	4	-
	32-36	4	-
	36-40	4	-
Lake City AAP Site 17D (8 borings; 2 composite samples per interval)	15-19	-	16
	19-23	-	16
	23-27	-	16
	27-31	-	16
	31-35	-	16
Grand Forks AFB Site TU504 (8 borings; 2 composite samples per interval)	10-15	-	16
	15-20	-	16

Hydraulic and Geophysics Testing

In addition to soil and groundwater sampling, a number of hydraulic and geophysics tests will be performed as part of this demonstration as shown in **Table 5.6** and summarized as follows:

- Pre- and post-enhancement hydraulic testing (aquifer pumping test) and tilt-metering will be performed at each of the three demonstration sites using CDM Smith's and subcontractor-provided SOPs shown in **Appendices E** and **F**. It should be noted that the post-enhancement aquifer performance test will be conducted approximately one month following the completion of all enhancement work at each of the sites. In addition, the pumping tests will be conducted upon completion of all groundwater performance monitoring activities to avoid any data biases. Details regarding the aquifer pumping test to be performed at each demonstration site will be included in the final version of the demonstration plan.
- Direct-push EC logging will be performed at the Grand Forks AFB Site TU504 before and after hydraulic enhancement.
- ERT will be performed at the Lake City AAP Site 17D and the Grand Forks Air Force Base Site TU504.
- ERT and EC logging will be performed in accordance with the subcontractors' SOPs and post-enhancement ERT and EC testing will be performed immediately after the enhancement work has been completed (Mobilization 2).

Table 5.6: **Hydraulic and Geophysics Testing**

Site	Tilt-metering during frac	Aquifer pumping test		EC logging		ERT	
		Pre-frac	Post-frac	Pre-frac	Post-frac	Pre-frac	Post-frac
Camp Pendleton Site 1115	✓	✓	✓				
Lake City AAP Site 17D	✓	✓	✓			✓	✓
Grand Forks AFB Site TU504	✓	✓	✓	✓	✓	✓	✓

6.0 Calculation of Data Quality Indicators

The following subsections list the parameters that will be assessed and the criteria used to review and validate data objectively and consistently. The practical quantitation limits (PQLs) for the individual parameters for both field and laboratory analyses have been outlined in the Demonstration Plan.

6.1 Accuracy

Accuracy of laboratory results will be assessed using the analytical results of method-defined surrogates, laboratory control samples, matrix spikes, and calibration standards. The percent recovery (%R) will be calculated using the following equation:

$$\%R = \frac{A - B}{C} \times 100$$

where:
A = analyte concentration determined experimentally in the spiked sample
B = analyte concentration determined by a separate analysis of the unspiked sample
C = concentration of spiked analyte

The only samples to be sent to an offsite laboratory that require matrix spikes are for VOC in groundwater. The accuracy goal for these samples is a percent recovery of 70-130%. Matrix spikes will be conducted as part of the laboratory QA/QC program. Trip blanks will be included for VOC samples to assess whether contamination during sample handling occurred. The accuracy goal for method-defined surrogates, laboratory control samples, and calibration standards are defined by the laboratory in their quality assurance plan and SOP methods.

6.2 Precision

Precision will be assessed by calculating RPD between the field duplicate samples and laboratory duplicate samples. The RPD will be calculated for each pair of duplicates using the following equation:

$$\%RPD = \frac{S - D}{(S + D)/2} \times 100$$

where:
S = first sample value
D = second sample value (duplicate value)

The precision goal for this project for sample pairs whose values are both greater than 10 times the PQL limit is an RPD $\leq$ 35%. For sample pairs that have one or both values less than 10 times the PQL, the precision goal is RPD $\leq$ 50%. Sample pairs that have one or both values that are less than the PQL will not have RPDs calculated. If the precision goals are not met for a given sampling round, the project manager and field team leader will perform a review of sample collection and handling procedures. For analyses performed in the field, the analytical procedure will also be reviewed.

6.3 Completeness

Completeness of data will be assessed as the percentage amount of usable data (i.e., meeting precision, accuracy requirements, and requirements discussed in **Section 9.3**) compared to the total amount of expected data using the following equation:

$$\%Completeness = \frac{Valid\ Data\ Obtained}{Total\ Data\ Planned} \times 100$$

The completeness goal for this project is 90% of all planned samples, as defined in the Demonstration Plan. Completeness will be tracked over the course of the demonstration.

6.4 Representativeness

Representativeness expresses the degree to which data accurately and precisely represent a characteristic of a population and parameter variations at a sampling point, a process condition, or an environmental condition. Representativeness is a qualitative parameter that is dependent on the proper design of the sampling program and proper laboratory protocol. The sampling program is described in **Section 5.5** of the Demonstration Plan.

Representativeness of the data will be assessed by the CDM Smith Project Manager and the QA Coordinator through review and comparison of the applicable data (field and laboratory duplicates, spikes, and blanks) and by verifying that the sampling and analysis plan/design set forth in the Demonstration Plan was followed for all data generated during the project activities.

6.5 Comparability

Comparability expresses the confidence with which one data set can be compared with another. The extent of comparability between existing and planned analytical data depends in part on the similarity of sampling and analytical methods. The procedures used to obtain the planned analytical data, as documented in the QAPP and Demonstration Plan, are expected to provide comparable data for these project activities.

7.0 Performance and System Audits

Field audits, laboratory audits, and self-assessments may be conducted to verify that sampling and analysis are performed in accordance with the procedures established in the Demonstration Plan and this QAPP. This section discusses the scope and frequency of each activity.

7.1 Field Audits

Internal audits of field activities (sampling and measurements) will be conducted by the CDM Smith QA Coordinator or QA-trained field auditor. A self-assessment will be conducted by the Principal Investigator or designated field team lead. The audits will include examination of field sampling records, field instrument operating records, sample collection, handling and packaging, chain-of-custody records, and the maintenance of QA procedures. These internal audits will be performed to make sure field work is in compliance with established procedures. It is currently anticipated that one onsite field audit will be performed at the second demonstration site.

If non-conformances are found, then the QA Coordinator working with the Project Manager and Principal Investigator will be responsible for ensuring that corrective actions are initiated by:

- Documenting them in an audit report to be added to the project file
- Evaluating all reported non-conformances
- Controlling additional work on nonconforming items
- Determining disposition or action to be taken
- Reviewing corrective action requests and corrective actions taken
- Ensuring corrective action requests are included in the final site documentation in project files

If appropriate, the QA Coordinator will verify that no additional work that is dependent on the nonconforming activity is performed until the corrective actions are completed.

Corrective action for field measurements may include:

- Repeat the measurement to check the error
- Check for all proper adjustments for ambient conditions such as temperature
- Check the batteries
- Recalibrate
- Check the calibration
- Replace the instrument or measurement devices
- Stop work (if necessary)

At this time it is not anticipated that external audits of the field activities will be needed. If the internal audits determine that deficiencies exist that require an outside organization or agent to resolve, external audits will be conducted by an independent subcontractor.

7.2 Laboratory Audits

CDM Smith is responsible for conducting laboratory pre-qualification evaluations consisting of the review of QA plans and the costs of various laboratories. A contingency laboratory may be contracted to perform general chemistry analyses, if necessary.

7.3 Self Assessments

CDM Smith will perform a self-assessment of the project files near the conclusion of the demonstration. This self-assessment will serve to ensure that documents have undergone appropriate review cycles. It also provides a check on records retention and management.

8.0 Quality Assurance Reports

8.1 ESTCP Quarterly Reports

The CDM Smith project manager will prepare ESTCP-required quarterly reports. These reports will update accomplishments on the demonstration and briefly describe any concerns that may affect technical or financial progress of the demonstration. These will be submitted using the web-based ESTCP reporting system. The Principal Investigator will also update ESTCP on progress and any issues affecting the project during annual in-progress review meetings.

8.2 Audit Reports

Reports will be prepared following each field and technical system audit by the QA Coordinator and reviewed by the Principal Investigator. The report will summarize the activities performed during the audit and will present the findings. Any non-conformances and associated corrective actions will be discussed.

Laboratory audits will be written and maintained by the individual laboratory. These will be reviewed by CDM Smith as needed during the demonstration.

9.0 Data Management

Data management requirements are an essential part of the demonstration. The data management requirements included in this section outline procedures necessary to document, track, and manage field and laboratory data generated during the course of the field activities. The purpose of this section is to identify:

- Data management personnel and responsibilities
- Field, laboratory, and development data to be recorded and maintained
- Data coding requirements
- Data to be included on progress and site investigation reports

This section provides format requirements for presenting raw data, tabulated data, and summary data of field and laboratory analyses.

9.1 Management and Organization

9.1.1 CDM Smith Principal Investigator

The CDM Smith Principal Investigator will be responsible for providing inputs in critical field decisions and reviewing data and deliverables.

9.1.2 CDM Smith Project Manager

The CDM Smith Project Manager will be responsible for checking that all field and laboratory information is collected and recorded accurately. The Project Manager will also be responsible for approving any changes in or deviations from the reporting of data, including data validation. Furthermore, the Project Manager will be responsible for performing inspections related to the generation, collection, and storage of data by laboratories.

9.1.3 CDM Smith Field Team Leader

The CDM Smith Field Team Leader will be responsible for maintaining and recording information and data required in the field logbook. In addition, the Field Team Leader will be responsible for checking that laboratory data are accounted for and accurately reflect field sampling and chain-of-custody information.

9.1.4 CDM Smith Technical Task Lead for Data Analysis and Interpretation

The Technical Task Lead for Data Analysis and Interpretation will be responsible for data entry, management, and evaluation. The Technical Task Lead will maintain project data in spreadsheets or databases as appropriate. The Technical Task Lead will also work with the Principal Investigator to form interpretations of Demonstration Plan data. The Technical Task Lead for Data Analysis and Interpretation will be responsible for maintaining trend charts and cumulative data tables. The Technical Task Lead for Data Analysis and Interpretation will work with the Technical Task Lead for Planning and Reporting as needed in order to produce the required project reports.

9.1.5 Laboratory Project Manager

Multiple laboratories may be contracted to analyze environmental samples collected during the demonstration. These laboratories will each provide a Laboratory Project Manager responsible for ensuring that all laboratory data submitted are recorded, documented, and presented in the proper formats.

9.1.6 CDM Smith QA Coordinator

The CDM Smith QA Coordinator is responsible for data management efforts related to detecting and correcting errors, and for data loss prevention.

9.2 Documentation and Records

Data, photographs, field logs, and calibration logs generated during the course of the investigation will be included as part of the project file. After completing the demonstration, data and reports will be maintained by CDM Smith.

9.2.1 Recording of Field Data

Field logbooks will be maintained by CDM Smith in accordance with CDM Smith's SOP 4-1 *Field Logbook Content and Control*. Separate field sheets may also be used to record field data. The front cover of each logbook will be labeled with the following information:

- Person or organization to whom the book is assigned
- Book number
- Project name and number
- Start date
- End date

Logbook entries will contain accurate and detailed documentation of daily project activities. Because the information contained in these logbooks forms a basis for subsequent reports, the field logbook will include the information specified below.

- Site identification
- Location of sampling points
- Description of sampling points
- References to any photographs
- Sample identification numbers
- Number of samples taken
- Date and time of sample collection
- Reference to sample location map
- Number of QA samples taken (e.g., duplicates)
- Collector's name
- Field observations
- Sample distribution (e.g., onsite laboratory, offsite laboratory)
- Field measurements made (e.g., pH, temperature, ORP, DO)

Any changes required to field logbook entries will not obscure the original entry. Changes will be made by striking a single line through the information to be changed and initialing and dating the change.

The Field Team Leader will perform quarterly reviews of field logbooks to check that data entries are being performed as specified above and in accordance with the CDM Smith SOP for field logbook content and control.

9.2.2 Recording of Laboratory Data

Particular procedures related to the management of data received from the laboratory will be recorded. These forms will not be included as part of the field logbook but will be maintained as part of the project files. The Laboratory Manager will be responsible for storing information and data recorded by the laboratory and related to the investigation. This information may include:

- Chain-of-custody forms
- Internal laboratory performance audits
- Raw data printouts
- Tabulated data printouts
- Laboratory QA/QC data

In addition, these data will be stored in a manner that protects their integrity.

For documentation purposes, each environmental sample or measurement will have the following applicable record details:

- A unique sample or field-measurement identification number
- Sample or field-measurement location
- Date sample or field measurement was taken
- Sample or field-measurement type
- Sample or field-measurement raw data
- Laboratory analysis qualifier
- Property or analysis measured
- Result of analysis (e.g., concentration)

9.2.3 Documentation of Sample Collection

Sample collection will be documented as described previously in **Sections 9.2.1** and **9.2.2**. The following information will be recorded, as applicable:

- Custody and document control
- Chain-of-custody from field to laboratory
- Laboratory custody through designated laboratory-sample custodian
- Sample designation number(s)
- Identity of sampler
- Date of sample collection, shipping, and laboratory analysis
- Physical data elements
- Sampling date and time
- Sampling location and description
- Sample collection technique
- Field preparation techniques (e.g., filtering)

- A description of the sampling methodology used
- Field preservation technique

9.2.4 Analytical Database

The primary objective for developing an analytical database is to ensure that a detailed record of data collection, analysis, verification, and reporting is maintained. In particular, environmental sampling data will be stored in an Excel database to facilitate data evaluation, statistical analyses, and reporting. CDM Smith will manage all field sampling and laboratory analytical data, which will be maintained in the project files.

9.2.5 Tabular Displays

Tabular displays will be used in the final report to present laboratory data, as appropriate. These displays may include:

- Unsorted (raw) data
- Data reduced for statistical analysis
- Sorted data by constituent monitored
- Other summarized data

9.2.6 Recording of Development Data

Development data are identified as those data or information developed using raw field or laboratory results (e.g., test kits, meter readings). Such data will be included in the final report and will be prepared in a clear, concise manner using graphical displays as appropriate.

9.3 Data Validation and Usability

Laboratory results will be reviewed for compliance with project objectives. Data validation and evaluation are discussed in the following sections.

9.3.1 Validation and Verification Methods

CDM Smith will evaluate analytical results to determine if they meet the expected performance criteria detailed in **Section 3** of this QAPP. For each sample delivery group, CDM Smith will review the data to flag any obvious discrepancies and compare the data with the expected performance metrics. Data quality reviews will include the evaluation of holding times, blanks, laboratory control samples, surrogate recoveries, internal standards, calibration checks, dilutions, and laboratory case narratives.

9.3.2 Data Reporting

The analytical laboratory will provide all project data in both hardcopy and electronic format. The laboratory will also be required to confirm sample receipt and log-in information. The laboratory will return a copy of the completed chain-of-custody and confirmation of the laboratory's analytical log-in to CDM Smith within 24 hours of sample receipt.

The laboratory is required to retain a full copy of the analytical data and QC documentation. Such retained documentation will include all hard copies and electronic storage media. Deficiencies in data deliverables will be corrected through direct communication with the laboratory. All significant data discrepancies noted during the validation process will be documented.

Data assessment will be based on the criteria that the sample was properly collected and handled in accordance with the Demonstration Plan and QAPP. An evaluation of data accuracy, precision, and completeness, based on the criteria presented in this QAPP, will be performed by the data validator. This data quality assessment will indicate that the data are: (1) usable as a quantitative concentration, (2) usable with caution as an estimated concentration, or (3) unusable due to excessive out-of-control QC results. The demonstration study report will include a quality assurance section that will include an explanation of any deviations, the extent to which objectives were met, the usability of the data collected, and if data precision and accuracy were met.

9.3.3 Data Turnaround Time Requirements

The standard turnaround times for most analytical deliverables is 14 days from the time of receipt by the laboratory; however, CDM Smith may request accelerated turnaround times. Advance notification will be provided to the laboratory prior to decreasing the turnaround time. The laboratory will store samples for a minimum of 90 days prior to appropriate disposal. The laboratory will dispose of samples in accordance with all applicable regulatory requirements.

10.0 Data Storage and Archiving Procedures

The documents outlined below shall be maintained in Denver, Colorado by CDM Smith in project files. The following documents shall be placed in the project file:

- Copy of the Demonstration Plan
- Copy of the Health and Safety Plan
- Copy of this QAPP
- Original chain-of-custody records and field logs
- Laboratory data (including electronic data deliverables)
- Copies of the Receipt of Sample Forms
- Original records obtained during the demonstration
- Complete copy of the analytical data and memoranda transmitting analytical data
- Official correspondence received by or issued by ESTCP, or subconsultants to ESTCP, relating to the demonstration
- Photographs associated with the project
- Reports (interim and final)

All records and documents that relate in any way to the site shall be preserved and retained for a minimum of ten years after the work has been completed. The CDM Smith Project Manager will review the files at the conclusion of the project in reference to this document to ensure they are complete.

Electronic documents generated through the demonstration will be retained on CDM Smith's server in Denver, Colorado and on ProjectWise. This server is backed up daily, minimizing the potential for data loss. The most current version of each document will be maintained on the server and working copies will be placed in a file marked as superseded. The Principal Investigator will be the point-of-contact to obtain copies of records from the project file.

11.0 References

CDM Smith. 2012. CDM Federal Programs Corporation. Quality Assurance Manual. Revision 20. January.

Environmental Protection Agency (EPA). 2002. Guidance for Quality Assurance Project Plans. EPA QA/G-5. EPA/240/R-02/009. December.

Environmental Security Technology Certification Program (ESTCP). 2010. Demonstration Plan Guidance, Environmental Restoration Projects. July.

APPENDIX C

Emplacement Volume Estimates

APPENDIX C

EMPLACEMENT VOLUME ESTIMATES

ROD – Radius of distribution is the extent of fracture. The fracture can consist of solid or liquid phase remediation amendment or of sand proppant.

ROI – Radius of influence will be larger than the ROD. In the case of a solution amendment, the extent of influence beyond the ROD will be a function of the matrix permeability, viscosity and mobility of solution, chemical gradient, and groundwater flow. In the case of a solid phase amendment, the extent of influence beyond the ROD will be a function of the matrix permeability, solubility and mobility of dissolved amendment, chemical gradient, and groundwater flow. In the case of injection or extraction of gasses or solutions using sand propped fractures, the extent of influence beyond the ROD will be a function of the matrix permeability, viscosity and mobility of solution or gas, pumping pressure or groundwater head, chemical gradient, and groundwater flow.

The predicted theoretical radius of distribution is estimated using volume pumped and assumption of pumping thickness of fracture. The pumping thickness of the fracture is the aperture of the fracture during propagation. The estimated area of the fracture is derived by dividing the volume pumped by the assumed pumping thickness. The radius is calculated from the area with the assumptions that the fracture will be close to horizontal and will propagate equally in all directions from the fracture borehole (length to width aspect ratio of 1) and will be centered on the fracture borehole.

It must be noted that fractures often have an aspect ratio that is greater or less than 1 and fractures typically have some degree of dip. In our experience, the majority of fractures have dip angles of 15 to 35 degrees but dip angles from horizontal to vertical have been observed. It is recommended that overlap of theoretical ROI is planned. In some cases we recommend overlap of ROD.

When propagation (pumping) stops some of fluid will move into the pore spaces of the surrounding matrix as the fracture closes. If the fracture fluid is carrying solids, such as sand, the fracture will be propped open and will not close completely; the thickness of resulting propped aperture is referred to as the propped thickness.

Grand Forks Air Force Base Site TU504: Desired ROI of 10 to 15 feet (ft). Planned fracture volume (deeper fractures) – 130 gallons for theoretical ROD of 14 ft. Conservative theoretical ROI of 14 to 15 ft.

Camp Pendleton Site 1115: Desired ROI of 20 to 25 ft. Planned fracture volume – 585 gallons for theoretical ROD of 23 ft. Conservative theoretical ROI of 25 to 28 ft, this may vary with depth as lithology varies.

Lake City Army Ammunition Plant Site 17D: Desired ROI of 20 to 25 ft. Planned fracture volume – 530 gallons for theoretical ROD of 22 ft. Conservative theoretical ROI of 23 to 24 ft.

APPENDIX D

Health and Safety Plan

APPENDIX E

CDM Smith’s Technical Standard Operating Procedures

APPENDIX F

Points of Contact

Appendix F

Points of Contact

Point of Contact	Organization	Phone/Fax/Email	Role in Project
Kent Sorenson, Jr	CDM Smith 555 17th Street, Suite 1100 Denver, CO 80202	Phone: 303-383-2300 Cell: 303-241-2156 Fax: 303-383-2300 SorensonKS@cdmsmith.com	Principal Investigator
Eva Opitz	CDM Smith 1050 North Reed Station Road, Suite D Carbondale, IL 62902	Phone: 618-351-4647 Cell: 618-559-4581 Fax: 618-351-1250 opitzem@cdmsmith.com	Program Manager
Nathan Smith	CDM Smith 555 17th Street, Suite 1100 Denver, CO 80202	Phone: 303-383-2300 Cell: 405-831-8863 Fax: 303-383-2300 SmithNT@cdmsmith.com	Project Manager
Michael Lamar	CDM Smith 555 17th Street, Suite 1100 Denver, CO 80202	Phone: 303-383-2300 Cell: 720-626-7180 Fax: 303-383-2300 LamarMR@cdmsmith.com	Technical Advisor
Dung Nguyen	CDM Smith 555 17th Street, Suite 1100 Denver, CO 80202	Phone: 303-383-2300 Cell: 206-743-4990 Fax: 303-383-2300 NguyenDD@cdmsmith.com	Project Engineer & Field Team Leader
Ralph Pearce	NAVFACSW 1220 Pacific Highway San Diego, CA 92132	Phone: 619-532-3768 ralph.pearce@navy.mil	Camp Pendleton's military point of contact
Sara Clark	Lake City Army Ammunition Plant 7 and 78 Highway, Building 6 Independence, MO 64051-1000	Phone: 816-796-7159 Fax: 816-796-7143 Sara.B.Clark4.civ@mail.mil	Lake City Army Ammunition Plant's Remedial Project Manager and Environmental Coordinator
Hunter Anderson	Technical Support Branch (CZTE) Air Force Civil Engineer	Phone: 210-395-9289 richard.anderson.55@us.af.mil	Grand Forks Air Force Base's military point of

Point of Contact	Organization	Phone/Fax/Email	Role in Project
	Center (AFCEC) Lackland AFB, TX		contact
Kaye Guille	ARGO/LRS Federal	KGuille@LRSFederal.com	Grand Forks Air Force Base's Contractor point of contact
Andrea Leeson	SERDP/ESTCP 901 N Stuart Street, Suite 303 Arlington, VA 22203	Phone: 703-696-2118 Fax: 703-696-2114 Andrea.Leeson@osd.mil	ESTCP Program Manager

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APPENDIX C UTILITY LOCATE REPORTS

ULS SERVICES CORP

GEOMARKOUT LOCATING CO a trade name of ULS

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CORPORATE ADDRESS

P.O. Box 724, Pocatello, ID 83204 (Mail only)

6742 West Buckskin Rd., Pocatello, Id 83204

FIELD SERVICES:

SEATTLE/ SAC / AK / HAW-PACIFIC RIM

1 866 804-5734

SOCAL

1 800 528-8206

Work Order Agreement

Job Site Location IR SITE 1115	PO TO WA	
City, State MCB CAMP PENDLETON, CA	Job Date 6-6-16	
CLIENT IO ENV	FIELD TIME 1.5 REPORT .5	LABOR HOURS W/REPORT/ HRS 2.
ADDRESS		FAXED
CITY, STATE, ZIP		TELEPHONED
PHONE/FAX		HAND DELIVERED
E-MAIL		E-MAILED

WORK REQUESTED: UTILITY SURVEY IN 50' X 50' AROUND 3 PROPOSED MW

WORK PERFORMED	PRELIMINARY REVIEW OF CLIENT PROVIDED UTILITY DRAWINGS/AS-BUILTS: NONE
VISUAL SITE INSPECTION (MANHOLES, DRAINS): YES SURFACE ONLY	EMPCL CONDUCTIVE UTILITY SURVEY: CHECKED GAS: X ELECTRIC: X COMM.: X WATER: X
EMIMD METAL DETECTION SURVEY : YES AMBIENT NOISE AND SETTINGS LOW NOISE | GAIN 6.5 | LOW ELV REBAR IN CONCRETE ?	EM INSERTION : NF - INSERTION METHODS NOT PROVIDED DUE TO HEALTH AND SAFETY. SEE NOTES BELOW REGARDING LATERALS
GPR NON-CONDUCTIVE SURVEY: POOR	CLIENT ON-SITE REVIEW OF FINDINGS: YES

GENERAL LIMITATIONS

NOTE: The work described herein is performed to industry standards (or higher) using multiple methodology and QA/QC protocol. ULS cannot guarantee the accuracy or the ability to detect all underground facilities and potential interferences. Non-conductive or conductive utilities/facilities may not be detected due to variables and constraints beyond ULS control. Where known, constraints and limitations will be brought to the client's attention. Excavation work may result in injury to persons and/or damage to facilities. Client and/or excavator are advised to take all steps necessary to avoid contact with underground facilities. This includes, but is not limited to, safe digging practices, hand tooling in congested areas and within two feet on side of marked utilities (distance may vary by law), utility drawing review, site facilities representative review, and "one-call" utilities notification. ULS and its representatives are not responsible for injury to persons or damage to facilities. This document and accompanying pages will be delivered to the client before commencement of intrusive work for the client's review. If any questions arise, please notify our office immediately.

NOTE: Specific comments/limitations/constraints, known and recognized will be recorded on attached pages (field notes). Caution – some facilities (conductive or non- conductive) may not be detected. Not all limitations and constraints may be recognized.

SIGNATURE OF ULS REPRESENTATIVE ON-SITE CHRIS REIMER		PAGE OF 1

ULS SERVICES CORPORATION

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CLIENT	**IO ENV**
LOCATION	**IR SITE 1115**
DATE	**6-6-16**

METHODS AND GENERAL OBSERVATIONS:

ARRIVED SITE AND COMPLETED H&S TAILGATE AND/OR PERMIT TO WORK WITH CLIENT. SET UP DELINEATORS AROUND VEHICLE AND NEAR BLINDSPOTS AND ENTRY WAYS. MADE GENERAL SITE WALK TO REVIEW SURVEY AREAS (PROPOSED ZONES). CHECKED FOR SURFACE UTILITY MANIFESTATIONS SUCH AS VALVES, METERS, CONDUITS, TRENCHING SEAMS, VAULT LIDS AND EXISTING ONE CALL MARKINGS. BEGAN MARKOUT WORK.

METHODS UTILIZED INCLUDE: EM PIPE AND CABLE LOCATOR USING AMBIENT, GROUND INDUCTION AND CONNNECTION MODE SWEEPS. EM INDUCTION METAL DETECTOR AND GPR. A CARTISIAN GRID PATH IS WALKED AT EACH PROPOSED ZONE USING ALL METHODOLOGY. OBSERVATIONS ARE MARKED WITH WHITE AND/OR PINK PAINT. ZONE IS MARKED OUT WITH WHITE AND/OR PINK MARKINGS (REFER TO PHOTOS).

SITE CALIBRATION - GENERAL OBSERVATIONS

EM PIPE AND CABLE TRANSMITTER TO RECIEVER (GROUND INDUCTION AND CONNECTION) BROADCASTING IS __GOOD_______ATTENUATION EFFECTS FROM CONCRETE STEEL REINFORCEMENT _NIL_____
EMIMD METAL DETECTOR BACKGROUND EM NOISE IS _LOW_____________
GPR PENETRATION AND RESOLUTION IS _POOR__________.

SEE QA / QC OBSERVATION COMMENTS TO RIGHT SIDE AND SPECIFIC OBSERVATIONS / COMMENTS BELOW ……………………………….>

	QA / QC Follows
X	**SITE WALK**
X	VISUALS
X	
X	**UTILITY MAINS**
X	**ELECTRIC** – OVERHEAD
X	**TELEPHONE** – OVERHEAD
X	**NAT GAS** NONE OBSERVED
X	**WATER** AWAY FROM ZONE
X	SEWER/STORM SEWER M/H NORTHEAST
X	**SEWER LATERAL**
X	**CAUTION NO CLEANOUT OBSERVED**
X	CAUTION PVC WATER
X	
X	**OTHER**
	FUELS SYSTEM
	USTS
	PIPING
	VENTS

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CLIENT **IO ENV**
LOCATION **IR SITE 1115**
DATE **6-6-16**

SPECIFIC OBSERVATIONS AND COMMENTS OR CONCERNS:

PROPOSED :

SURVEY ZONE IS APPROX 50' X 50' AROUND 3 PROPOSED MW LOCATIONS

NO EM SIGNALS FOUND WITHIN SURVEY ZONE LIMITS.

SOME CAUTION FOR POTENTIAL TRENCH PATCHING OBSERVED AT 5' TO 6' NORTH OF MW2. NO EM SIGNAL OBSERVED AND GPR RESPONSE BEING POOR SHOWED NO PARABOLIC REPONSE OF SOIL DISTURBANCE

ASPHALT PATCHING AT THE FENCE NORTH OF PROPOSED WELLS SHOWED SOME SHALLOW GPR RESPONSE INDICATING POSSIBLE SOIL DISTURBANCE

ELECTRIC AT POLE TO BREAKER BOXES ON POLE DO NOT GO UNDERGROUND, GROUND WIRING AT THE SUPPORT POLE ONLY.

VISUAL AT SEWERMANHOLE NORTHEAST OF SURVEY ZONE (OUTSIDE FENCE) SHOWED PIPING TRENDING EAST ONLY AWAY FROM SURVEY ZONE

END REPORT/ PHOTO EDITS ATTACHED

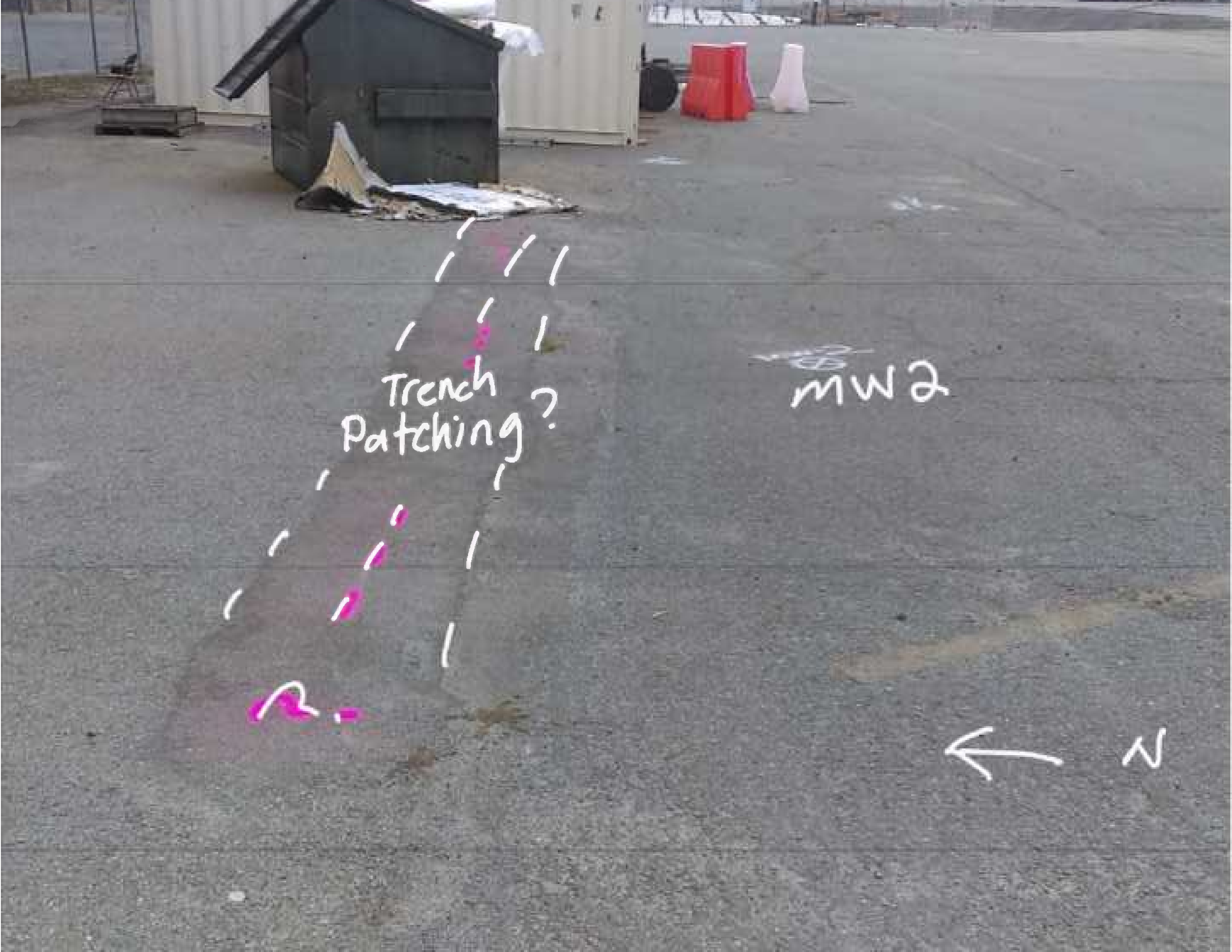
LOCATE ENERGY ISOLATION INCLUDING WATER AT THIS SITE AND SAWCUT, JACKHAMMER, AIRKNIFE DIG CAREFULLY IN EACH LOCATION.

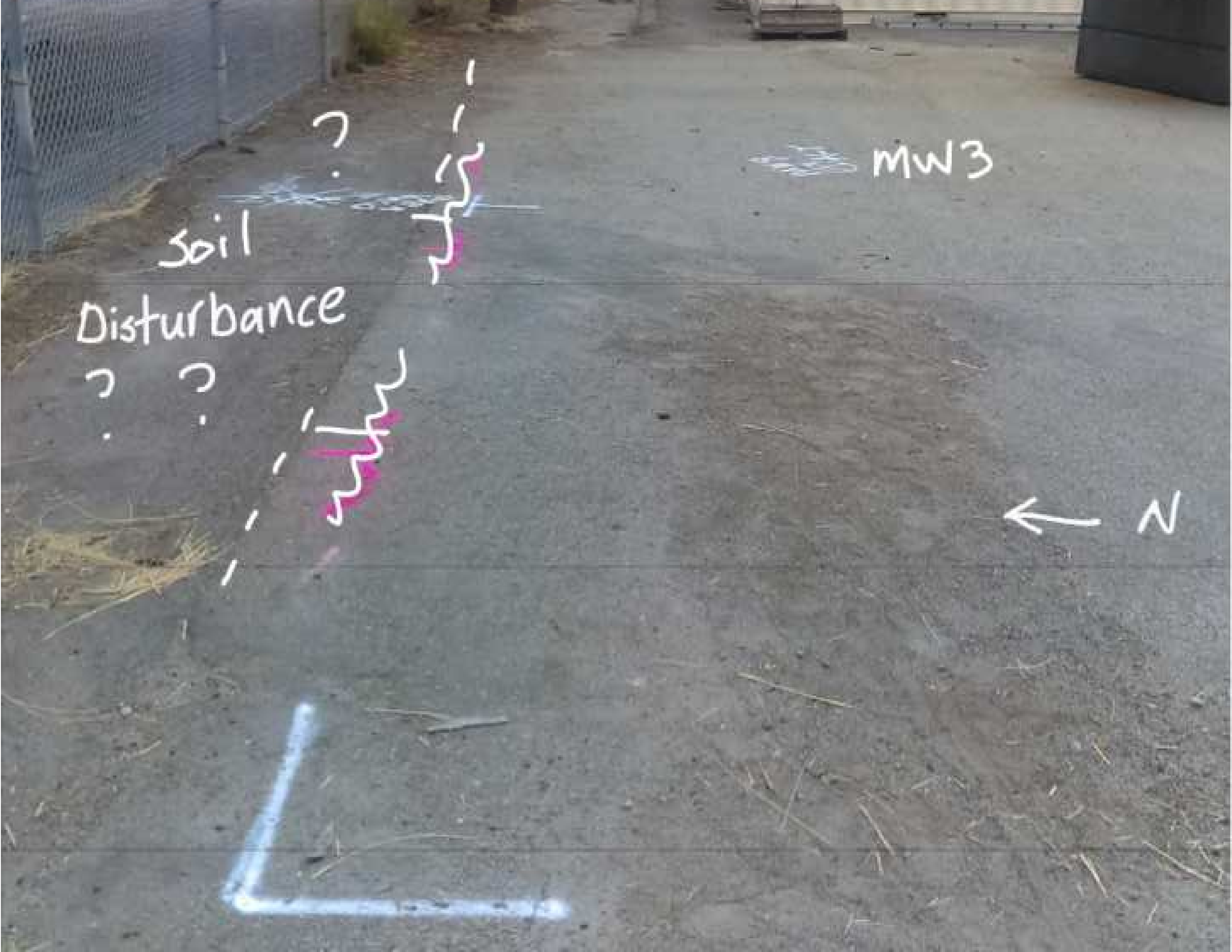
.

CHRIS REIMER
ULS / GEOMARKOUT


MW2
MW1
N


MW1
N
U.S


Trench
Patching?
MW2
N



MW3
Soil
Disturbance
?
? ?
N


MW3
N
Ground


Survey Zone C
END
N

From:	Kaye Guille
To:	Nguyen, Dung D.
Subject:	FW: Ticket: 16127863
Date:	Thursday, September 08, 2016 5:32:06 AM

From: Dan Parker
Sent: Tuesday, August 30, 2016 9:14 AM
To: Kaye Guille
Subject: FW: Ticket: 16127863

From: nd@occinc.com [mailto:nd@occinc.com]
Sent: Monday, August 29, 2016 6:08 PM
To: Dan Parker <dparker@lrsfederal.com>
Subject: Ticket: 16127863

NORTH DAKOTA ONE-CALL

You can check that the ticket information and mapping location are correct, and that no work will take place outside the area indicated on the map, by clicking on the TicketLINK. Should any changes be needed, you can use the 'Update' or 'Correct' Ticket functions on ITIC.

The map is ONLY used to determine which facility operators may have facilities in your dig area. The Utilities do NOT receive a copy of this map. The precise excavation area and scope of work MUST be described in the extent of work field on the ticket.

The TicketLINK may also be used to view utility status, request a 'Relocate' or 'Cancel' a request. If you have any questions, call 563-884-7762.

Ticket Summary

Request #	16127863	**LORQ ROUTINE**			
Work to Begin Date :	9/06/16 8:00 AM CT	**Original Call Date:**	8/29/16 10:35 AM CT		
Type of Work:	SOIL BORINGS				
County:	GRAND FORKS	**Place:**	GRAND FORKS AFB CDP		
Address:	0 EIELSOM ST				
Nearest Intersection:	TUSKEGEE AIRMAN BLVD				
Township:		**Rng:**		**Sect-Qtr:**	
Caller Lat:	47.951267	**Lon:**	-97.388164	**Zone:**	**Nad:** 83
Depth:	10FT	**Explosives:**	N	**Tunneling/Boring:** Y	

Location of Work:

300 FEET WEST OF THE INTERSECTION OF EIELSOM ST AND TUSKEGEE AIRMAN BLVD, MARK SELECTED AREA WITH FLAGS AND PAINT (SEE ATTACHED MAP)

GO TO LINK TO OBTAIN ADDITIONAL INFORMATION THAT WAS PROVIDED BY THE EXCAVATOR REGARDING THIS LOCATION.

Remarks: CALLER REQUESTS AREA BE MARKED WITH PAINT AND FLAGS

Caller Information

Company:	LRS FEDERAL LLC	**Fax:**	
Contact Name:	DANIEL PARKER	**Phone:**	(410)544-3570
Address:	8221, STE 300 RITCHIE HWY		

	PASADENA, MD 21122		
Alt. Contact:	DAN PARKER	**Phone:**	(412)965-0831
Contact Email:	dparker@lrsfederal.com		
Work Being Done For:	AIRFORCE CIVIL ENGINEER CENTER		

Members Notified:

CTLND01	-	CTLQL-CENTURYLINK	(800)283-4237
TCI05	-	MIDCONTINENT COMMU	(605)271-0202

If there are any private underground facility operators in the excavation area, you should notify them directly.

* Per North Dakota Century Code, it is the responsibility of the ticket holder to remove all tangible marking material (ex - pin flags) upon completion of the excavation. Failure to comply is subject to penalties and fines up to $25,000.

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P.O. Box 724, Pocatello, ID 83204 (Mail only)
6742 West Buckskin Rd., Pocatello, Id 83204

FIELD SERVICES:
SEATTLE/ SAC / AK / HAW-PACIFIC RIM
15151 52nd Avenue S., Suite 2 Seattle WA 98188
1 866 804-5734
SOCAL
9065 Calle Del Verde, Santee CA 92071
1 800 528-8206

ULS SERVICES CORP

GEOMARKOUT a trade name of ULS

Work Order Agreement

Job Site Location SITE 17 D LAKE CITY ARMY AMMUNITION PLANT	Job W.A.	
City, State INDEPENDENCE, MO	Job Date 29 FEB 16	
CLIENT CDM	FIELD TIME	LABOR HOURS W/REPORT/ 1.5 DAYS
CITY, STATE, ZIP DENVER		
E-MAIL		E-MAILED

WORK REQUESTED: UTILITY LOCATION AT PROPOSED "DEMONSTRATION " AREA(S). LOCATE MAROUT, AND REPORT. UTILIZE EM PIPE AND CABLE, EM INDUCTION, AND GPR.

WORK PERFORMED	PRELIMINARY REVIEW OF CLIENT PROVIDED UTILITY DRAWINGS/AS-BUILTS: NONE
VISUAL SITE INSPECTION (MANHOLES, DRAINS): SURFACE ONLY	EMPCL CONDUCTIVE UTILITY SURVEY: CHECKED YES GAS: ELECTRIC: COMM.: WATER:
EMIMD METAL DETECTION SURVEY : AMBIENT NOISE AND SETTINGS LOW NOISE / GAIN 7.5 / LOW ELV REBAR IN CONCRETE? N/A	EM INSERTION : NF - INSERTION METHODS NONE DUE TO HS / N/A
GPR NON-CONDUCTIVE SURVEY YES	CLIENT ON-SITE REVIEW OF FINDINGS:

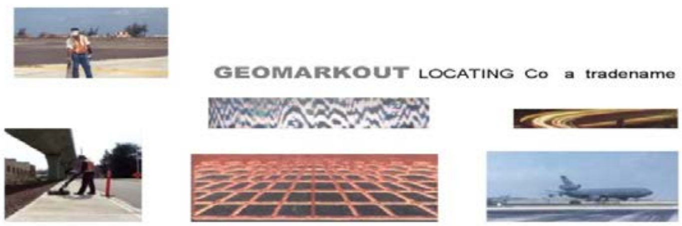
GENERAL LIMITATIONS

NOTE: The work described herein is performed to industry standards (or higher) using multiple methodology and QA/QC protocol. ULS cannot guarantee the accuracy or the ability to detect all underground facilities and potential interferences. Non-conductive or conductive utilities/facilities may not be detected due to variables and constraints beyond ULS control. Where known, constraints and limitations will be brought to the client's attention. Excavation work may result in injury to persons and/or damage to facilities. Client and/or excavator are advised to take all steps necessary to avoid contact with underground facilities. This includes, but is not limited to, safe digging practices, hand tooling in congested areas and within two feet on side of marked utilities (distance may vary by law), utility drawing review, site facilities representative review, and "one-call" utilities notification. ULS and its representatives are not responsible for injury to persons or damage to facilities. This document and accompanying pages will be delivered to the client before commencement of intrusive work for the client's review. If any questions arise, please notify our office immediately.

NOTE: Specific comments/limitations/constraints, known and recognized will be recorded on attached pages (field notes). Caution – some facilities (conductive or non- conductive) may not be detected. Not all limitations and constraints may be recognized.

SIGNATURE OF ULS REPRESENTATIVE ON-SITE MWB		PAGE OF 1

ULS SERVICES CORPORATION



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	QA / QC Follows
X	SITE WALK
X	VISUALS
X	ONECALL /DIG ALERT RECALL – ADVISE CALLING
X	UTILITY MAINS NONE ON SITE.
X	ELECTRIC – NONE
X	TELEPHONE NONE ON SITE. ONE CALL MARKS NOTED OUTSIDE GATE ALONG ROAD.
X	NAT GAS NONE
X	WATER NONE
X	SEWER/STORM SEPTIC NONE
X	
X	SOLAR ELECTRIC POLE TO EAST
X	
X	
	FUELS SYSTEM NONE BELOW
	PIPING
	VENTS

....

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SITE 17

LAKE CITY ARMY AMMUNITION PLANT

29 FEB 16

METHODS AND GENERAL OBSERVATIONS:

METHODS:

ARRIVED SITE OBTAINED PASSID AND COMPLETED SITE SAFETY TRAINING ORIENTATION. MOBILIZED TO SITE 17D WITH SITE REP.
MADE GENERAL SITE WALK TO REVIEW SURVEY AREAS (PROPOSED ZONES). CHECKED FOR SURFACE UTILITY MANIFESTATIONS SUCH AS VALVES, METERS, CONDUITS, TRENCHING SEAMS, VAULT LIDS AND EXISTING ONE CALL MARKINGS. BEGAN MARKOUT WORK.

METHODS UTILIZED INCLUDE: EM PIPE AND CABLE LOCATOR USING AMBIENT, GROUND INDUCTION AND CONNNECTION MODE SWEEPS. EM INDUCTION METAL DETECTOR, AND GPR. A CARTISIAN GRID PATH IS WALKED AT EACH PROPOSED ZONE USING ALL METHODOLOGY. OBSERVATIONS ARE MARKED WITH ORANGE AND BLUE PAINT WITH ORANGE PIN FLAGS. CLIENT ADVISED TO FLAG MARKINGS AS NEEDED. NO PHOOS ALLOWED. MARKINGS ARE COPIED WITH GPS FOR MAPPING.

SITE CALIBRATION - GENERAL OBSERVATIONS

EM PIPE AND CABLE TRANSMITTER TO RECIEVER (GROUND INDUCTION AND CONNECTION) BROADCASTING IS VERY GOOD.. ATTENUATION EFFECTS FROM CONCRETE STEEL REINFORCEMENT IS NA. EMIMD METAL DETECTOR BACKGROUND EM NOISE IS LOW ALLOWING FOR MAX GAIN OF 7, 5. GPR RESPONSE TO SOIL MEDIUM IS GOOD.

.

SEE GENERAL QA / QC OBSERVATION COMMENTS TO RIGHT SIDE / ABOVE AND / COMMENTS BELOW ....>

…………………………………………………………………

ULS / GEOMARKOUT

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SITE 17

LAKE CITY ARMY AMMUNITION PLANT

29 FEB 16

GENERAL OBSERVATIONS AND COMMENTS OR CONCERNS:

EXISTING UTILITIES

THERE ARE NO UTILITIES IN AREA. NO. BUILDINGS. A ISOLATED SOLAR CELL POLE IS NOTED EAST OF SURVEY AREA. TELEPHONE IS MARKED OUTSÎDE THE GATE ALONG MAIN ROAD.

GEOPHYSICAL ANOMALIES

RESULTS FROM EM INDUCTION CONDUCTIVITY, GPR, AND MAGNETIC SURVEY INDICATE A NARROW CONDUCTIVE ANOMALY TRENDING NW-SE ACROSS THE GRAVEL ROAD AND EXTEDING INTO EACH OF THE TWO SURVEY ZONES. MAGNETIC LOCATOR RESULTS INDICATE SOME SCATTERED FERROOUS (IRON –STEEL) MAGNETIC ANOMALIES WITHIN CONDUCTIVE ANOMALIE. GPR TRANSECTSC ACROS ANOMALY SUGGEST A POTENTIAL SHALLOW TRENCH . A FEW OF THE MAGNETIC ANOMLIES ARE PICKED UP WITH GPR EXHIBITING SEMI-PARABOLIC PATTERN WITH DEPTH FROM TWO TO SIX FEET. **REFER TO GPR TRANSECTS T-1 AND T-2 AND GPS MAPS.**

CLIENT OR CONTRACTER ADVISED TO HAND DIG NEAR MARKINGS ANDOR OBSERVATIONS TO CONFIRM VISUALLY PRIOR TO ANY MECHANICAL EXCAVATION. DO NOT JAB WITH HAND TOOLS OVER OR NEAR UTILITIES.

ONE –CALL NOTIFICATION RECOMMEND IF NOT CALLED.

****

END REPORT /

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APPENDIX D ERT REPORTS

Electrical resistivity tomography (ERT) at Grand Forks Air Force Base (GFAFB)

Judy Robinson, Lee Slater and Pauline Kessouri

BACKGROUND

Rutgers University Newark was subcontracted by CDM Smith to conduct 3D cross-borehole electrical resistivity tomography (ERT) characterization and monitoring of hydraulic fracturing activities at Grand Forks Air Force Base (GFAFB). These activities consisted of hydraulic fracturing after which an amendment spiked with potassium bromide was injected. We assume that electrical current flow pathways are modified by the fracturing and agent injection. Electrical resistivity is strongly controlled by soil porosity, the connectivity of pores/fractures and the specific electrical conductance of the groundwater. Fracturing increases porosity and connectivity whereas the amendment injection locally increases the groundwater specific conductance within the impacted region. The rationale for this geophysical imaging method is that when newly-created hydraulically conductive pathways (i.e. through fracturing) are invaded with an amendment with high specific conductance, ERT will be able to provide evidence of the distribution of these pathways in between borehole locations. Cross borehole 3D ERT imaging occurred before, during and after fracturing and injection activities. To compare with the 3D ERT imaging, a 2D surface ERT profile was collected which spanned across the length of the boreholes used to acquire the 3D ERT datasets.

METHODS – ELECTRICAL RESISTIVITY TOMOGRAPHY

Surface (2D) and borehole (1D, 2D or 3D) electrical resistivity surveys are performed by connecting spatially distributed electrodes through a wire or cable to a centrally located resistivity meter. At GFAFB, 2D surface and 3D cross borehole arrays were used to collect ERT data. The 2D surface survey was conducted to provide additional information on near-surface conductivity features. For both the 2D and 3D measurements, a Syscal Pro 96 (Iris Instruments, France) was used for data acquisition.

ERT measurement sequences are composed of a large number of four electrode measurements. For a single measurement, a current (I) is injected into two electrodes and the change in potential (ΔV) between two receiving electrodes is recorded. As the distance from the current injection increases (and the current density decreases), the resolution of the method decreases. For surface ERT, this means that the resolution of conductivity structures will be enhanced closer to the surface and degrades with distance from the surface. For borehole ERT, this means that the resolution will be enhanced closer to the boreholes and degrades with distance from the boreholes. For a borehole survey, a recommended aspect ratio (defined as the total depth of imaging D divided by the horizontal distance between wells H) is 0.75 or less (Labrecque et al. 1996).

ERT resolution depends on many factors, including the geometry of the four electrode measurements used for data acquisition and data noise levels. Data noise was estimated by collecting reciprocal measurements whereby current and potential electrodes are interchanged (in theory, these measurements should be equal). Measurements where the reciprocal measurement differed by more than 100% were filtered from the dataset.

Inverse methods are used to solve for a subsurface resistivity structure that is consistent with the acquired field datasets. The objective function for the inversion solves for a model with the lowest root mean squared error (RMSE) between the proposed model and field dataset subject to constraints on the resulting model structure. Since the solution to this problem is non-unique (i.e. there are an infinite number of models that can fit the field data), constraints are imposed to limit the number of models to those that contain the minimum amount of structure needed to fit the data to the appropriate level based on the data quality.

To solve the ERT inversion, finite element modeling is often employed whereby discretization of the subsurface is necessary. In this study, forward and inverse modeling of these measurements was achieved in 2D using R2 (http://www.es.lancs.ac.uk/people/amb/Freeware/R2/R2.htm) and in 3D with E4D (https://e4d.pnnl.gov).

ERT measurements were collected before and after fracturing and injection activities at each site. The pre-activity measurements were used to generate background, or characterization images. These images are presented in units of conductivity, which is the inverse of resistivity, for direct consideration of changes in fluid specific conductance associated with amendment injection. The general conductivity structure shown in the background image is dependent on porosity, grain size, temperature, and groundwater composition. A time-lapse inversion was therefore performed on the post-activity measurements to invert for changes from the background image. We anticipated that these images would highlight increases in electrical conductivity resulting from newly formed hydraulically conductive pathways associated with fracturing and injection activities. We also recognize that fracturing activities could potentially alter the subsurface structure in ways that cause a *decrease* in conductivity in certain regions (e.g. through localized compaction). Given our objective of monitoring the injection of a conductive amendment, we have chosen to focus our results to emphasize increases in conductivity.

a. 2D SURFACE

Forty-eight stainless steel electrodes spaced 1 meter apart were used for the surface survey. The survey consisted of 1266 measurements which include a combination of Wenner and dipole-dipole measurements to better capture vertical and horizontal conductivity contrasts. The 2D surface line was centered on the locations where the monitoring wells contained the electrodes for 3D ERT imaging (Figure 1). To achieve the desired penetration depth (i.e. the depth of the monitoring wells), it was necessary for the 2D profile line to extend laterally beyond the borehole locations to increase the electrode separation distances in the survey. Surveys were collected before and after the fracturing activities. For security reasons, the resistivity instrument was positioned at the opposite ends of the profile line for the pre- and post-data collection, limiting the post processing of the datasets in a time-lapse sense.

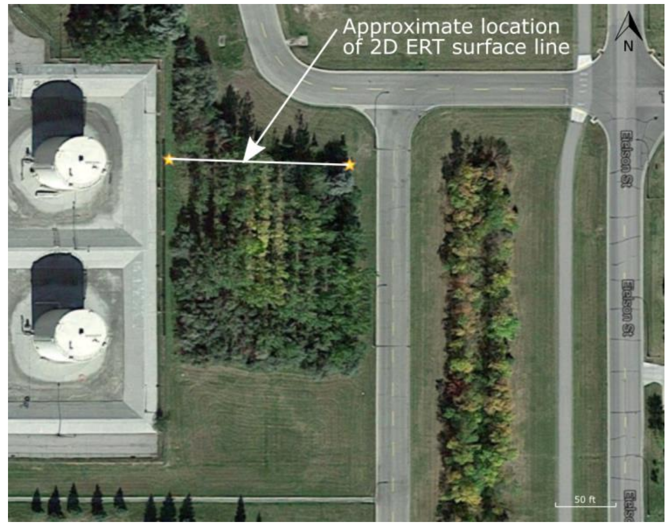

Figure 1: Location of 48 m surface line used to collect 2D ERT data

b. 3D CROSS BOREHOLE

At GFAFB, 4-inch monitoring well casing (screened and slotted intervals) for five boreholes designated 15-19 were outfitted with electrodes by CDM Smith prior to installation (Figure 2). Each electrode consisted of a low-profile band clamp made of 201 stainless steel with a 20 AWG wire attached which was then run to the surface. A total of ninety six electrodes were spaced 1.25 feet apart in each monitoring well. All wells contained 19 electrodes, except the center well (17) which contained 20 electrodes. We used a dipole-dipole array with varying skipped electrode spacings, Wenner configurations (within a single borehole), and cross borehole measurements with current and/or potential electrodes spanning two or three boreholes.

A total of eight electrodes across the five monitoring wells did not have sufficient electrical contact with the formation for the background measurements. To speed up the time-lapse data acquisition, a smaller measurement sequence was collected for subsequent datasets. Measurements with poor data quality were filtered from the original background survey. This is reflected in the sensitivity structure of the model (Figure 3).

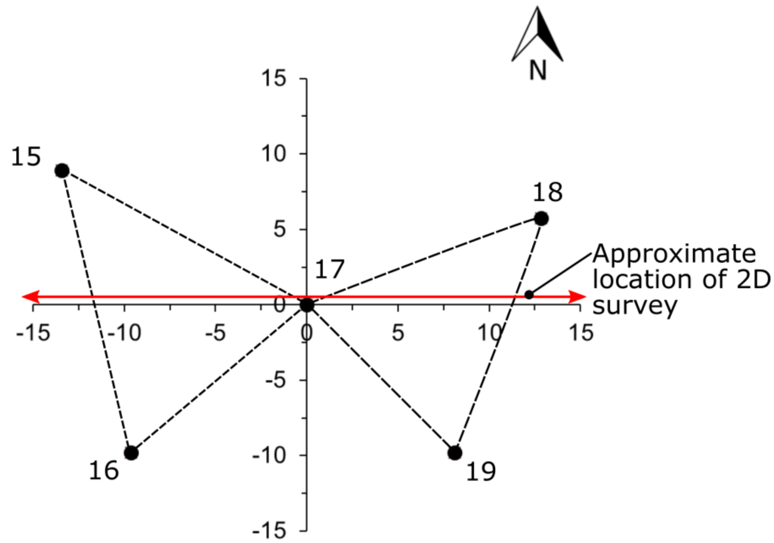

Figure 2: Well schematic consisting of five wells. Each triangle represents the imaged area from cross-borehole measurements.

We assumed boreholes to be vertical and caution that significant unaccounted for borehole deviations can cause modeling errors (Wilkinson et al. 2008). Discretization of the subsurface into a model space inherently introduces numerical errors. For each site, numerical errors of each measurement were calculated based on forward modeling of a homogeneous earth. The discretization of each site was optimized such that fewer measurements were filtered based on numerical errors. The numerical error cutoff value used was 3% against a theoretical value of the measurements based on a homogeneous subsurface earth. Thus, we assume that changes in the subsurface less than ~3% cannot be accurately detected with the ERT measurements.

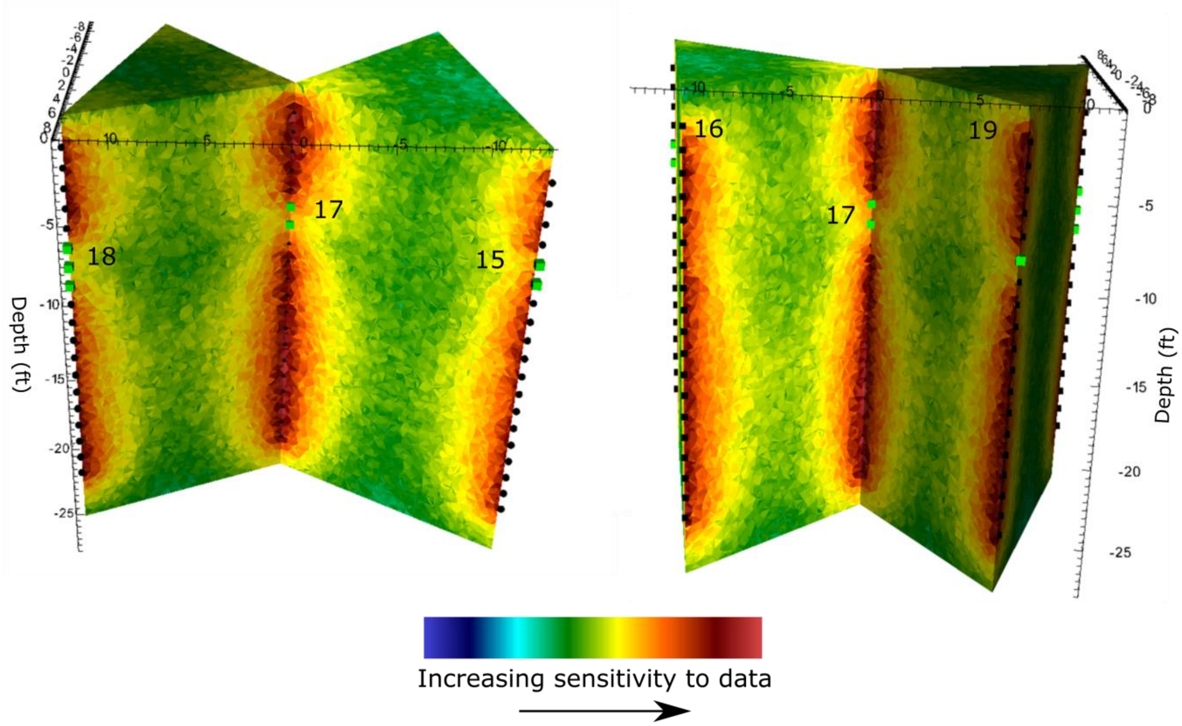

Figure 3: Sensitivity structure of the ERT inversion model reflecting higher sensitivities near the monitoring wells except at locations where electrodes do not have contact with the formation (shown in green).

RESULTS

a. 2D SURFACE

Positioning the instrument at opposite ends of the profile line resulted in a low number of measurements where the injection and potential readings exactly matched. For a true time-lapse inversion, the measurement sequences must be the same so that the sensitivity structures of the inverted models match. Subtracting independently inverted images will propagate and/or exaggerate noise and artifacts in the images. Thus, we focus the results on before and after images.

Figure 4 shows the conductivity structure pre- and post-fracturing activities. In the area surrounding MH17, there is an increase in the conductivity in the near surface. Near x=30 m, there is a decrease in conductivity in the top 4 m. Overall the conductivity structure before and after appears to be unchanged in most regions of the image.

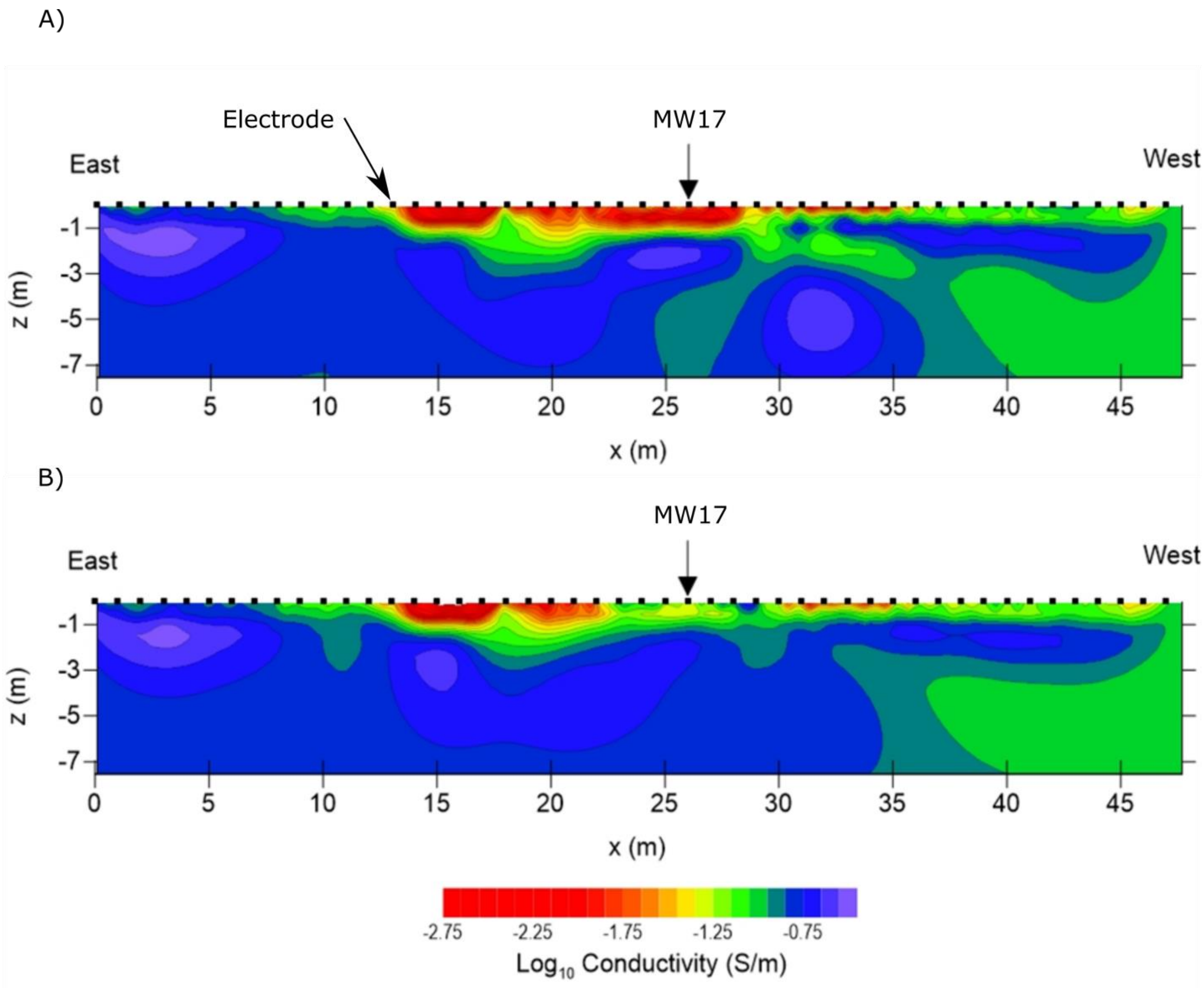

Figure 4: 2D ERT results in A) pre-fracturing activity and B) post-fracturing activity

b. 3D CROSS BOREHOLE

The 3D background ERT inversion images are shown in Figures 5a-d. The resistive surface layer is interpreted as the unsaturated zone, where lower moisture content results in lower electrical conductivity. Electrical conductivity is higher below this boundary; however this is not evident near MW15. Overall the images depict a highly heterogeneous background. The electrodes with no contact may partly exaggerate these effects due to lower data sensitivity to the model surrounding these locations.

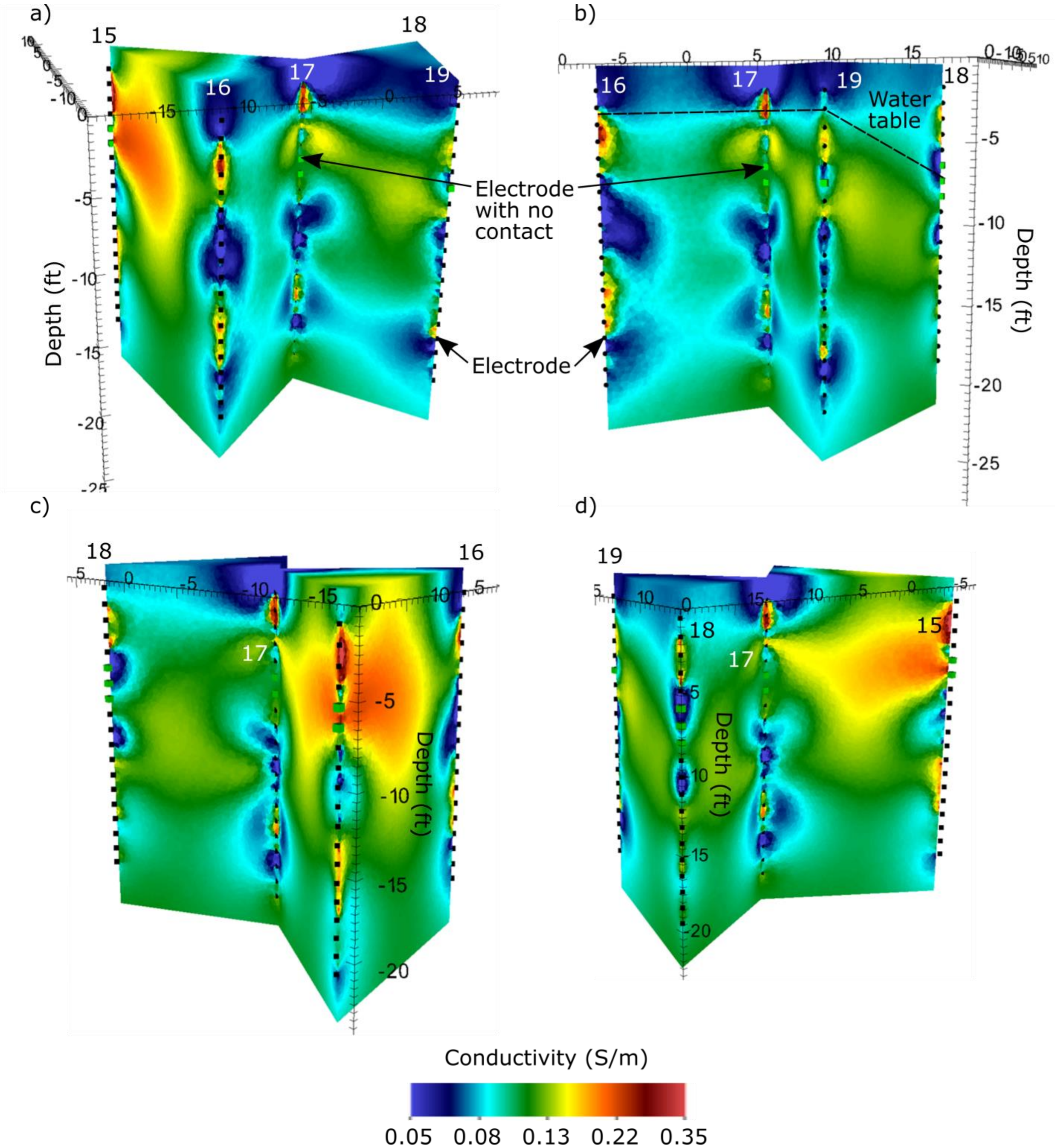

Figure 5: Background conductivity structure for four vantage points a)-d). Electrodes with no contact are shown as green cubes, and those with contact in black cubes.

Figure 6 shows the 3D time-lapse changes for two time-steps at two different viewing angles (a-b and c-d). Extensive changes are shown in between the monitoring wells, in particular surrounding the center monitoring well 17. A strong connection is can be observed between monitoring wells 15 and 17 and a shallow connection is evident between monitoring wells 17 and 19.

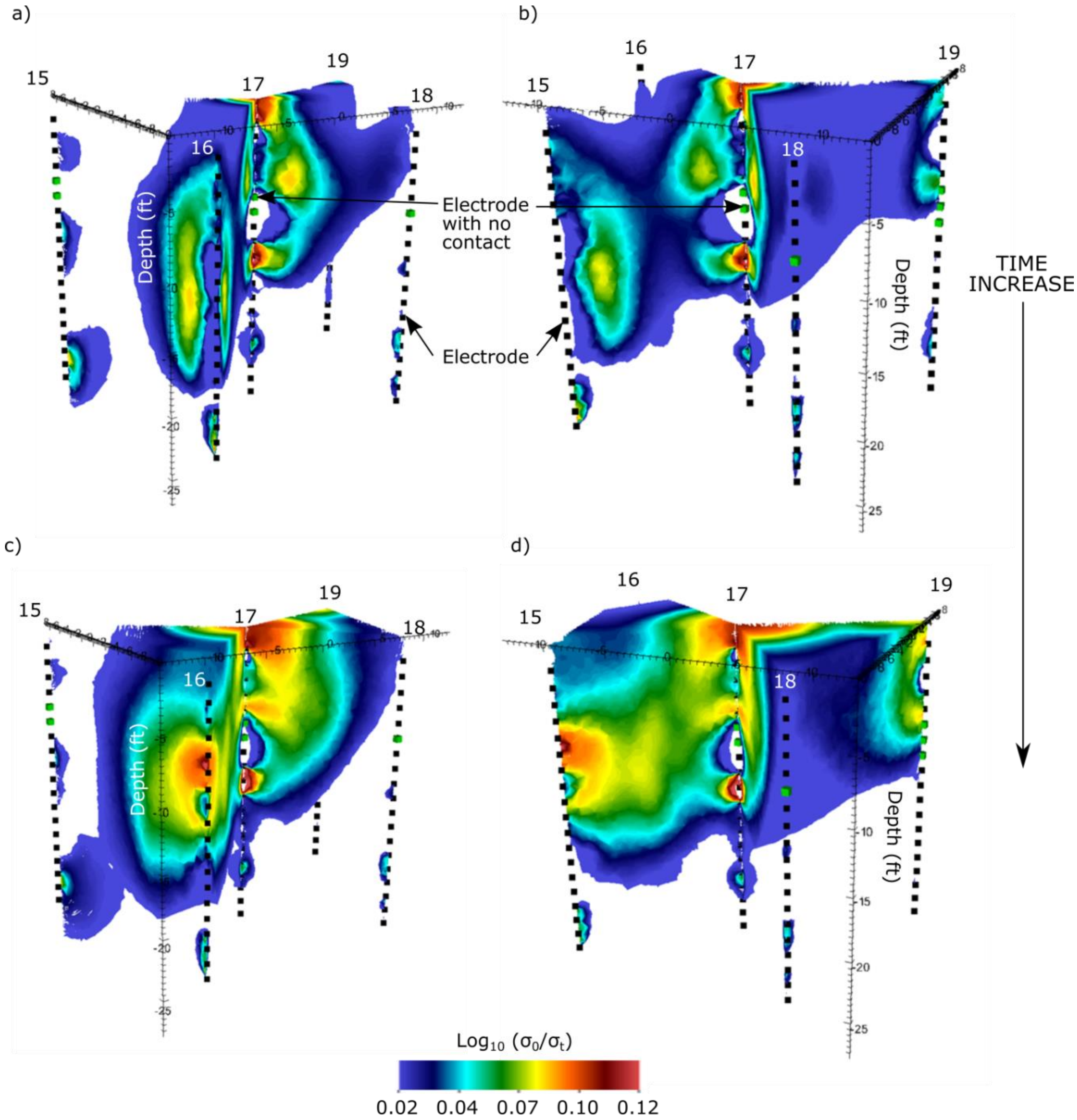

Figure 6: Logarithmic changes in conductivity surrounding the 3D borehole ERT arrays where a) and b) reflect time-lapse changes at the first time-step and c) and d) reflect changes at the second time-step. Only changes that reflect increases in conductivity are shown. The logarithmic changes shown correspond to a conductivity change range of 3.5-32%.

DISCUSSION AND COMPARISON WITH FIELD DATA

The 2D surface ERT provided very little supplementary electrical information at GFAFB. We presume this was due to the lower resolution of features resulting from the relatively large electrode spacing (1 m, 3.28 ft) required to reach the deeper region of interest, along with the lower data sensitivities to the model as the distance from the surface increased. The 3D borehole arrays dramatically improve the possibility of imaging the enhanced fracturing activities at GFAFB.

Inverse modeling of the 3D ERT datasets provided a view of the conductivity structure in between borehole locations, at spatial scales extending beyond the boreholes that are inaccessible to established borehole-based observations. ERT imaging at GFAFB detected changes in resistivity attributed to the fracturing activities. The imaging also resolved the electrical structure of the field site well, including the transition from the vadose zone to saturated zone sediments.

The percentage of resistance measurements with high measurement errors filtered from the complete dataset was a little larger than observed at most sites. Conservative filtering of noisy measurements based on high reciprocal errors, low receiver voltages and low current injections, minimized the possibility of including data into the inversion that can generate artifacts in the images. Careful assessment of numerical modeling errors further limited the possibility of erroneous data points entering the inversion. Such meticulous error assessment is often overlooked in applications of ERT and readily leads to misinterpretation of image structure.

Figure 7 shows changes in conductivity structure between MW17 and MW18 alongside pre-fracturing TOC and fluorescein data from three composite samples from MW18 and MW19 and post injection discrete sampling from TOC and fluorescein data from wells HCB-03. TOC and fluorescein have no direct physically or empirically derived control on electrical conductivity. However a first-order comparison of these profiles is worthwhile assuming that potassium bromide plus amendment solution was well-mixed such that increases in TOC and fluorescein concentration reflect those locations where the injected solution reached newly formed pathways following fracturing. HCB-03 is located closest to MW18 within the inner triangle of MW17-18-19. The largest changes in electrical conductivity are in the top 10 ft, which coincides with a decrease in TOC compared to background values. The largest change in TOC values is within this top 10 ft however a decrease in indicated in the direct sampling which is inconsistent with the injection of the amendment. Changes in fluorescein are shown to increase with depth whereas the ERI results show changes to approximately 15 m.

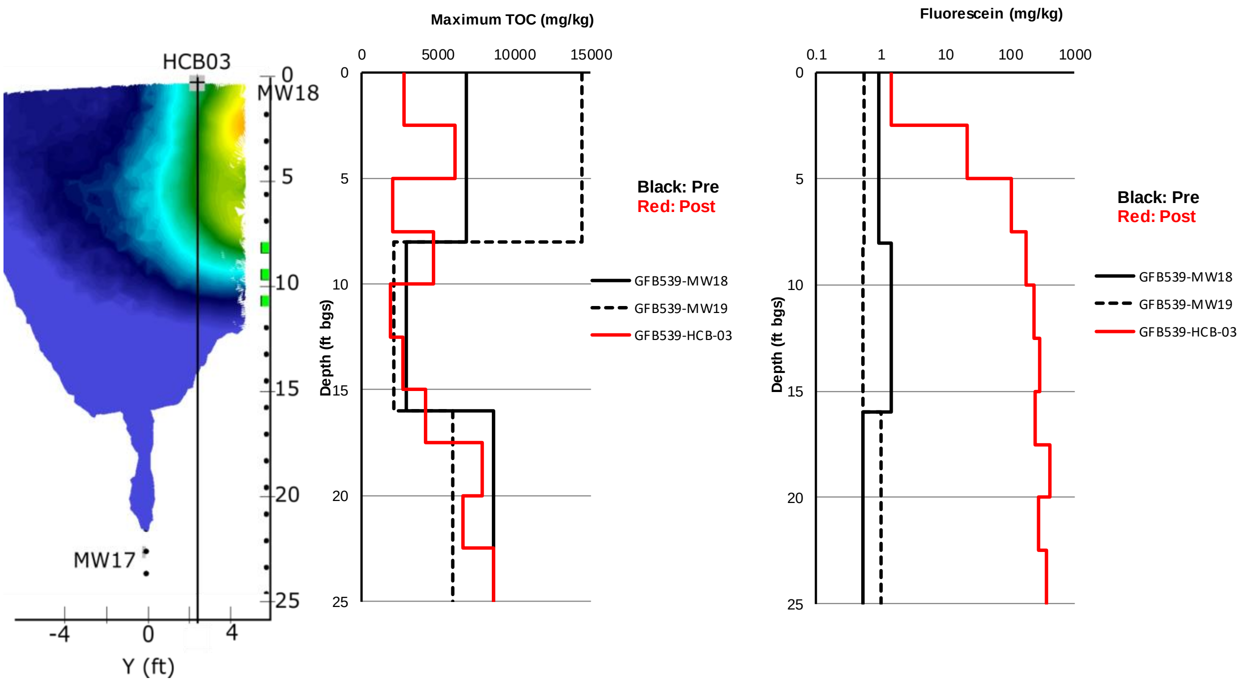

Figure 7: Time-lapse ERT changes from time-step 2 alongside TOC and Fluorescein measurements acquired from three (averaged) composite samples in MW18 and MW19 before fracturing (pre) and injection and afterwards (post) from discrete samples collected in HCB-03. Green colored electrodes in the ERT image had no electrical contact.

Figure 8 shows changes in conductivity structure between MW16 and MW17 alongside pre-fracturing TOC and fluorescein data from three composite samples from MW15 and MW16 (Rutgers does not have pre-enhancement data for MW17) and post injection discrete sampling from TOC and fluorescein data from well HCB-02. HCB-02 is located closest to MW17 within the inner triangle of MW15-16-17. TOC data from HCB-02 show an increase in conductivity corresponding with a decrease in TOC in the top 10 ft. There is no change in electrical conductivity detected below 15 ft in HCB-02. The TOC data indicates very little change in this region. Changes in fluorescein are shown to increase with depth to 25 m. ERT results show extensive changes in the top 17 m but no changes below this depth.

Figure 9 shows changes in the conductivity structure between monitoring wells 15, 18 and 17 alongside pre-fracturing TOC data from a composite sample from MW15 and MW16 and post injection discrete sampling from TOC data from borehole HCB-01. Well HCB-01 is closest to MW-15. Similarities between the time-lapse ERT imaging and the HCB-01(post) fracturing TOC profiles exist (Figure 9). In general, there is little change in the TOC except between 20-25 feet. This coincides well with increases in electrical conductivity. Fluorescein concentrations are shown to increase with depth. The ERT image (Figure 9) indicates an increase in conductivity from below 17 m, however the changes are not as extensive as indicated in the fluorescein concentrations.

Our results show broad changes occurring in the time-lapse electrical conductivity structure. However, the spatially extensive ERT results are inconsistent with the handful of direct sampling points of fluorescein and TOC sampling showed very little change or counterintuitive decreases. Limited success may reflect challenges with installing electrodes in the unsaturated zone encountered at this site. In addition, changes in fluorescein concentration may not reflect changes in conductivity. Also, the resolution of direct samples and ERT measurements vary.

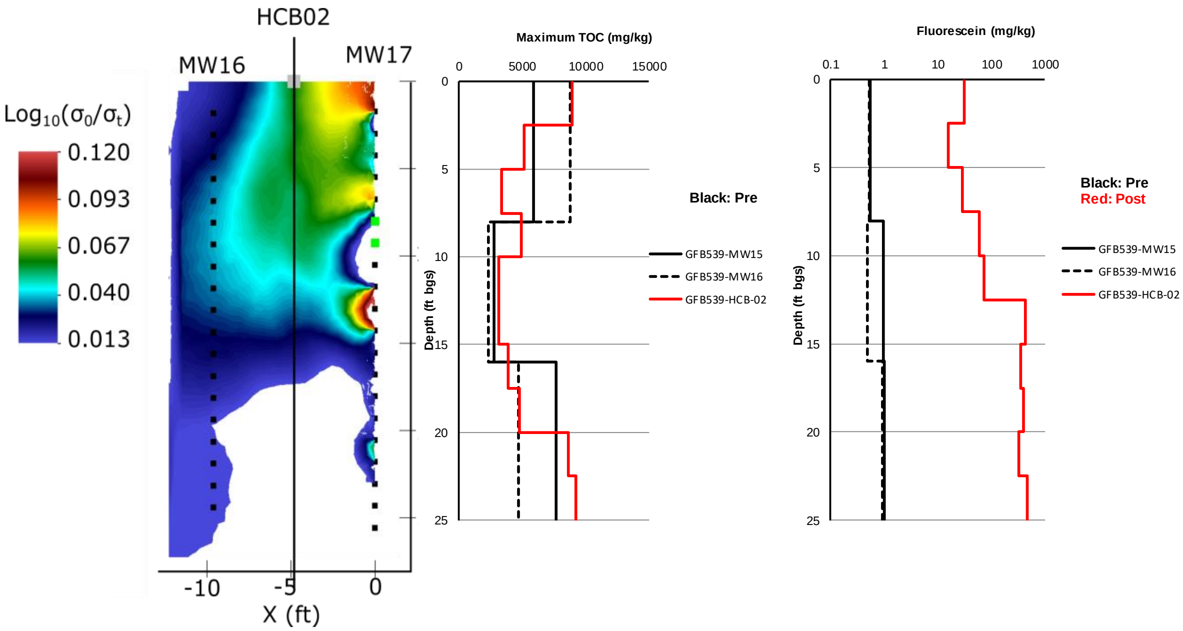

Figure 8: Time-lapse ERT changes from time-step 2 alongside TOC and fluorescein measurements acquired from three composite samples in MW15 and MW16 before fracturing (pre) and injection and afterwards (post) from discrete samples collected in HCB-02. Green colored electrodes in the ERT image had no electrical contact.

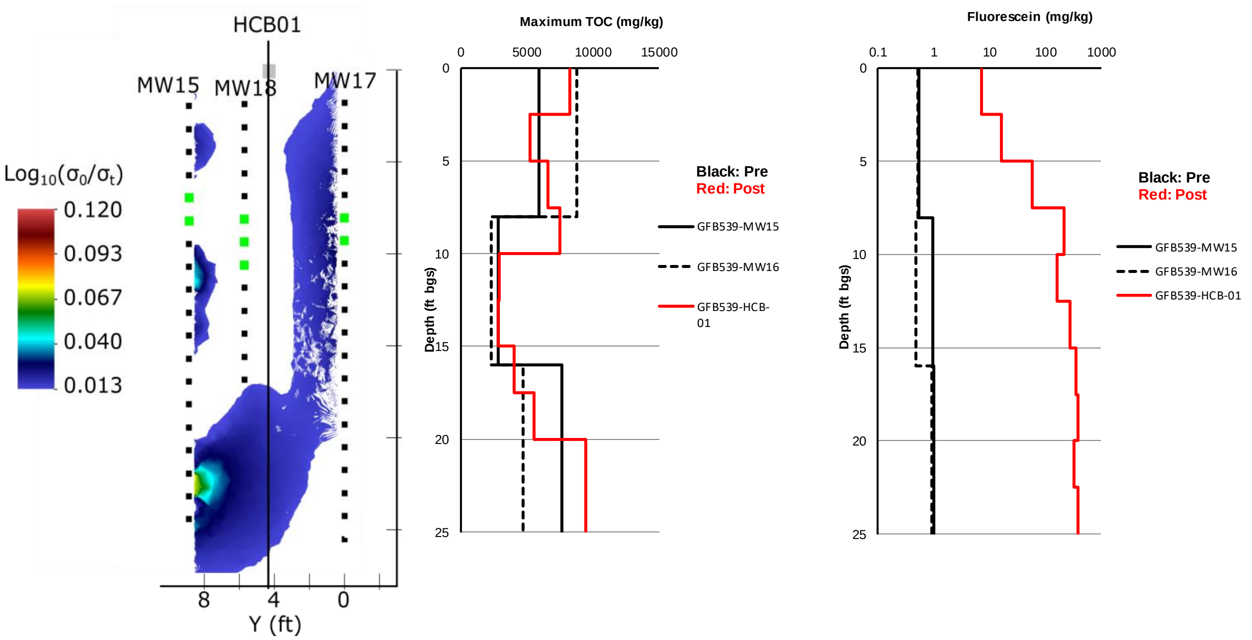

Figure 9: Time-lapse ERT changes from time-step 2 alongside TOC and fluorescein measurements acquired from three composite samples in MW15 and MW16 before (pre) fracturing and injection and afterwards (post) from discrete samples collected in HCB-01. Green colored electrodes in the ERT image had no electrical contact.

SUMMARY

ERT was able to provide spatiotemporal information on the distribution of amendments in between the monitoring wells. Expansive changes in electrical conductivity were detected as a result of enhanced amendment delivery through fracturing, suggesting that a substantial volume of the investigated region was impacted by these activities. TOC direct sampling indicated very little change in concentration or a counterintuitive increase in concentration. The changes in ERT are inconsistent with the number of limited direct samples of fluorescein concentrations. This inconsistency may be due to challenges installing electrodes in the vadose zone, no direct mapping of fluorescein concentration to electrical conductivity or the different measurement resolutions between direct sampling and ERT measurements.

The ERT results shown here suggest that the subsurface was much more extensively impacted by enhanced fracturing activity at GFAFB than at Lake City Army Ammunitions Plant (LCAAP).

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173(1): 49–62. http://gji.oxfordjournals.org/cgi/doi/10.1111/j.1365-246X.2008.03725.x (March 27, 2014).

RUTGERS
Newark College of Arts and Sciences

Electrical resistivity tomography (ERT) at Lake City Army Ammunitions Plant (LCAAP)

BACKGROUND

Rutgers University Newark was subcontracted by CDM Smith to conduct 3D cross-borehole electrical resistivity tomography (ERT) characterization and monitoring of fracturing activities at two contaminated sites. The two sites, within close proximity of each other, were contaminated with free and dissolved phase TCE products. Hydraulic fracturing was performed at one site whereas pneumatic fracturing was applied at the other site. We assume that electrical current flow pathways are modified by the fracturing and agent injection. Electrical resistivity is strongly controlled by soil porosity, the connectivity of pores/fractures and the specific electrical conductance of the groundwater. Fracturing increases porosity and connectivity whereas the amendment injection locally increases the groundwater specific conductance within the impacted region. The rationale for this geophysical imaging method is that when newly-created hydraulically conductive pathways (i.e. through fracturing) are invaded with an amendment with high specific conductance, ERT will be able to provide evidence of the distribution of these pathways in between borehole locations. Cross borehole 3D ERT imaging occurred before and after fracturing and injection activities at both sites. An attempt was made to collect additional measurements during hydraulic fracturing activities, but field delays prevented successful data collection on this occasion.

METHODS

Cross-borehole ERT is performed by placing electrodes within a borehole, typically at evenly spaced intervals and running many wires to a resistivity meter at the surface. For the two sites at LCAAP, 4-inch monitoring well casing (screened and slotted intervals) was outfitted with electrodes prior to installation. Each electrode consisted of a low-profile band clamp made of 201 stainless steel with a 20 AWG wire attached which was then run to the surface. The resistivity meter used for data collection was a Syscal Pro 96 (Iris Instruments, France).

ERT measurement sequences are composed of a large number of four electrode measurements. For a single measurement, a current (I) is injected into two electrodes (commonly denoted A and B) and the change in potential (ΔV) between two receiving electrodes (commonly denoted as M and N) is recorded (Figure 1). As the distance from the current injection increases (and the current density decreases), the resolution capability of the method decreases. For borehole ERT, this means that the resolution of conductivity structures will be enhanced closer to the boreholes and degrades with distance from the boreholes (Figure 2). Consequently, the aspect ratio (defined as the total depth of imaging D divided by the horizontal distance between wells H) should be less than 0.75 (Labrecque et al. 1996). This criterion was taken into account during the planning process but site conditions prevented the installation of the total planned length of well casing for most wells. Aspect ratios for the hydraulic and pneumatic sites are reported below between each well.

ERT resolution depends on many factors, including the geometry of the four electrode measurements used for data acquisition. Dipole-dipole (Figure 1a) with varying skipped electrode spacings [0,1,3,5,7,9] and cross borehole (Figure 1b) sequences were used here. Data noise was estimated by collecting reciprocal measurements whereby current and potential electrodes are interchanged (in theory, these measurements should be equal). Measurements where the reciprocal measurement differed by more than 50% were filtered from the dataset.

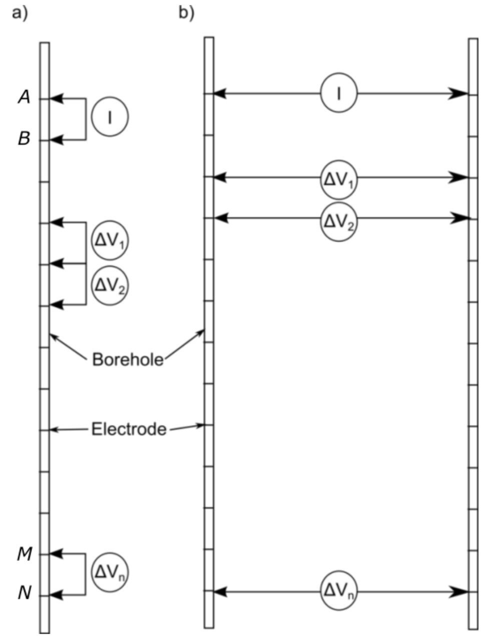

Figure 1: a) Skip sequence in a single borehole; skip-0 is shown b) Cross borehole measurement between two boreholes; a 3D sequence was constructed for LCAAP

Vertical apparent resistivity profiles were produced from dipole-dipole skip sequences (Figure 1a) within each borehole. These profiles give a localized summary of the resistivity structure surrounding the borehole. The depths represent the midpoint of the four-electrodes in the measurement. Where depths overlap, an average of the measurement was calculated. The vertical apparent resistivity for each measurement was calculated as:

$$\rho_{app} = \frac{\Delta V}{I} k \quad (1) \quad ,$$

where

$$k = 4\pi \left[\left(\frac{1}{\mathrm{A_iM}} + \frac{1}{\mathrm{AM}} \right) - \left(\frac{1}{\mathrm{B_iM}} + \frac{1}{\mathrm{BM}} \right) - \left(\frac{1}{\mathrm{A_iN}} + \frac{1}{\mathrm{AN}} \right) + \left(\frac{1}{\mathrm{B_iN}} + \frac{1}{\mathrm{BN}} \right) \right] \quad (2)$$

In eq. 2, AM, represents the linear distance between current electrode A and potential electrode M. Similarly, BM represents the linear distance between current electrode B and potential electrode M. To account for the surface boundary, the method of images is used and image lengths are associated with current electrodes, hence the notation A_iM and A_iN. The inverse of the apparent resistivity is the apparent conductivity which is equal to:

$$\sigma_{app} = \frac{1}{\rho_{app}} \quad (3) \quad ,$$

Inverse methods were used to solve for a cross-borehole resistivity structure that is consistent with the acquired field datasets. The objective function for the inversion solves for a model with the lowest root mean squared error (RMSE) between the proposed model and field dataset subject to constraints on the resulting model structure. Since the solution to this problem is non-unique (i.e. there are an infinite number of models that can fit the field data), constraints are imposed to limit the number of models.

To solve the ERT inversion, finite element modeling is often employed whereby discretization of the subsurface is necessary. Forward and inverse modeling of these measurements was achieved with E4D (https://e4d.pnnl.gov) which employs tetgen (http://wias-berlin.de/software/tetgen/) as an unstructured tetrahedral mesh generator.

Discretization of the site into a model space inherently introduces numerical errors. For each site, numerical errors of each measurement were calculated based on forward modeling of a homogeneous earth. The discretization of each site was optimized such that fewer measurements were filtered based on numerical errors. The numerical error cutoff value used was 3%. Thus, we assume that changes in the subsurface less than ~3% cannot be accurately detected with the ERT measurements.

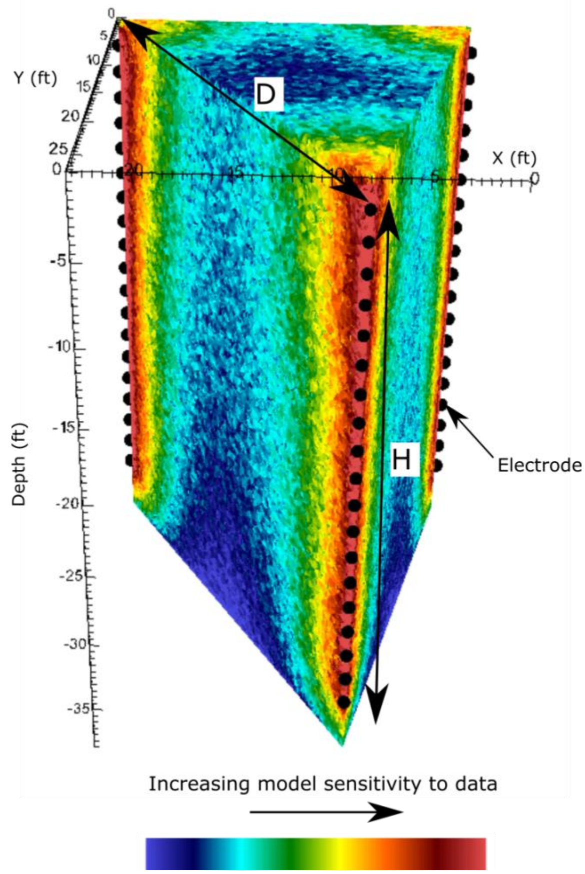

Figure 2: Sensitivities decrease as the distance from the borehole electrodes increase. This illustration is typical for ERT surveys.

Fracturing activities were followed by injection of a lactoid remedial agent spiked with potassium bromide resulting in a factor of 10 conductivity contrast with native groundwater (1 mS/cm). ERT measurements were collected before and after fracturing and injection activities at each site. The pre-activity measurements were used to generate background, or characterization images. These images are presented in units of conductivity, which is the inverse of resistivity, for direct consideration of changes in fluid specific conductance associated with amendment injection. We assumed boreholes to be vertical and caution that significant borehole deviations not accounted for can cause modeling errors (Wilkinson et al. 2008). The general conductivity structure shown in the background image is dependent on porosity, lithology, temperature, and groundwater composition. A time-lapse inversion was therefore performed on the post-activity measurements to invert for changes from the background image. We anticipated that these images would highlight increases in electrical conductivity resulting from newly formed hydraulically conductive pathways associated with fracturing and injection activities. We also recognize that fracturing activities could potentially alter the subsurface structure in ways that cause a *decrease* in conductivity in certain regions (e.g. through localized compaction). However, analysis of the raw data (Appendix A) shows that the measurements are dominated by decreases in resistance, consistent with increases in conductivity. Given our objective of monitoring the injection of a conductive amendment, we have chosen to focus our results to emphasize increases in conductivity.

a. Hydraulic fracturing site

Three monitoring wells (HMW01, HMW02 and HMW03) were outfitted with 19 electrodes each for a total of 57 electrodes. Electrodes within each borehole were spaced 1.8 feet apart along the well casing. The aspect ratios between well pairs HMW01-HMW02, HMW02-HMW03, and HMW01-HMW03 were calculated as 0.72, 0.95 and 0.86, respectively (Figure 3). Without further information, the site is assumed to be level. Depth to groundwater was recorded by CDM Smith at approximately 7 feet below top of casing for these wells. The measurement sequence consisted of 3,010 measurements.

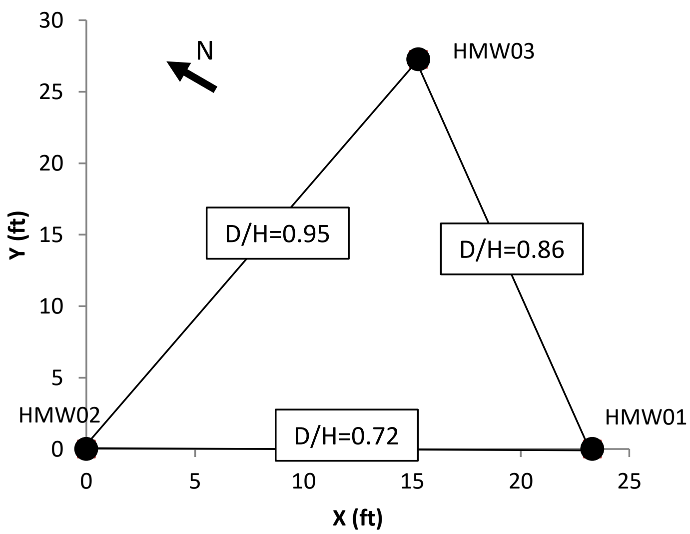

Figure 3: Hydraulic fracturing site well layout with aspect ratios equal to the depth of imaging (D) / horizontal distance (H) shown.

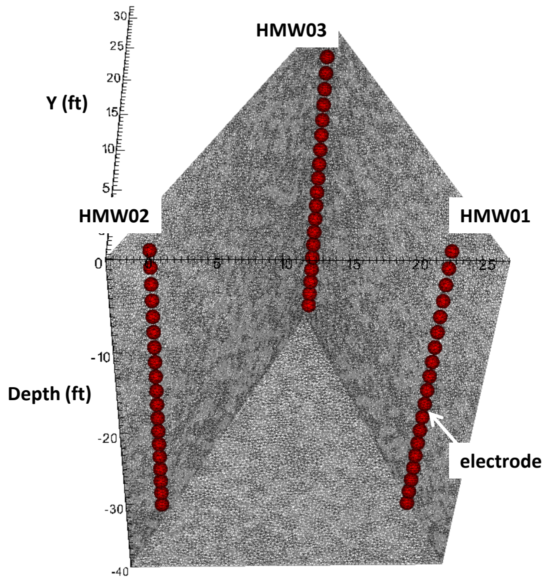

Figure 4: Hydraulic fracturing site: finite element mesh with 1,296,589 tetrahedral elements. Electrode locations are shown in red.

The discretization of the hydraulic fracturing site contained 1,296,589 tetrahedral elements (Figure 4). Forward modeling analysis found that 721 measurements had numerical errors greater than 3%. After all filtering (reciprocal, numerical and low and high potentials), 2,010 common measurements were retained for the time-lapse inversion.

a. Pneumatic fracturing site

Four monitoring wells (PMW01-PMW-4) were installed at the pneumatic fracturing site. Well casings for PMW01and PMW03 were installed with 22 electrodes each; PMW02 was installed with 24 electrodes; PMW04 was installed with 21 electrodes. In total 89 electrodes were installed at this site. Electrodes within each borehole were spaced 1.8 feet apart along the well casing. The aspect ratios between outer borehole well pairs PMW01-PMW02, PMW02-PMW03, and PMW01-PMW03 were calculated as 0.78, 0.85 and 0.74, respectively (Figure 5). There was minor surface topography. The measurement sequence consisted of 7,543 measurements.

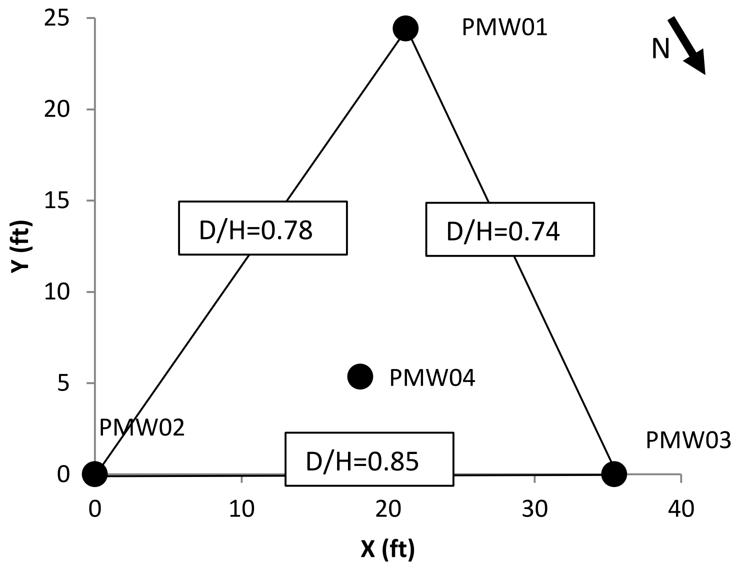

Figure 5: Pneumatic fracturing site well layout with aspect ratios equal to the depth of imaging (D) / horizontal distance (H) shown between wells PMW01-02, PMW01-03, and PMW02-03. D/H ratios not shown are less than 0.75.

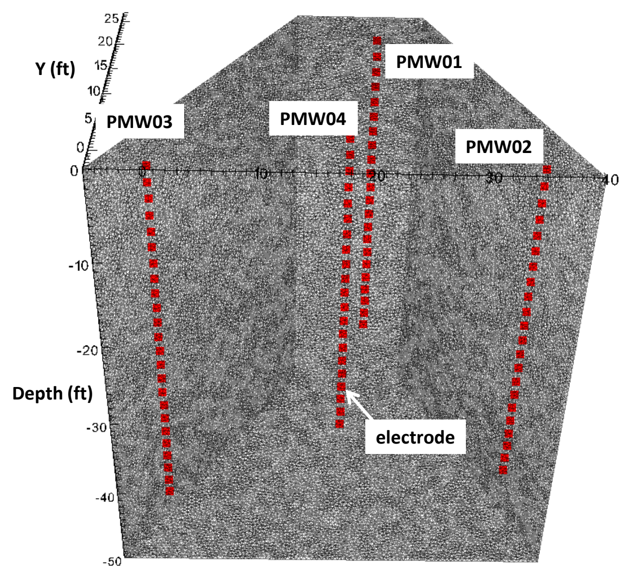

Figure 6: Pneumatic fracturing site discretized with 1,871,784 tetrahedral elements. Electrode locations are shown in red.

The discretization of the pneumatic fracturing site contained 1,871,784 tetrahedral elements (Figure 6). Forward modeling analysis found that 1,447 measurements had numerical errors greater than 3%. After all filtering (reciprocal, numerical and low and high potentials), 3,124 common measurements were retained for the time-lapse inversion.

RESULTS

a. Hydraulic fracturing site

The background ERT inversion images are shown in Figures 7b-d. The resistive surface layer is interpreted as the vadose zone; the bottom boundary of this layer is consistent with the depth to groundwater recorded by CDM Smith on the day of the background survey. Electrical conductivity is higher below this boundary. A high conductivity layer exists between 15-25 feet, being within the screened intervals in these monitoring wells.

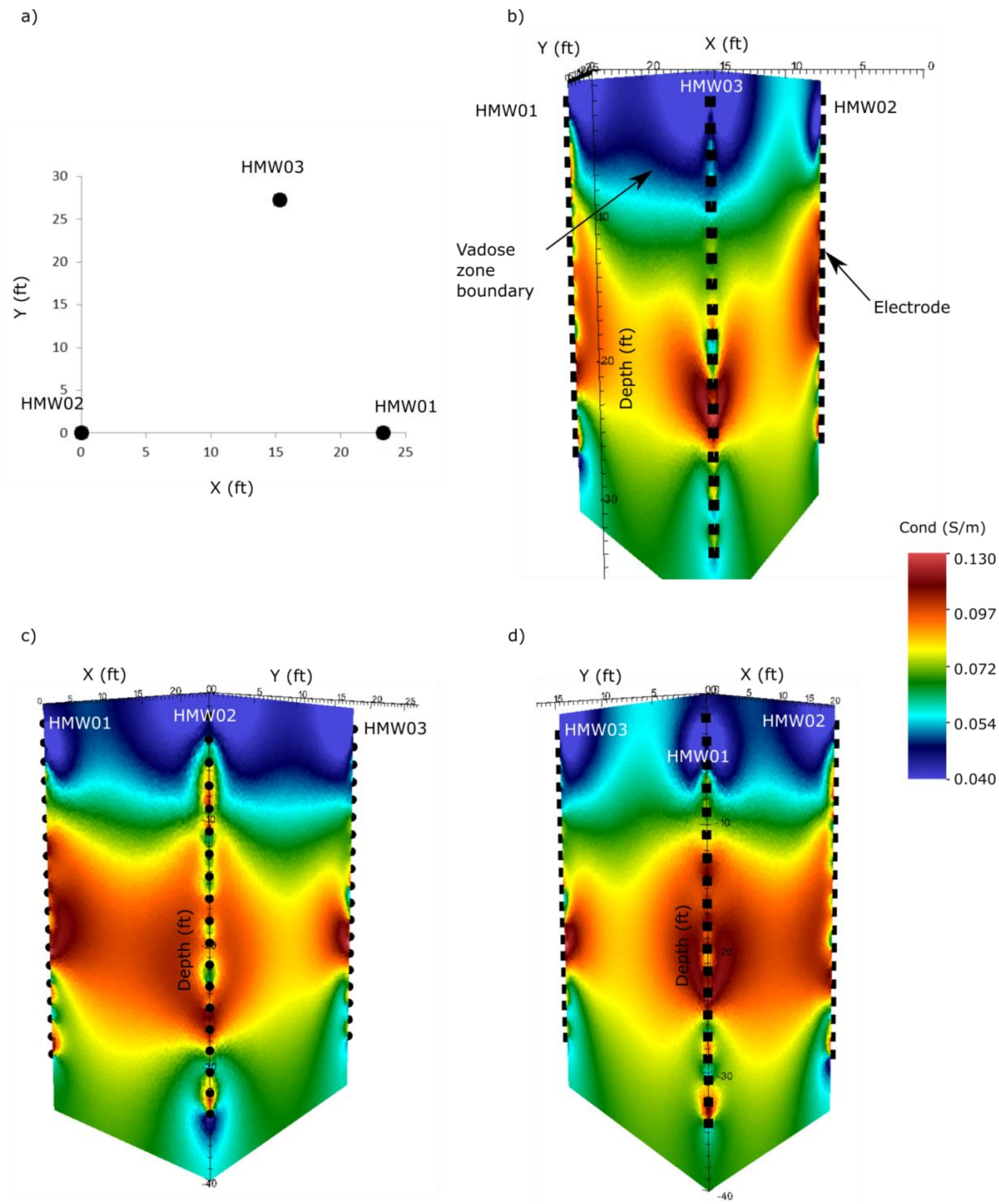

Figure 7: Hydraulic fracturing site: a) Plan view of boreholes for reference. ERT background inversion conductivity images for vantage points a) HMW01-03-02 b) HMW-01-02-03 and c) HMW03-01-02. The interpreted vadose zone boundary is shown in a).

Vertical apparent conductivity profiles, plotted as the log of the relative change in conductivity from the background (σ_0), are shown in Figure 8 for the hydraulic fracturing site. Positive changes represent an increase in conductivity. Most changes shown represent an increase in conductivity, which would be expected with the injection of the lactoid with potassium bromide. Increases in resistivity (i.e. those changes less than zero) might represent localized compaction due to hydraulic fracturing (Figure 8a). The largest change is shown in Figure 8b, at locations closest to the surface in the top 10 feet. Borehole HWM03 shows the smallest overall change (Figure 8c).

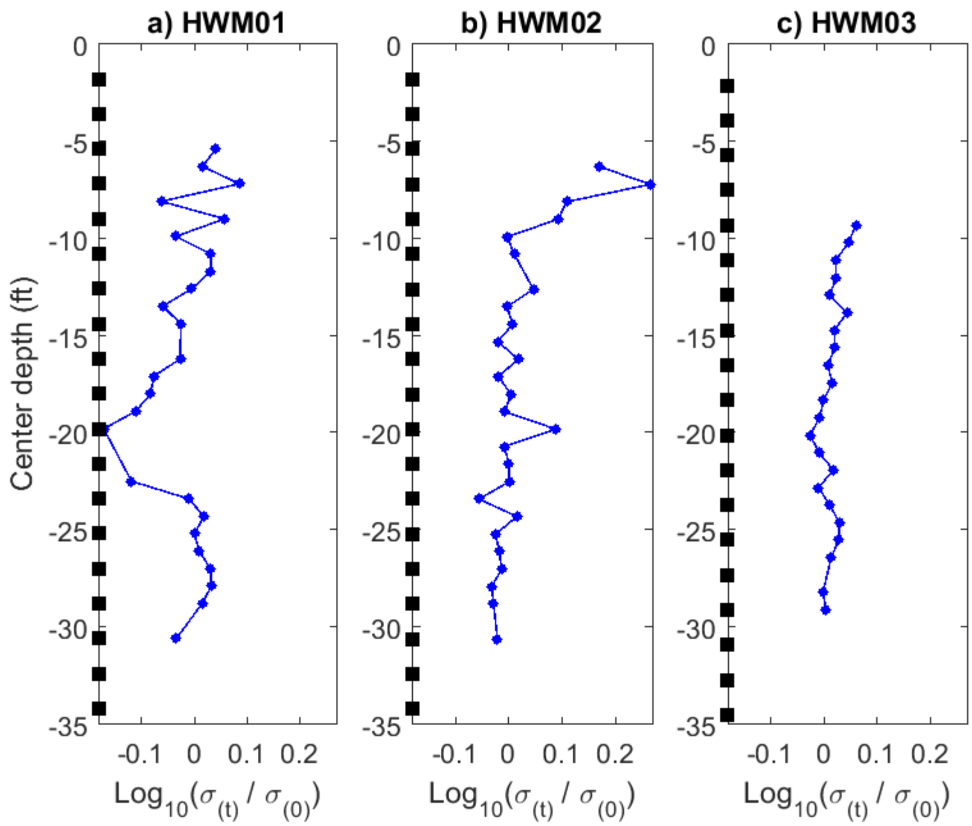

Figure 8: Vertical apparent conductivity profiles for the three monitoring wells HMW01 a) HMW02 b) and HMW03 c) at the hydraulic fracturing site. Note that positive values represent an increase in conductivity after hydraulic fracturing and injection. The scale shown represents changes in apparent conductivity between -17 to 35%. Black squares denote electrode locations. Center depths are the midpoint location of the current and potential electrodes.

Figure 9 shows differences from background for the post fracturing dataset using three vantage points. This figure has been scaled to show only positive changes in conductivity to [1] highlight image pathways created through hydraulic fracturing which presumably contain the conductive injected tracer and [2] reduce image artifacts as we expect conductive changes to dominate over compaction changes with the injection of the conductive amendment. The changes in the raw data in Appendix A support this by showing that overall the changes in the data from the background are dominated by increases in conductivity. The scale shown corresponds to a range of percent changes between 2.5-25%.

All of the changes shown appear local to the monitoring well locations (Figure 9c), with the largest conductivity changes in the top 10 m of HMW02, which corresponds to the vertical apparent conductivity profile in Figure 8b. There is little to no change between the depths of approximately 15-25 feet.

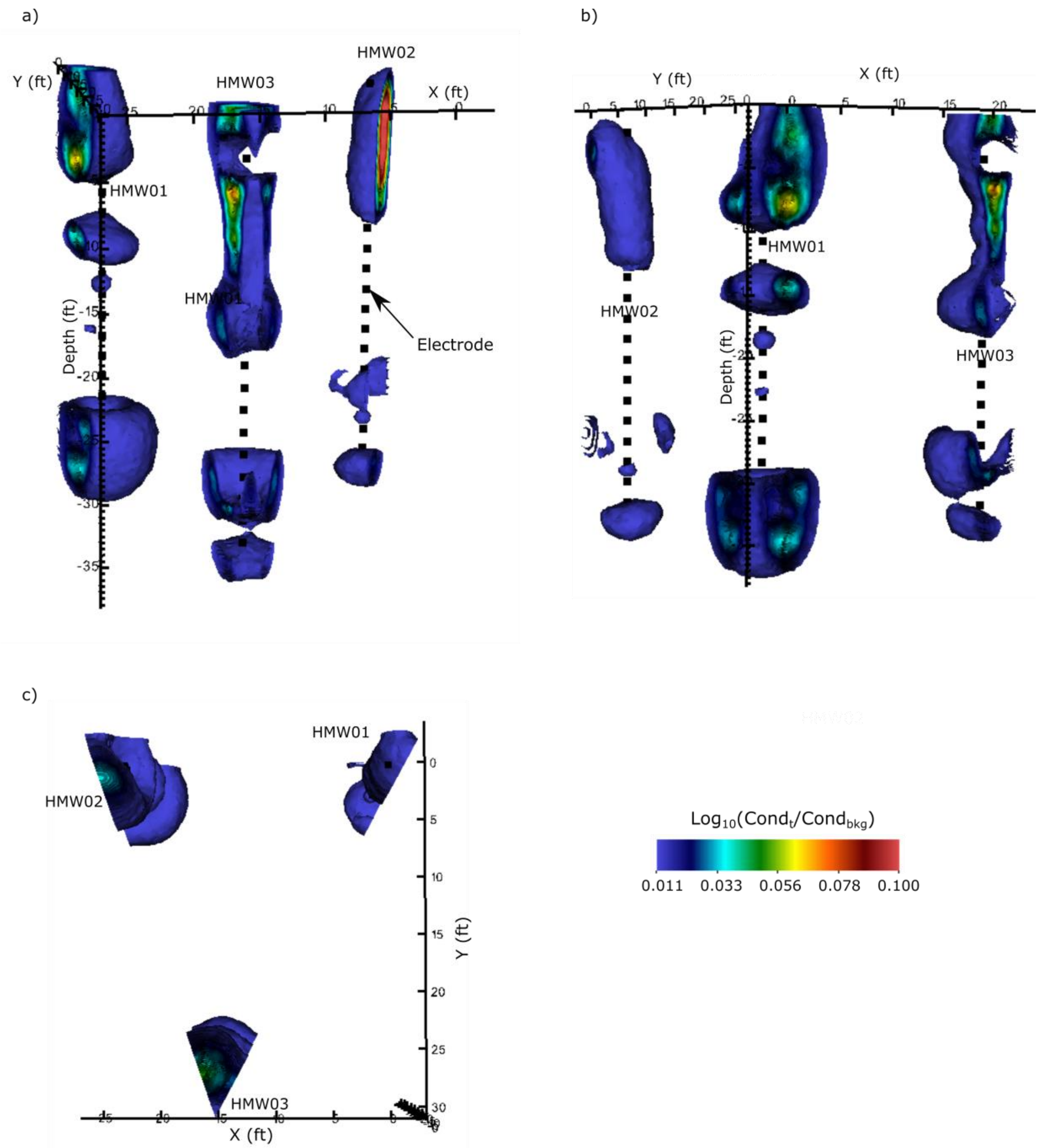

Figure 9: Logarithmic changes in conductivity for the hydraulic fracturing site. Only changes that reflect increases in conductivity are shown. The logarithmic changes shown correspond to a conductivity change range of 2.5-25%.

b. Pneumatic fracturing site

The background ERT inversion images are shown in Figures 10b-d. The resistive surface layer is interpreted as the vadose zone. Electrical conductivity is higher below this boundary. A high conductivity layer exists between 20-30 feet, being within the screened intervals in these monitoring wells.

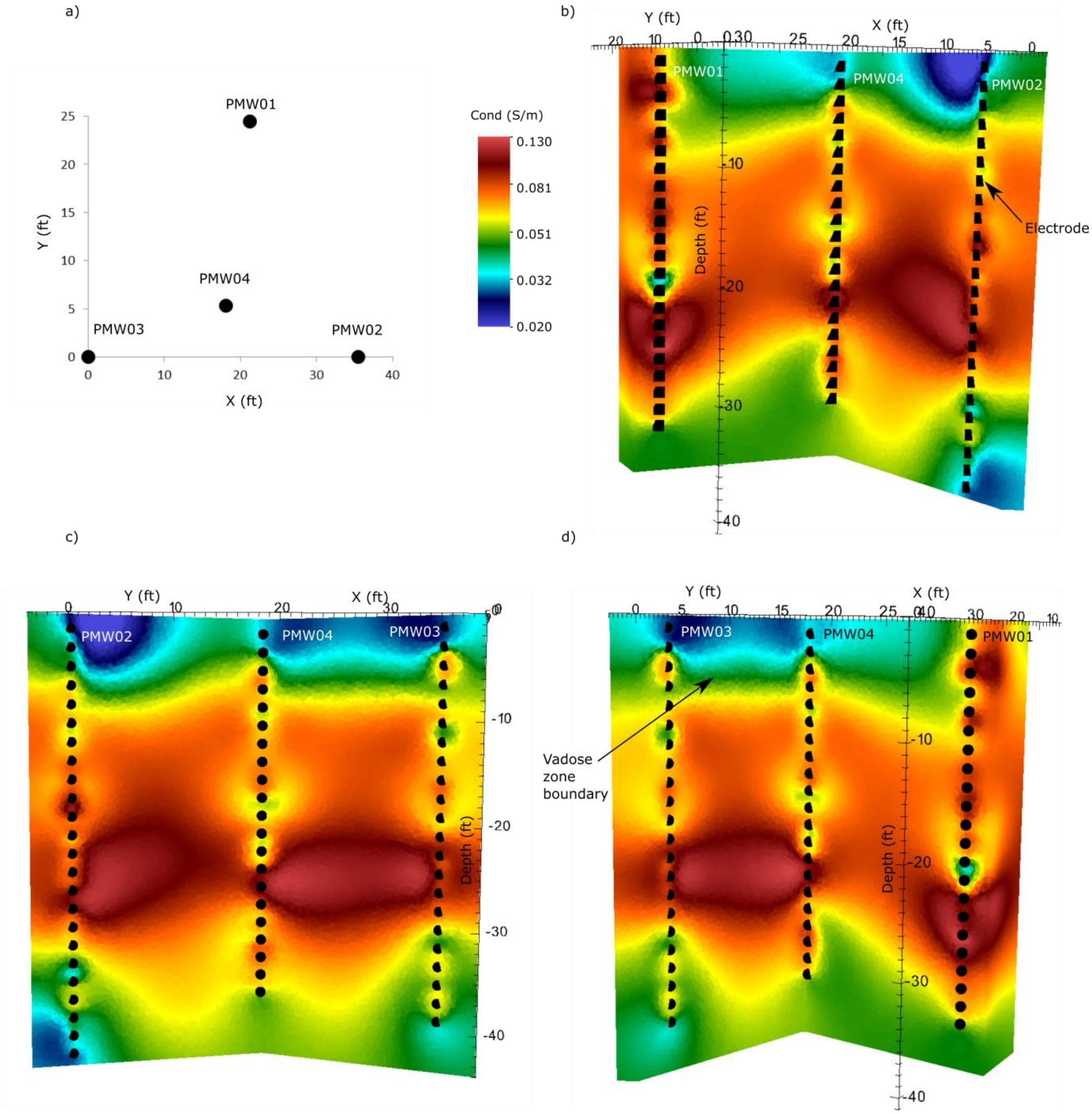

Figure 10: Pneumatic fracturing site: a) Plan view of boreholes for reference. ERT background inversion conductivity images for vantage points b) PMW03-04-02 c) PMW-02-04-03 and d) PMW03-04-01. The interpreted vadose zone boundary is shown in d).

Vertical apparent conductivity profiles, plotted as a logarithmic change in conductivity from the background (σ_0), are shown in Figure 11 for the pneumatic fracturing site. Increases in resistivity (i.e. negative values in Figure 11) may represent compacted areas due to pneumatic fracturing. Considerable changes are noticeable in Figure 11a to depths of approximately 11 feet and in Figure 11b, at a depth of 32 feet.

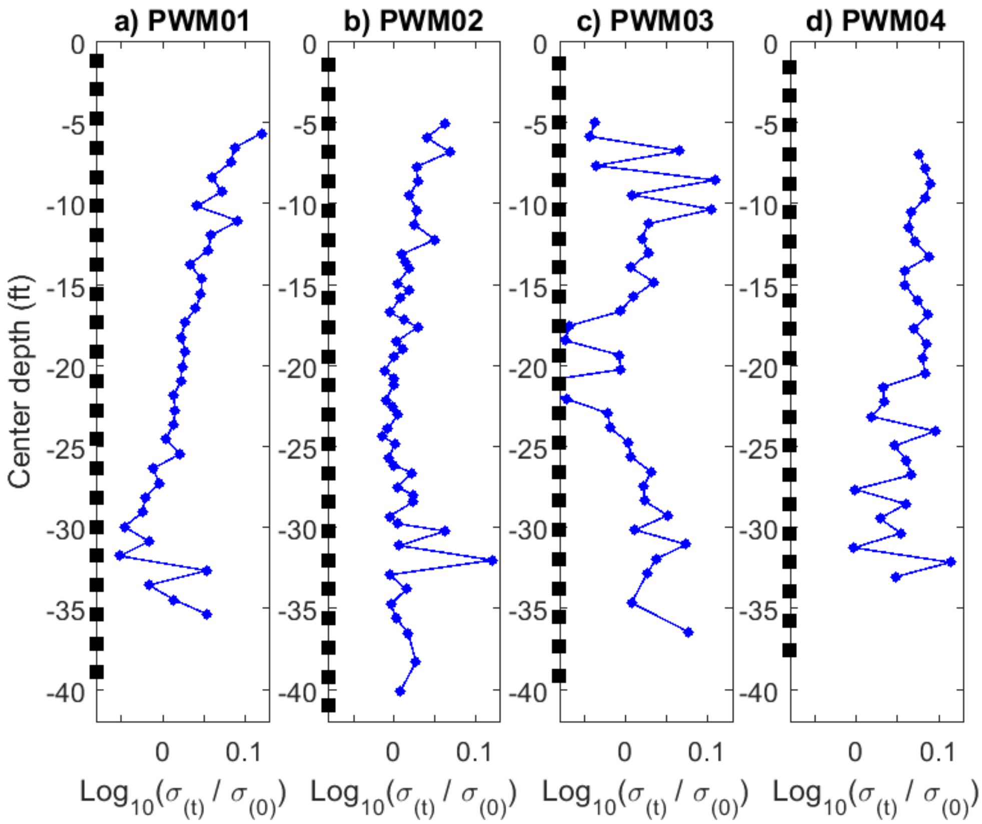

Figure 11: Vertical conductivity profiles for the four monitoring wells PWM01 a), PMW02 b), PMW03 c) and PMW04 d) at the pneumatic fracturing site. Positive values represent an increase in conductivity after pneumatic fracturing and injection. The scale shown represents changes in apparent conductivity between -33 to 86%. Black squares denote electrode locations. Center depths are the midpoint location of the current and potential electrodes.

Figure 12 shows differences from background for the post fracturing dataset using three vantage points. This figure has been scaled to show only positive changes in conductivity. The scale shown corresponds to a range of percent changes between 2.5-25%. All of the changes shown are local to the monitoring well locations (Figure 12b) and limited in radial extent beyond the borehole walls. The changes in apparent conductivity observed in Figures 11a and 11b are manifest as a small change in model conductivity (Figure 12a). The largest changes in the model are at the top of PMW02 yet this does not mimic the profile shown in Figure 11a. This highlights a benefit of dense ERT datasets: although a few localized measurements within the borehole showed large temporal changes in conductivity, the ERT inversion was able to fit the 3D dataset without placing a large conductivity contrast at this location.

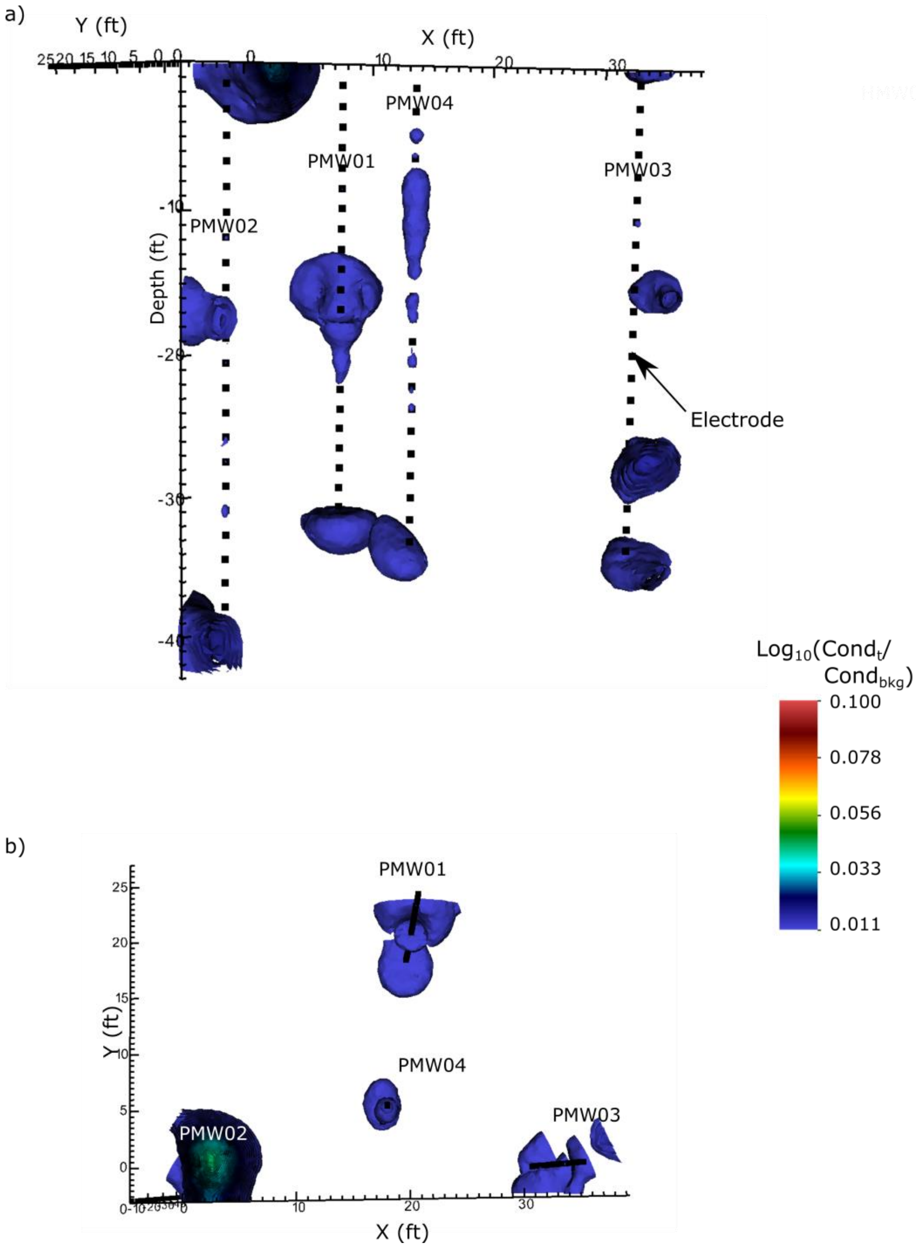

Figure 12: Logarithmic changes in conductivity for the pneumatic fracturing site. Only changes that reflect increases in conductivity are shown. The logarithmic changes shown correspond to a conductivity change range of 2.5-25%.

DISCUSSION AND RECOMMENDATIONS

Inverse modeling of the 3D ERT dataset provided a view of the conductivity structure in between borehole locations, at spatial scales extending beyond the boreholes that are inaccessible to established borehole-based observations. ERT imaging at LCAAP detected changes in resistivity attributed to the fracturing activities. The imaging also resolved the electrical structure of the field site well, including the transition from the vadose zone to saturated zone sediments.

The imaging showed that the screened interval at the site is a region of anomalously high electrical conductivity.

The percentage of resistance measurements filtered from the complete dataset was a little larger than observed at most sites, but still within an acceptable range. Conservative filtering of noisy measurements based on high reciprocal errors, low receiver voltages and low current injections, minimized the possibility of including data into the inversion that can generate artifacts in the images. Careful assessment of numerical modeling errors further limited the possibility of erroneous data points entering the inversion. Such meticulous error assessment is often overlooked in applications of ERT and readily leads to misinterpretation of image structure.

The primary goal of this project was to image changes in subsurface electrical structure due to fracturing and subsequent amendment injection. Raw data (Appendix A) show that measurable decreases occurred at both sites following amendment injection. The inverted images show that resolvable changes in conductivity at both sites were localized around monitoring well locations. The absence of resistivity changes greater than 2.5% further away from the boreholes has two possible explanations: (1) changes in conductivity in these regions were below the noise levels and thus undetectable with this ERT survey; (2) the decreased sensitivity away from the boreholes (Figure 2) prevented true conductivity changes greater than 2.5% from being detected in this region using the selected data acquisition and processing parameters.

A comparison of the increases in conductivity observed at the hydraulic and pneumatic fracturing sites shows a larger change at the hydraulic fracturing site relative to at the pneumatic fracturing site (Figures 9 and 11). Total organic carbon (TOC) data acquired from post-injection boreholes at both sites (Figures 13 and 14) also show larger changes from background at the hydraulic fracturing site relative to the pneumatic fracturing site.

Figure 13 shows changes in the conductivity structure at the hydraulic site well HMW-01 alongside pre-fracturing TOC data from a composite sample from HMW-01and post injection discrete sampling from TOC data from borehole HCB-01. Well HCB-01 is adjacent to HMW-01 within the ‘inner triangle’ of wells HMW-01, HMW-02 and HMW-03. TOC has no direct physically or empirically derived control on electrical conductivity. However a first-order comparison of these profiles is worthwhile assuming that potassium bromide plus lactoid solution was well-mixed such that increases in TOC concentration reflect those locations where the injected solution reached newly formed pathways following fracturing.

Similarities between the time-lapse ERT imaging and the HCB-01(post) fracturing TOC profiles exist (Figure 13). Large changes in electrical conductivity generally coincide with relatively high concentrations of TOC. Both TOC and conductivity change are elevated above ~20 ft. and below ~28 ft. Both TOC and conductivity change are low between 20-28 ft.

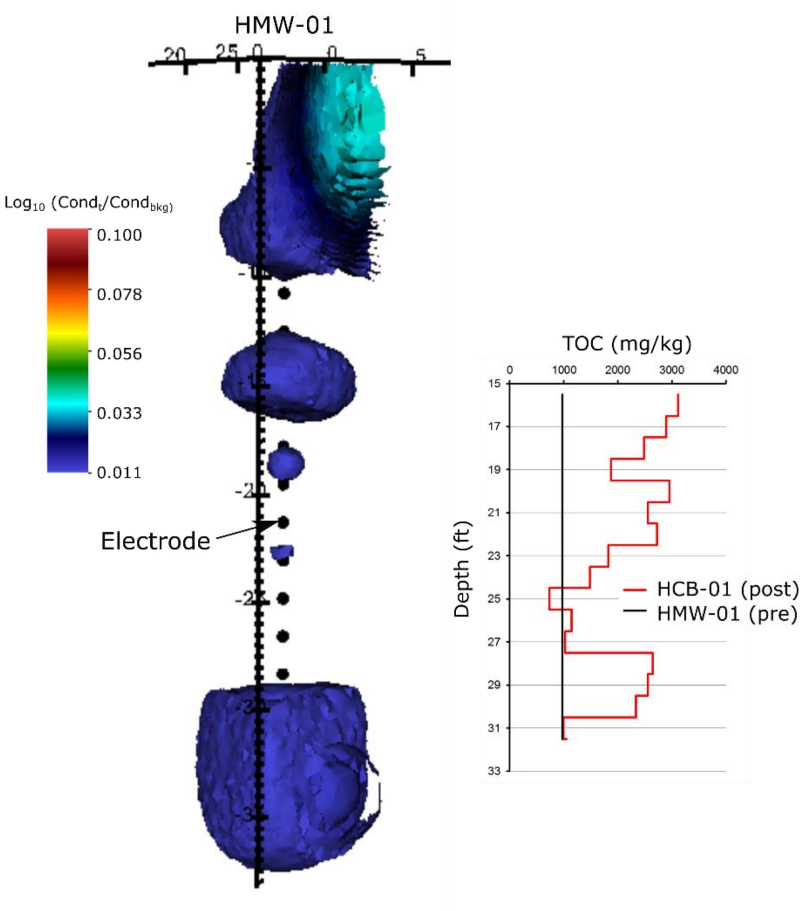

Figure 13: Time-lapse ERT changes at HMW-01 alongside TOC measurements acquired from three (averaged) composite samples in HMW-01 before fracturing (pre) and injection and afterwards (post) from (put number of points) discrete samples collected in HCB-01.

Figure 14 shows changes in conductivity structure at the pneumatic site well PMW-04 alongside pre-fracturing TOC data from three (averaged) composite samples from PMW-04 and post injection discrete sampling from TOC data from wells PCB-01 and PCB-02. Wells PCB-01 and PCB-02 are located within a few linear feet to the west and northeast, respectively, of PMW-04. TOC data from PCB-01 and PCB-02 suggest that few hydraulically connected fractures were generated by pneumatic fracturing relative to hydraulic fracturing. Since PMW-04 is in between these locations, TOC values are assumed to be within a similar range at this location. The low TOC values for the pneumatic fracturing relative to the hydraulic fracturing are consistent with the relatively small changes in resistivity at the pneumatic fracturing location relative to the hydraulic fracturing location. In particular, the time-lapse ERT profile for PMW-04 suggests that minimal change occurred.

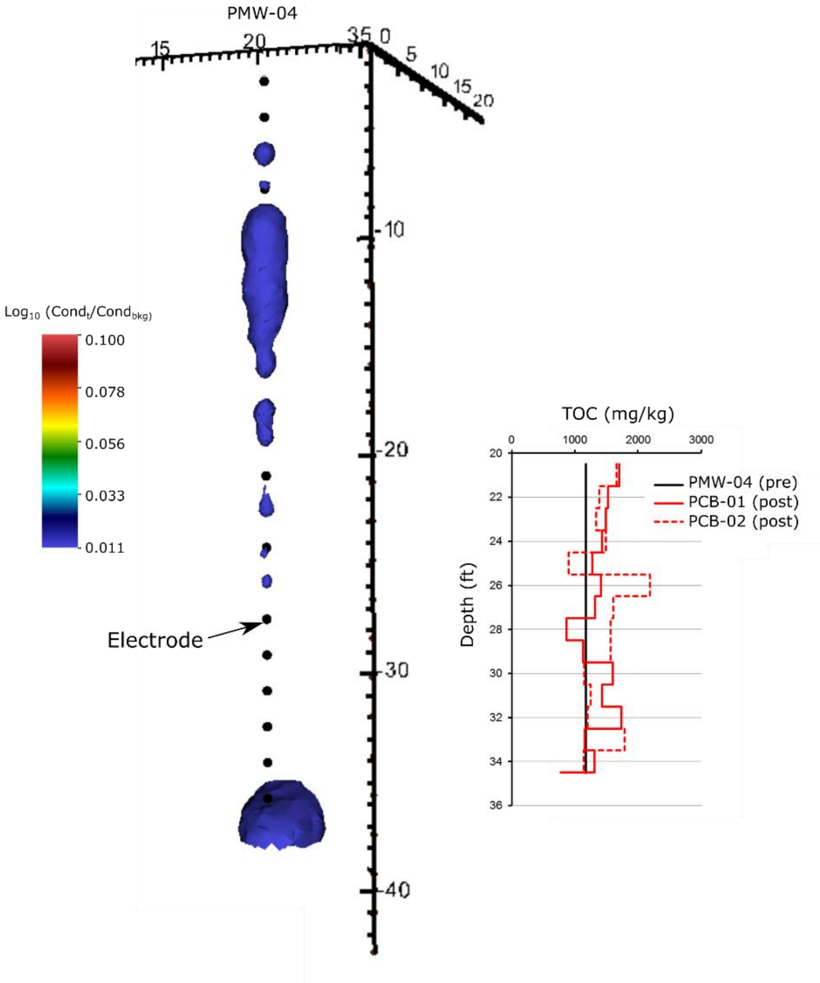

Figure 14: Time-lapse ERT changes at PMW-04 alongside TOC measurements acquired from three (averaged) composite samples in PMW-04 before fracturing (pre) and injection and afterward (post) from discrete samples collected in two adjacent boreholes, PCB-01 and PCB-02.

Based on the results of this field study and discussions with CDM Smith, we recommend the following for our next field ERT campaign at Grand Forks AFB:

1) Plan ERT/monitoring wells with a maximum aspect ratio of 0.70 to limit reduction in image resolution away from boreholes.
2) Increase the conductivity contrast between the native groundwater and the injection solution.
3) Use an optimized ERT sequence to increase sensitivity of the model to the measurements away from the boreholes.
4) Conduct continuous time-lapse ERT monitoring during fracturing to better resolve the effectiveness of fracturing and amendment delivery away from boreholes.

APPENDIX A

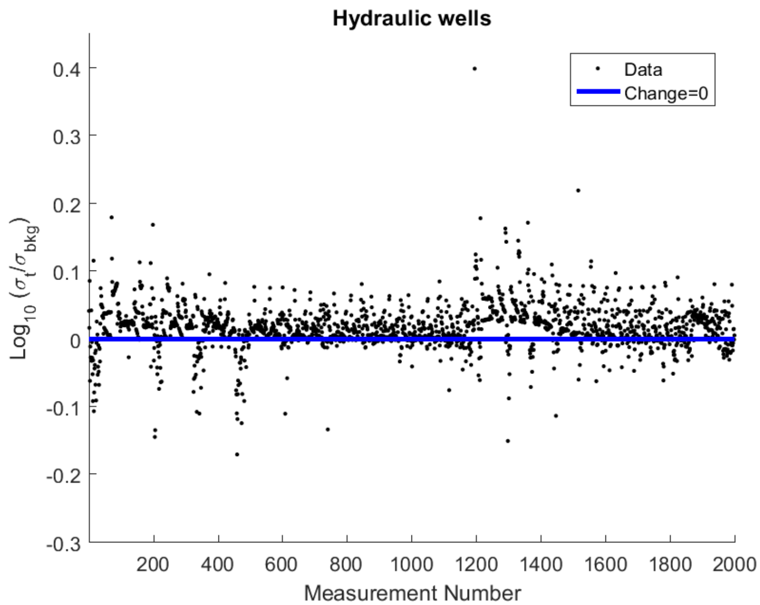

Figure A1: Changes in apparent conductivity at the hydraulic site. The inverted changes are shown in Figures 9. The data exhibits both increases and decreases in conductivity. Our time-lapse interpretation focuses on increases associated with the amendment injection.

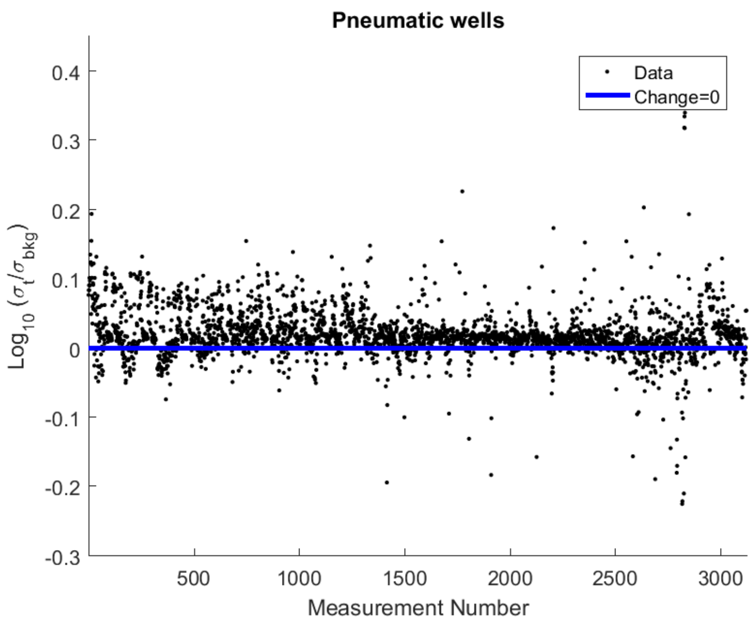

Figure A2: Changes in apparent conductivity at the pneumatic site. The inverted changes are shown in Figures 12. The data exhibits both increases and decreases in conductivity. Our time-lapse interpretation focuses on increases associated with the amendment injection.

REFERENCES

Labrecque, D. et al. 1996. "ERT Monitoring of Environmental Remediation Processes." *Measurement Science and Technology* 7: 375–83.

Wilkinson, Paul B. et al. 2008. "Extreme Sensitivity of Crosshole Electrical Resistivity Tomography Measurements to Geometric Errors." *Geophysical Journal International* 173(1): 49–62. http://gji.oxfordjournals.org/cgi/doi/10.1111/j.1365-246X.2008.03725.x (March 27, 2014).

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APPENDIX E SURVEY REPORTS

MONITORING WELLS

WELL	NORTHING (FEET)	EASTING (FEET)	LATITUDE (DD)	LONGITUDE (DD)	TOR (ELEVATION)	FS (ELEVATION)	TOC (ELEVATION)	RISER_HT
1115-HIW-01	2058785.86	6236903.73	33.3119478	-117.3130481	336.21	336.21	335.69	-0.52
1115-HMW-01	2058770.46	6236911.01	33.3119057	-117.3130237	336.90	336.90	336.46	-0.44
1115-HMW-02	2058775.70	6236889.72	33.3119195	-117.3130936	336.78	336.78	336.25	-0.53
1115-HMW-03	2058798.12	6236898.67	33.3119814	-117.3130650	335.68	335.68	335.23	-0.45
1115-MW-35	2058792.29	6236876.73	33.3119647	-117.3131367	335.95	335.95	335.65	-0.30
1115-MW-37	2058761.45	6236901.73	33.3118807	-117.3130538	337.55	337.55	337.03	-0.52

SOIL BORING LOCATIONS

LOCATION	NORTHING (FEET)	EASTING (FEET)	LATITUDE (DD)	LONGITUDE (DD)		FS (ELEVATION)		
1115-HCB-01	2058782.83	6236916.35	33.3119399	-117.3130067		336.26		
1115-HCB-02	2058788.15	6236890.17	33.3119537	-117.3130925		336.08		

Professional's Name:
Armando D. Dupont

Professional's License Type:
Professional Land Surveyor

Professional's License Number:
7780

NOTE:
RISER_HT - RISER HEIGHT
RISER HEIGHT: THE MEASURED DISTANCE FROM GROUND SURFACE TO TOP OF WELL CASING
DD: DECIMAL DEGREES
TOR: TOP OF RIM
TOC: TOP OF CASING
FS: FINISHED SURFACE

DATE OF SURVEY: SEPTEMBER 1, 2016

BENCHMARK:
THE ELEVATIONS SHOWN HEREON ARE BASED UPON STATIC GPS OBSERVATION,
HOLDING THE LEICA S.N.N.A. C.O.R.S. "CAOS"; ELEVATION = 105.18 FEET (NAVD 88)

COORDINATES:
THE COORDINATES SHOWN HEREON ARE BASED UPON THE CALIFORNIA COORDINATE SYSTEM (CCS 83),
ZONE 6, 1983 DATUM, DEFINED BY SECTIONS 8801 TO 8819 OF THE CALIFORNIA PUBLIC RESOURCES CODE,
BASED UPON STATIC GPS OBSERVATION, HOLDING THE LEICA S.N.N.A. C.O.R.S. "CAOS"

"Location Survey"

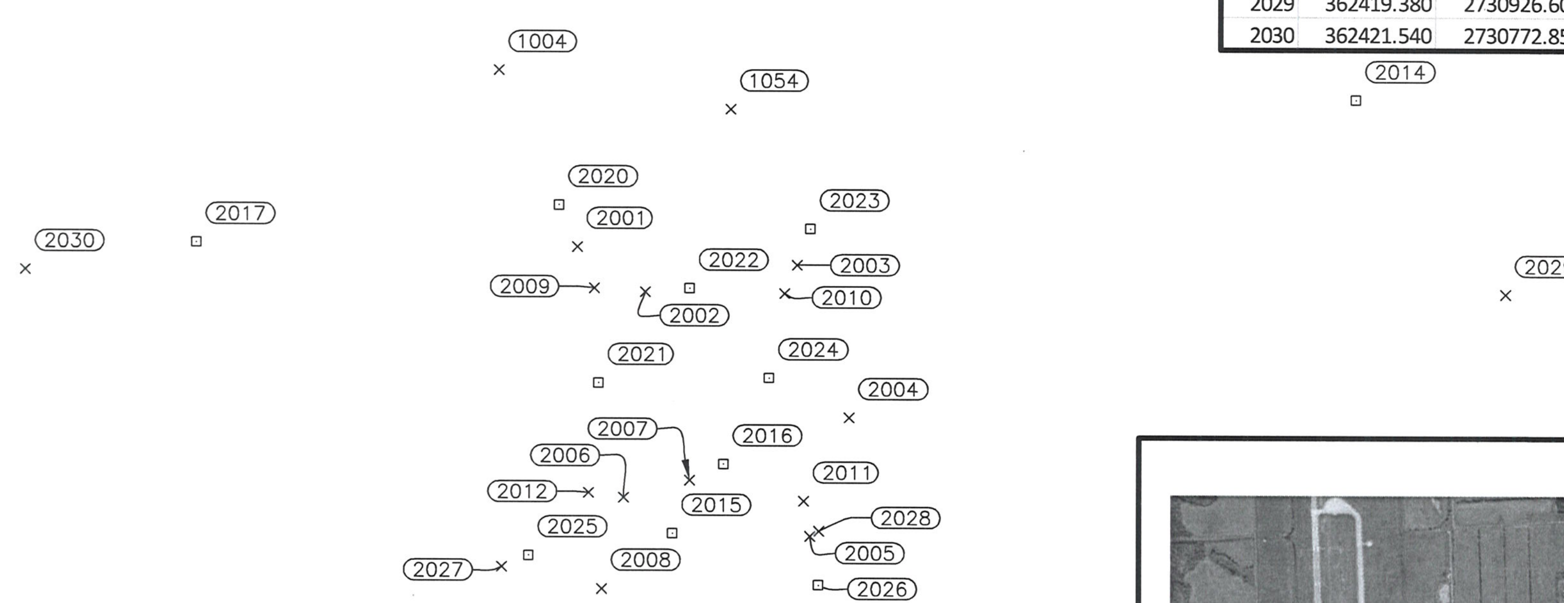
for

Monitoring Wells Located on Grand Forks Air Force Base

	NAD 83 NDN SPC Grid		NAVD 88	
Point	North	East	Elev	Code
	(Feet)	(Feet)	(Feet)	
1004	362442.559	2730821.972	897.32	CP1
1005	362441.613	2731216.167	895.09	CP2
1054	362438.527	2730846.036	895.69	CP3
2001	362424.090	2730830.130	897.73	GFB539-HCB01
2002	362419.400	2730837.200	897.81	GFB539-HCB02
2003	362422.230	2730852.970	897.50	GFB539-HCB03
2004	362406.340	2730858.380	897.61	GFB539-HCB04
2005	362393.890	2730854.350	897.36	GFB539-HCB05
2006	362397.910	2730834.990	897.49	GFB539-HCB06
2007	362399.720	2730841.840	897.42	GFB539-HCB07
2008	362388.360	2730832.740	897.34	GFB539-HCB08
2009	362419.790	2730831.910	897.89	GFB539-HIP01
2010	362419.270	2730851.660	897.51	GFB539-HIP02
2011	362397.570	2730853.690	897.54	GFB539-HIP03
2012	362398.410	2730831.360	897.64	GFB539-HIP04
2013	362526.860	2730817.170	895.11	GFB539-MW03
2014	362439.710	2730910.990	897.12	GFB539-MW04
2015	362394.150	2730840.060	897.21	GFB539-MW05
2016	362401.430	2730845.350	897.14	GFB539-MW06
2017	362424.440	2730790.590	897.22	GFB539-MW09
2018	362358.060	2730808.380	897.52	GFB539-MW10
2019	362320.030	2730878.830	897.79	GFB539-MW11
2020	362428.460	2730828.210	897.40	GFB539-MW15
2021	362409.930	2730832.360	897.62	GFB539-MW16
2022	362419.780	2730841.790	897.54	GFB539-MW17
2023	362426.010	2730854.330	897.37	GFB539-MW18
2024	362410.470	2730850.060	897.49	GFB539-MW19
2025	362391.820	2730825.140	897.55	GFB539-MW20
2026	362388.780	2730855.220	897.21	GFB539-MW21
2027	362390.630	2730822.360	897.89	GFB539-POSTEC1
2028	362394.420	2730855.280	897.36	GFB539-POSTEC2
2029	362419.380	2730926.600	897.16	Y.FLAG
2030	362421.540	2730772.850	897.83	Y.FLAG

Grid North

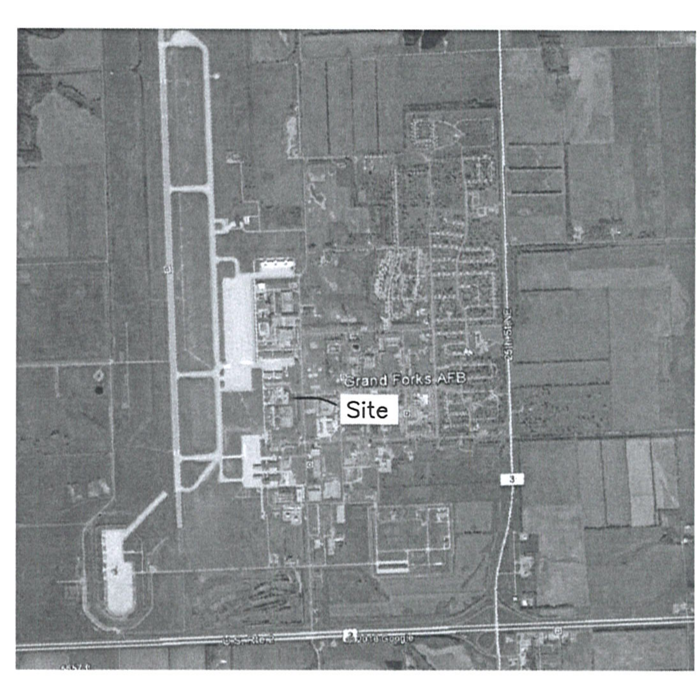
Scale: 1 inch = 20 feet



Surveyor's Note:

Benchmark USGS T261, 1963, PIP - SL0405
Elevation: 900.03 feet NAVD 88.

Horizontal Coordinates are in NAD 83 North Dakota North State Plane Grid. Control Points were established by GPS using DigiFarm VBN (Virtual Base Network)



Vicinity Map
Grand Forks Air Force Base
Scale: None

Legend

- Section Lines
- Quarter Section Lines
- Forty/Eighty Lines
- Public Right of Way
- Boundary Line
- Adjoining Parcels
- ■ Monuments Found
- ● Monument Set (#5 Rebar, 18" long capped #3856)
- ○ Monument Computed
- △ Points on Line

All Dimensions in Feet

0 10 20 40

Scale: 1 inch = 20 feet

REGISTERED PROFESSIONAL ENGINEER AND REGISTERED LAND SURVEYOR
DANIEL V. FISCHER
LS-3856
PE-3856
DATE 9-23-16
NORTH DAKOTA

CFedS No: 1027

Surveyor's Certificate:

I, Daniel V. Fischer, a Professional Land Surveyor, do hereby certify that the survey plat shown hereon was made by me or under my direction from a ground survey and that I have computed or established the monuments and lines as shown, the same is true and correct to the best of my knowledge and belief.

Daniel V. Fischer, PLS — 9-23-16 Date

Fischer

Fischer Land Surveying & Engineering

ND PE/PLS-3856, MN PE/PLS-26037

Certified Federal Surveyor

Subdivision Plats, Legal Surveys, Drainage, Construction Staking GPS Data Collection

Daniel V. Fischer, PE/PLS/CFedS
PO Box 66
Langdon, North Dakota 58249
Tel. (701) 256-5728
email: dfischer@utma.com

Lake City Army Ammunition Plant, Site 17D

CDM Federal Programs Corporation

Final Survey Report

Powell and Associates, LLC

901 NW Vesper Street — Blue Springs, MO 64015

T: 816.228.7070 F: 816.228.1545 W: www.powellsurveying.com

3D Laser Scanning + Land Surveying + Mapping

Certification

County: Jackson
City: Independence
Site: Lake City Army Ammunition Plant, Site 17D
CDM Project No: ER-20143
Powell Project No: 16-950
Subcontractor: Powell and Associates, LLC
Project Manager: Jeremy M. Powell, PLS, CFedS

I hereby certify: That the information contained in this Survey Report is based on actual surveys made by me or under my direct supervision and that said surveys were completed in accordance with the Statement of Work/Specifications for land surveying services, dated January 2016.

Jeremy M. Powell, PLS, CFedS

Professional Land Surveyor of Record

Project Summary

Powell and Associates, LLC (Powell) is providing surveying support to CDM Federal Programs Corporation (CDM Smith/Contractor) for a technology demonstration under the United States Department of Defense's Environmental Security Technology Certification Program (ESTCP) project ER-20143 at the Lake City Army Ammunition Plant (LCAAP), Site 17D (Site). This report presents the results of the site survey conducted to acquire data for the location of monitoring and injection wells and characterization/confirmation sampling locations.

CONTENTS

Project Description

The Site is located within LCAAP, in part of Sections 32 and 33, Township 50 North, Range 30 West in the City of Independence, Jackson County, Missouri.

The work included surveying of horizontal coordinates and vertical elevations for up to 20 standard monitoring and injection wells and up to 20 characterization/confirmation sampling locations.

Scope of Services

Establishment of a horizontal and vertical control network at the Site.

Locating monitoring and injection wells and characterization/confirmation sampling locations.

Personnel and Equipment

Personnel

Aaron Norman, Drafting Technician III

Joseph McLaughlin, Professional Land Surveyor II

Gene Pacas, Survey Technician II

Jeremy M. Powell, Professional Land Surveyor IV

Equipment

Data collection for this project was performed utilizing the following equipment:

Sokkia GRX2 GPS System

Leica TPS 1200 Robotic Total Station

Leica DNA 03 Digital Level

Carlson + Data Collectors with Carlson SurvCE Software

Data Collection

The survey was conducted on March 31, 2016. Data collection included the recovery and location of existing control monuments, the establishment of a horizontal and vertical control network at the Site, and the location of monitoring and injection wells and characterization/confirmation sampling locations, as directed by the Contractor. The surveyor's field notes are provided in Appendix A.

Survey Control

Horizontal Control

A horizontal and vertical control network was established using the following control monuments:

Missouri Geographic Reference System:

JA-56: 1st Order Horizontal Control Point (2003 adjustment)

JA-16 Reset: 1st Order Horizontal Control Point

STATION	GRID NORTHING	GRID EASTING	GROUND NORTHING	GROUND EASTING	ELEVATION
JA-56	1,072,118.85	2,855,577.06	1,072,211.60	2,855,824.09	
JA-16 RESET	1,061,769.09	2,851,576.34	1,061,860.94	2,851,823.02	
HORIZONTAL REFERENCES: STATE PLANE, MISSOURI WEST ZONE, NAD 1983 (US FT) GRID FACTOR: 0.9999135					

Horizontal control for the survey was based on the Missouri State Plane Coordinate System, West Zone, NAD83 and vertical control was based on NAVD88. Documentation of the survey control points are provided in Appendix A.

Three primary control points were established at the Site (CP #5012, CP #5016, and CP #5020). All control points were monumented with a 3/8" rebar with a plastic cap stamped "Control Point". All coordinates were established by GPS triple observations of 30 epoch and were adjusted to ground coordinates using a grid factor of 0.9999135 (1/X=1.00008651).

STATION	GRID NORTHING	GRID EASTING	GROUND NORTHING	GROUND EASTING	ELEVATION
CP #5012	1,070,655.72	2,863,482.81	1,070,748.34	2,863,730.52	766.52
CP #5016	1,070,824.96	2,863,178.83	1,070,917.59	2,863,426.52	757.43
CP #5020	1,070,438.66	2,863,631.40	1,070,531.26	2,863,879.13	769.52
HORIZONTAL REFERENCES: STATE PLANE, MISSOURI WEST ZONE NAD 1983 (US FT) GRID FACTOR: 0.9999135					

Vertical Control

Elevations are based on the National Geodetic Survey (NGS) control monument “K 328”, Vertical Order – First Class II. Elevation=886.40

Site benchmark: Set cut square on the northeasterly corner of concrete pad for existing standup well 16MW103. Elevation=765.69

Field Survey

The field survey consisted of locating seven (7) new monitoring wells, four (4) new injection wells, three (3) existing monitoring wells, one (1) existing injection well, and eleven (11) proposed borehole locations. The proposed borehole locations were marked with pin flags by the Contractor. The existing well locations were delineated by a notch cut in the north side of the PVC casing on each structure. Horizontal locations were established using a Leica TPS 1200 total station. Vertical locations were established by differential leveling using a Leica DNA 03 digital level.

STATION	GROUND NORTHING	GROUND EASTING	ELEVATION	DESCRIPTION
PMW-01	1,070,676.95	2,863,747.85	767.20	NEW PNEUMATIC MONITORING WELL
PMW-02	1,070,690.47	2,863,777.27	766.46	NEW PNEUMATIC MONITORING WELL
PMW-03	1,070,704.95	2,863,745.03	765.51	NEW PNEUMATIC MONITORING WELL
PMW-04	1,070,692.98	2,863,758.52	766.31	NEW PNEUMATIC MONITORING WELL
PIW-01	1,070,685.77	2,863,752.60	766.19	NEW PNEUMATIC INJECTION WELL
PIW-02	1,070,693.75	2,863,768.25	766.11	NEW PNEUMATIC INJECTION WELL
PIW-03	1,070,700.02	2,863,756.08	765.85	NEW PNEUMATIC INJECTION WELL
HMW-01	1,070,703.58	2,863,672.75	764.01	NEW HYDRAULIC MONITORING WELL
HMW-02	1,070,726.41	2,863,668.62	763.45	NEW HYDRAULIC MONITORING WELL
HMW-03	1,070,716.00	2,863,698.12	764.89	NEW HYDRAULIC MONITORING WELL
HIW-03	1,070,721.91	2,863,679.52	763.48	NEW HYDRAULIC MONITORING WELL
16MW-076	1,070,692.29	2,863,742.73	769.44	EXISTING MONITORING WELL
16MW-077	1,070,698.90	2,863,745.33	768.54	EXISTING MONITORING WELL
16MW-103	1,070,701.88	2,863,705.97	768.22	EXISTING MONITORING WELL

16IW-013	1,070,683.16	2,863,770.10	768.23	EXISTING INJECTION WELL
PCB-01	1,070,693.44	2,863,754.11	766.05	BOREHOLE
PCB-02	1,070,695.60	2,863,763.40	766.26	BOREHOLE
PCB-03	1,070,685.09	2,863,761.35	766.27	BOREHOLE
PCB-04	1,070,682.14	2,863,752.20	766.51	BOREHOLE
HCB-01	1,070,706.28	2,863,674.69	764.17	BOREHOLE
HCB-02	1,070,705.47	2,863,694.05	764.28	BOREHOLE
HIW-01	1,070,713.50	2,863,684.41	763.80	BOREHOLE
HIW-02	1,070,715.42	2,863,689.82	764.19	BOREHOLE
HIW-04	1,070,709.73	2,863,678.99	764.01	BOREHOLE
CONTINGENCY 1	1,070,720.88	2,863,686.84	763.89	BOREHOLE
CONTINGENCY 2	1,070,713.19	2,863,676.62	763.92	BOREHOLE

Appendices

Appendix A

SURVEYOR'S FIELD NOTES

EXISTING CONTROL DATA SHEETS

16-950 LAKE CITY - ATK

MONITORING WELLS

BASE: JA-56 HI 4.97

GRID 1072118.849 2855577.065

GRND 1072211.595 2855824.094

EL= 792.977 STORED AS PT# 5000

GF: 0.9999135 Y/X = 1.00008650748

5001-5003 TBM SET NUB & TACK

5004 Avg EL= 881.2179

5005-5007 FND JA-16 RESET

5008 Avg M= 1061860.8756 2851822.9229

G 1061860.942 2851823.0234

-0.0656 - 0.1005

5009-5011 CP Set 3/8 B&C "CONTROL POINT"

5012 Avg

5013-5015 "

5016 Avg

5017-5019 "

5020 Avg

5021-5023 BM SET CUT "□" NE'LY

COR EX STANDUP WELL 16MW103

ADJUSTED EL= 765.694

USED 5000-5065

3/3/16

JHMc GWP 77/50

16-950 LAKE CITY ATK

STA	+	HI	-	EL
		887.4551		881.1409
	6.3142	887.5321		881.2179
		887.8432		886.40
	1.4431	887.9201	1.0550	886.4770
				881.1400
			6.7032	881.2170

3/31/06 JHMc GWP 77/51

Desc.

TBM SET HUB & TACK EL = 881.2179

BM K 328 EL = 886.40

TBM

ADJUSTED EL OF TBM = 881.1409

OUR MEASUREMENTS - 0.077

16-950 LAKE CITY - ATK
MONITORING WELLS

⊼: 5012 HI 5.37
BS: 5016 HT: 6.0
ΔHD = -0.018 ΔEL = -0.041

FS: 5025 BKCK 5016
OUT 0.02 RT 0.00 F 0.04
FS: 5026 ✓ 5020
IN 0.00 LT 0.00 C 0.02

5027 HIW 03 ✓
5028 HMW 02 ✓
5029 HMW 01 ✓
5030 HMW 03 ✓
5031 16MW103 ✓ EX STANDUP WELL
5032 HCB-02 ✓
5033 HIW-02 ✓
5034 HIW-01 ✓
5035 CONTINGENCY 1 ✓
5036 HIW 04 ✓
5037 CONTINGENCY 2 ✓
5038 HCB-01 ✓
5039 PMW 03 ✓
5040 PIW 03 ✓
5041 PMW 04 ✓

3/31/16 JHMC GWP 77/52

5042 PIW01 ✓
5043 PMW01 ✓
5044 PIW02 ✓
5045 PMW02 ✓
5046 PCB-02 ✓
5047 PCB-01 ✓
5048 PCB-03 ✓
5049 PCB-04 ✓
5050 16IW13 ✓ EX STANDUP WELL
5051 16MW77 ✓ "
5052 16MW76 ✓ "

NOTE: ZOOM DUNG NGUYEN SAID THAT THE HORIZONTAL LOCATION SHOULD BE AT THE SAME PLACE AS THE VERTICAL LOCATION A NOTCH IN THE N. SIDE OF THE PVC CASING. WE WERE UNABLE TO ACCESS EXISTING WELLS 16MW028 & 16MW029, THEY WERE LOCKED. ZOOM SAID NOT TO WORRY ABOUT THEM.

16-950 LAKE CITY - ATK

MONITORING WELLS

JHMC GWP 77/53

3/31/16

62.76
7.8935

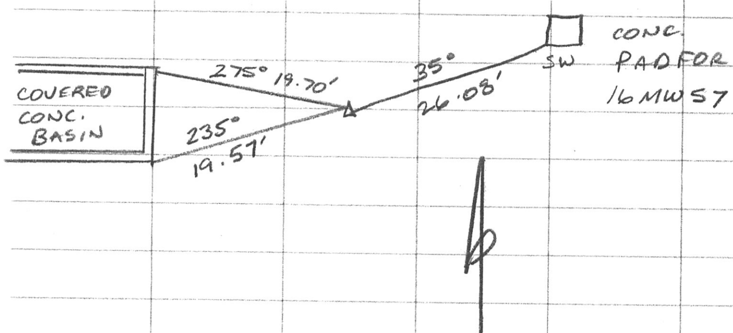
STA	+	HI	-	EL	Desc.
	6.1224	771.8164		765.694	BM SET CUT "□" NE'LY COR CONC. PAD FOR EX STANDUP WELL 16MW103 EL=765.694
			3.5937	768.2227	16MW103
			6.9269	764.8895	HMW 03
			8.3319	763.4845	HIW 03
			8.3710	763.4454	HMW 02
			7.8068	764.0096	HMW 01
				764.1732	HCB 01
			7.8050	764.0114	HIW 04
			7.8935	763.9229	CONTINGENCY 2
			8.0137	763.8027	HIW 01
			7.9229	763.8935	CONTINGENCY 1
			7.6239	764.1925	HIW 02
			7.5397	764.2767	HCB 02
			6.3076	765.5088	PMW 03
			5.9616	765.8548	PIW 03
			5.7067	766.1097	PIW 02
			5.3552	766.4612	PMW 02
			5.5076	766.3088	PMW 04
			5.6301	766.1863	PIW 01
			5.4.6183	767.1981	PMW 01
			5.3085	766.5079	PCB 04

STA	+	HI	-	EL		
		771.8164				
			5.5479	766.2685		PCB03
			5.7714	766.0450		PCB01
			5.5520	766.2644		PCB02
			3.5903	768.2261		16IW13
			3.2731	768.5433		16MW 77
			2.3754	769.4410		16MW 76
	6.3456	772.8616	5.3004	766.5160		CP 5012
	0.9860	770.5014	3.3462	769.5154		CP 5020
	9.7063	767.1368	13.0708	757.4306		CP 5016
			1.4395	765.6973	765.694	BM CUT '□'

16-950 LAKE CITY ATK MONITORING

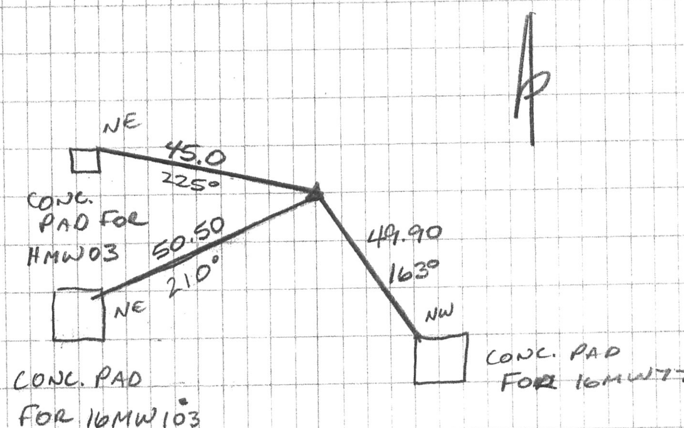
CONTROL TIES

CP 5020 3/8" B&C

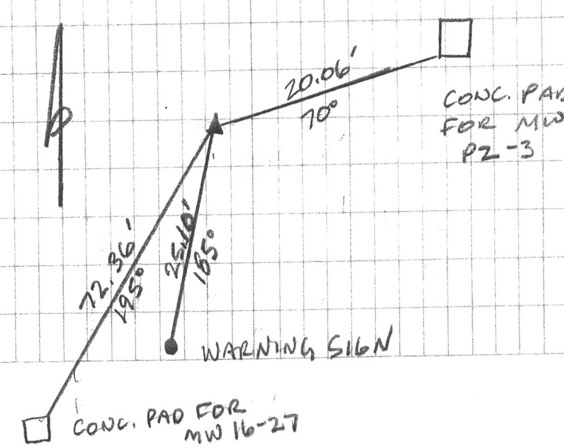


3/31/16 JHMK GWP 77/55

CP 5012 3/8" B&C



CP 5016 3/8" B&C



MISSOURI GEOGRAPHIC REFERENCE SYSTEM
MISSOURI DEPARTMENT OF NATURAL RESOURCES
GEOLOGICAL SURVEY AND RESOURCE ASSESSMENT DIVISION
LAND SURVEY PROGRAM
PO Box 250, Rolla, Missouri 65402, (573) 368-2300

STATION NAME: JA-56 **PID:** 095056
COUNTY: Jackson STATE: Missouri
TOWNSHIP: 50 NORTH, RANGE: 30 WEST, SECTION: 31
USGS 7.5' QUAD: Blue Springs
DATE MONUMENTED: 1988 MONUMENTED BY: MODNR

TECHNICAL DATA TABLE:
(All data in meters 1 meter = 3.28083333 feet)

HORIZONTAL: NAD 1983
DATE OF OBSERVATIONS: 2003
DATE OF ADJUSTMENT: 2003
ORDER: 1st
LATITUDE: 39°06'39.09846”
LONGITUDE: 94°15'51.61010”

VERTICAL: NAVD 1988
DATE OF OBSERVATIONS: 2003
DATE OF ADJUSTMENT: 2003
ORDER:
ELEVATION: 241.7
ELLIPSOID HEIGHT: 209.11

MISSOURI COORDINATE SYSTEM 1983:
NORTH (Y): 326782.479
EAST (X): 870381.631
ZONE: West
CONVERGENCE: 00°08'55"
GRID FACTOR: .9999135

AZIMUTH INFORMATION:
STATION: AZIMUTH MARK:
GEODETIC:
ASTRONOMIC:
GRID:

REMARKS

The HORIZONTAL POSITION was determined by GPS observations and adjusted by the Missouri Department of Natural Resources in 2003

The ELEVATION was determined by GPS observations

The ELLIPSOID HEIGHT was determined by GPS observations referenced to NAD83

GEOID 99 was used in determining ELEVATION and/or ELLIPSOID HEIGHT

Date of Report, 2003

STATION: JA-56

DESCRIPTION: The station is a KC Metro aluminum GRS disk set in concrete and flush with the ground. The station is stamped JA-56, 1988.

STATION, AZIMUTH MARKS AND REFERENCE TIES: The station is about 5.5 miles north of the I-70 and Highway 7 intersection, on the north side of the Lake City Army Ammunition Plant and at the intersection of Elsea Smith Road and Heidelberger Road. It is 17.0 ft southwest of the center of Heidelberger Road; 36.7 ft. southeast of a gate post; 34.4 ft. west of a brace post; and 1.7 ft. north of a carsonite witness post in the fence.

STATION & AZIMUTH MARK TO REACH: To reach the station from the intersection of Highway 24 and Highway 7, go east on Highway 24 1.5 miles to the intersection with Highway 24 and Elsea Smith Road, go south on Elsea Smith Road 1.9 miles to the intersection with Heidelberger Road and the station as described.

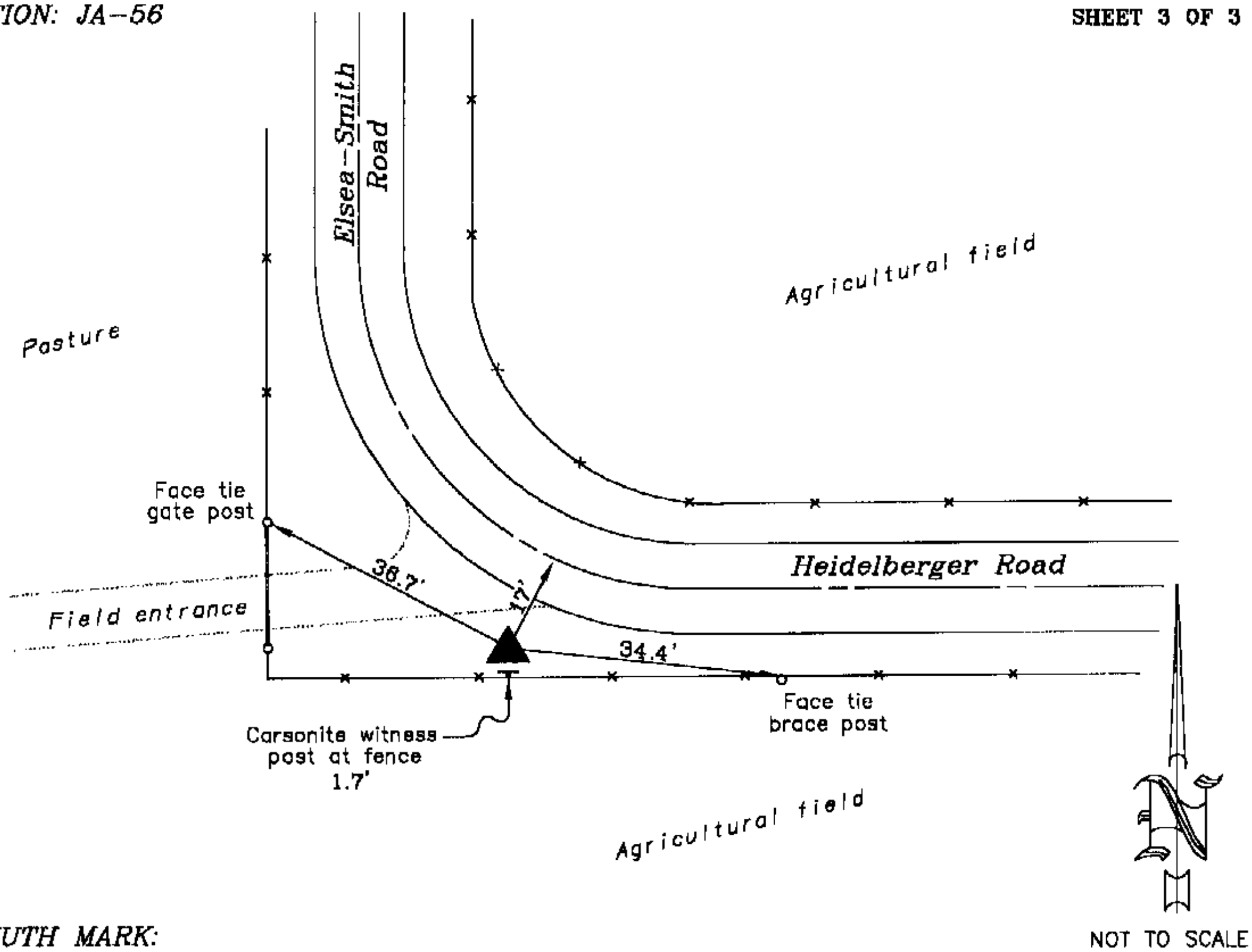
SPECIAL INFORMATION:

Superseded Control

MODNR 1989 LAT: 39°06'39.10642" LONG: 94°15'51.60412"

Date of Report, 2003

STATION: JA-56



AZIMUTH MARK:

DATE OF SKETCH 2002

MISSOURI GEOGRAPHIC REFERENCE SYSTEM
DEPARTMENT OF AGRICULTURE LAND SURVEY PROGRAM
1251A Gale Drive, Rolla, Missouri 65401, (573) 368-2300

STATION NAME: JA 16 Reset
COUNTY: JACKSON
TOWNSHIP: 49 NORTH, RANGE: 31 West,
USGS 7.5' QUAD: Blue Springs
DATE MONUMENTED: 2014

PID: 095016
STATE: MISSOURI
SECTION: 1
MONUMENTED BY: MOAG

TECHNICAL DATA TABLE:
(All data in meters 1 meter = 3.28083333 feet)

HORIZONTAL: NAD 1983 (2011)
DATE OF OBSERVATIONS: 2014
ORDER: 1st
LATITUDE: 39°04'56.89695"
LONGITUDE: 94°16'42.68859"

VERTICAL: NAVD 1988
DATE OF OBSERVATIONS: 2014
ORDER: GPS
ORTHOMETRIC HEIGHT: 283.40
ELLIPSOID HEIGHT: 250.750

MISSOURI COORDINATE SYSTEM 1983:
NORTH (Y): 323627.866
EAST (X): 869162.207
ZONE: West
CONVERGENCE: 0º08’23”
GRID FACTOR: 0.9999064

AZIMUTH INFORMATION:
STATION: JA 16 Reset
AZIMUTH MARK:
GEODETIC:
ASTRONOMIC: None Established
GRID:

REMARKS

The HORIZONTAL POSITION was determined by GPS observations and adjusted by the Missouri Department of Agriculture in 2015.

The ORTHOMETRIC HEIGHT was determined by GPS observations and the latest published high resolution geoid model from NGS.

The ELLIPSOID HEIGHT was determined by GPS observations referenced to NAD83(2011).

GEOID12A was used to determine GEOID SEPARATION and ELEVATION.

Date of Report: 3/16/2015

STATION: JA 16 Reset

DESCRIPTION: The station is a KC Metro Control aluminum pipe monument set in concrete and projecting 1 inch. The station is stamped JA 16 Reset, 2014.

STATION REFERENCE TIES: The station is about 3.5 miles north of the I-70 and Highway 7 overpass (exit 20) in Blue Springs and at the intersection of Highway 7 and Route FF. It is 47.0 ft. northeast of the center of Highway 7; 32.8 ft. west of a right-of- way marker; 57.4 ft. southwest of the 7th fence post north of the corner of the chain link fence for LAKE CITY; 12.8 ft. east of an ATT manhole cover and 1.4 west of a carsonite witness post.

STATION TO REACH: To reach the station from the intersection of I-70 and Highway 7 (exit 20) go north on Highway 7 for 3.7 miles to the intersection of Highway 7 and Route FF and the station as described.

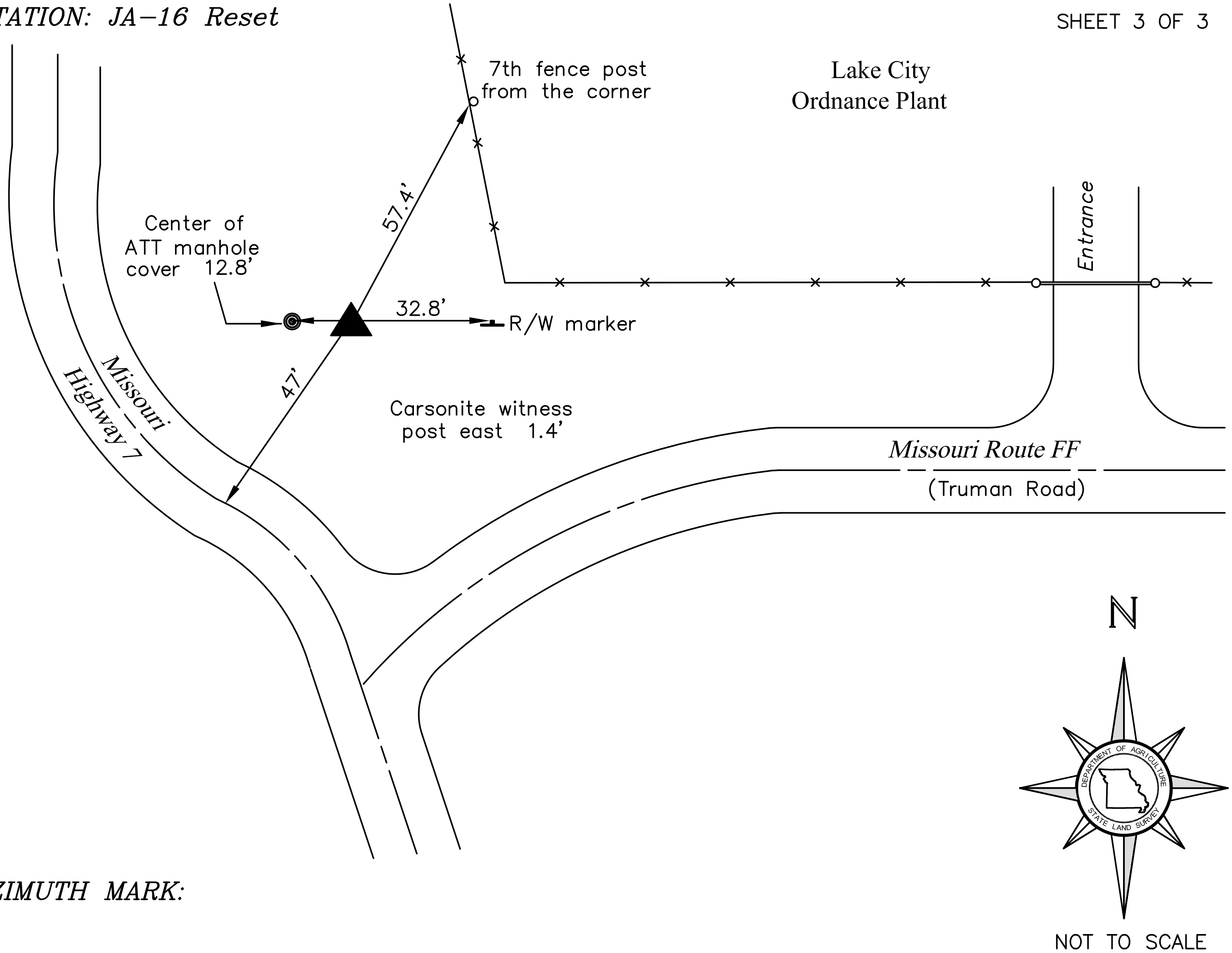
SPECIAL INFORMATION:

SUPERSEDED SURVEY CONTROL:

The original monument was set in 1987. It was reported to our office in 2014 that the cap only had been removed from this pipe monument. Missouri Department of Agriculture replaced the cap on the existing pipe monument and stamped it as "JA 16 Reset, 2014".

No Superseded control is available for this station.

STATION: JA–16 Reset



AZIMUTH MARK:

An azimuth mark was not established at this time.

DATE OF SKETCH 2014

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

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1        National Geodetic Survey,   Retrieval Date = APRIL 19, 2016
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 KE1123  DESIGNATION -  K 328
 KE1123  PID         -  KE1123
 KE1123  STATE/COUNTY-  MO/JACKSON
 KE1123  COUNTRY     -  US
 KE1123  USGS QUAD   -  MISSOURI CITY (1990)
 KE1123
 KE1123                         *CURRENT SURVEY CONTROL
 KE1123  ______________________________________________________________________
 KE1123* NAD 83(1986) POSITION- 39 08 10.1    (N) 094 17 29.1    (W)    HD_HELD2
 KE1123* NAVD 88 ORTHO HEIGHT -    270.176 (meters)      886.40  (feet) ADJUSTED
 KE1123  ______________________________________________________________________
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 KE1123  DYNAMIC HEIGHT  -        270.004 (meters)      885.84  (feet) COMP
 KE1123  MODELED GRAVITY -    979,985.7   (mgal)                        NAVD 88
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 KE1123  VERT ORDER      -  FIRST     CLASS II
 KE1123
 KE1123.The horizontal coordinates were established by autonomous hand held GPS
 KE1123.observations and have an estimated accuracy of +/- 10 meters.
 KE1123.
 KE1123.The orthometric height was determined by differential leveling and
 KE1123.adjusted by the NATIONAL GEODETIC SURVEY
 KE1123.in June 1991.
 KE1123
 KE1123.Significant digits in the geoid height do not necessarily reflect accuracy.
 KE1123.GEOID12B height accuracy estimate available here.
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 KE1123.The dynamic height is computed by dividing the NAVD 88
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 KE1123;                   North         East     Units  Estimated Accuracy
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 KE1123
 KE1123.No superseded survey control is available for this station.
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 KE1123_SP_SET: PIER
 KE1123_STAMPING: K 328 1986
 KE1123_MARK LOGO: NGS
 KE1123_STABILITY: A = MOST RELIABLE AND EXPECTED TO HOLD
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KE1123+STABILITY: POSITION/ELEVATION WELL
KE1123_SATELLITE: THE SITE LOCATION WAS REPORTED AS NOT SUITABLE FOR
KE1123+SATELLITE: SATELLITE OBSERVATIONS - February 03, 2009
KE1123
KE1123  HISTORY     - Date     Condition        Report By
KE1123  HISTORY     - 1986     MONUMENTED       NGS
KE1123  HISTORY     - 20050904 GOOD             GEOCAC
KE1123  HISTORY     - 20090203 GOOD             MODNR
KE1123
KE1123                          STATION DESCRIPTION
KE1123
KE1123'DESCRIBED BY NATIONAL GEODETIC SURVEY 1986
KE1123'8.8 KM (5.45 MI) EAST FROM INDEPENDENCE.
KE1123'8.8 KM (5.45 MI) EASTERLY ALONG U.S. HIGHWAY 24 FROM ITS JUNCTION WITH
KE1123'STATE HIGHWAY 291 IN INDEPENDENCE, SET VERTICALLY IN THE WEST FACE OF
KE1123'THE MOST WESTERLY 1 OF 3 COLUMNS OF THE CENTER PIER OF TWYMAN ROAD
KE1123'(STATE HIGHWAY 7) OVERPASS OF THE HIGHWAY, 12.7 M (41.7 FT) NORTH OF
KE1123'THE CENTERLINE THE EAST BOUND HIGHWAY LANES, AND 12.7 M (41.7 FT)
KE1123'SOUTH OF THE CENTERLINE OF THE WEST BOUND HIGHWAY LANES.
KE1123'THE MARK IS 1.5 M ABOVE THE GROUND.
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KE1123'RECOVERY NOTE BY GEOCACHING 2005 (RCF)
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KE1123
KE1123                          STATION RECOVERY (2009)
KE1123
KE1123'RECOVERY NOTE BY MO DEPT OF NAT RES 2009 (TLS)
KE1123'RECOVERED IN GOOD CONDITION.

*** retrieval complete.
Elapsed Time = 00:00:01
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The word "Certify" or "Certification", as shown and used hereon, means an expression or professional opinion regarding the facts of the survey and does not constitute a warranty or guarantee, expressed or implied.

Declaration is made to the parties named hereon and it is not transferable to additional institutions or subsequent owners.

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APPENDIX F PERMEABILITY ENHANCEMENT REPORTS

Report on the Emplacement of a Remediation Amendment Using Environmental Hydraulic Fracturing Techniques

Lake City Army Ammunition Plant
Site 17D
Independence, Missouri

August 2017

Prepared for:
CDM Federal Programs Corporation
3201 Jermantown Road
Suite 400
Fairfax, VA 22030

Prepared by:
Geo Tactical Remediation Ltd.
#2, 4416 5 Street NE
Calgary, Alberta
T2E 7C3

On Behalf of:
Frac Rite Remediation Inc.

Subcontract No. 6446-001-005-SI
J1604

Executive Summary

Geo Tactical Remediation Ltd. was retained by Frac Rite Remediation Inc. ("Frac Rite") on behalf of CDM Federal Programs Corporation ("CDM") to emplace a remediation amendment using environmental hydraulic fracturing techniques at the Lake City Army Ammunition Plant ("LCAAP") Site 17D site ("the site") in Independence, Missouri. The work was a part of the Environmental Security Technology Certification Program (ESTCP).

ESTCP Project Number ER-201430 involves the demonstration and validation of hydraulic and pneumatic fracturing technologies to enhance the delivery of remediation amendments to low permeability zones and using tiltmeter monitoring technology to quantify the emplaced fracture networks (CDM ESTCP ER-201430 Draft plan May 2015).

The program was conducted between March 22 and March 29, 2016 according to the design and scope of work developed by CDM.

The hydraulic fracturing work consisted of emplacing silica sand proppant as discrete fractures to enhance the formation permeability, followed by injection of LactOil® into the sand propped fractures.

Sand fracture emplacements and pneumatic fractures with subsequent LactOil® injections were mapped with tiltmeter monitoring technology. Tiltmeter data was collected for six hydraulic fractures and five pneumatic fractures/injections. Analysis of the data indicated that discrete planar features were created in each instance.

A total of 12 individual sand fractures were initiated and propagated from four hydraulic fracture borehole locations at the site. Six fractures were initiated from the primary fracture borehole. The additional three fracture boreholes were required due to surfacing of fracture fluid. Fracture initiation intervals ranged from 16 to 30 ft bgs. Approximately 1,590 gal of sand slurry was emplaced containing approximately 11,250 lbs of sand proppant.

An injection well was installed into one of the additional boreholes, 101 gal of LactOil® in 1,876 gal of solution was injected into this well. With the exception of some minor venting at the well seal, the solution was successfully injected into the subsurface.

Table of Contents

1.0 Introduction

Geo Tactical Remediation Ltd. ("Geo Tactical") was retained by Frac Rite Remediation Inc. ("Frac Rite") on behalf of CDM Federal Programs Corporation ("CDM") to emplace a remediation amendment using environmental hydraulic fracturing techniques at the Lake City Army Ammunition Plant ("LCAAP") Site 17D site ("the site") in Independence, Missouri. The work was a part of the Environmental Security Technology Certification Program (ESTCP).

ESTCP Project Number ER-201430 involves the demonstration and validation of hydraulic and pneumatic fracturing technologies to enhance the delivery of remediation amendments to low permeability zones and using tiltmeter monitoring technology to quantify the emplaced fracture networks (CDM ESTCP ER-201430 Draft plan May 2015).

The hydraulic fracturing work consisted of emplacing silica sand proppant as discrete fractures to enhance the formation permeability, followed by injection of LactOil® into the sand propped fractures. Sand fracture emplacement was mapped with tiltmeter monitoring technology. Pneumatic fracturing (completed by Cascade Technical Services) was also mapped using tiltmeter monitoring technology. The program was conducted between March 22 and March 29, 2016 according to the design and scope of work developed by CDM.

2.0 Background

The site was established in December 1940 for manufacturing and testing of small caliber ammunition for the United States Army (USEPA 2008). The site has been in continuous operation except for a single 5-year period following World War II. The site consists of 3,935 acres with 458 buildings (Figure 1). The small community of Lake City is located adjacent to the northern boundary of LCAAP and relies on private groundwater wells (CDM 2015).

The area has a chlorinated solvent plume that extends over 2,000 ft from the southeastern source area to the northwest, effectively following the groundwater flow that moves in a west-northwest direction from the source area. Chlorinated solvent concentrations are between approximately 1 and 10 mg/L in the source area near the southeast end of the plume. The area of the 17D plume is estimated to be 7 acres (Figure 2), with an estimated impacted saturated interval of up to 30 ft (CDM 2015).

Previous investigations indicate that three distinct hydrostratigraphic units exist at the 17D area (Arcadis 2006). A silty clay overburden consisting of both alluvial silty clays and fine silty sands is approximately 20 to 30 ft thick in this area. Hydraulic conductivity for the silty clay colluvium unit has been measured as 4 $\times 10^{-5}$ cm/s. Underlying this unit is a silty clay and weathered shale residuum with a thickness of approximately 10 to 15 ft. The water table in the 17D source area is approximately 5 to 10 ft bgs (below ground surface). This water table is most likely influenced by Abshier Creek, which is approximately 400 ft to the north of the source area (CDM 2015).

3.0 Objectives

The overall objective of this project is to compare the performance and cost benefits of hydraulic and pneumatic fracturing for in situ treatment at low permeability sites. The technical objectives of this project are to:

- Demonstrate the amendment distribution capabilities of environmental hydraulic fracturing in low permeability soils.
- Demonstrate and validate the use of tiltmeter monitoring as a high-resolution, and non-invasive mapping technique to aid in evaluating the performance of environmental fracturing.

4.0 Field Program

4.1 Hydraulic Fracture Emplacement of Sand Proppant

Fracture emplacement of sand slurry commenced at the site on March 21, 2016 using Geo Tactical's EF9300 skid-mounted fracturing unit, downhole fracturing equipment, and high viscosity fracture fluid system.

Plains Environmental Services ("Plains") based in Salina, KS provided drilling for fracturing operations. Drilling was completed using a 7822DT direct push drill rig

The sand slurry was batch mixed aboard the fracturing unit using potable water and Geo Tactical's GTR Enviro high viscosity fracturing fluid system. The high viscosity slurry carries the sand in suspension for even distribution throughout the fracture.

The fracturing process began with Plains driving Geo Tactical's direct push fracture tooling to the first fracture initiation depth. The mixed fracture slurry was then pumped from the fracturing unit downhole through the rods and propagated away from the borehole until the pre-determined volume was emplaced, or fluid surfacing occurred. When the pumping ceased, the rods were advanced to the next desired depth and the process repeated until fracture initiation and propagation at the bottom depth were completed. This method is the top down approach and ensures that discrete fractures are emplaced at each depth.

Fracturing with inflatable straddle packers was also completed at the site. The straddle packer system uses upper and lower inflatable sealing elements connected by an interval pipe. Sand slurry is pumped through ports in the interval pipe into the open borehole between the sealing elements to initiate and propagate the sand fracture. The interval is isolated by expanding the packer sealing elements by inflating them with water. This forms a seal between the packer sealing elements and the borehole above and below the target fracture interval, preventing slurry from entering the borehole above or below the selected interval.

Plains drilled an open borehole with their 6-inch auger tooling for the straddle packer assembly. Their rig was used to lower Geo Tactical's inflatable straddle packer assembly to the first (deepest) fracture initiation depth. When the packers were set, the sand slurry was pumped into the open borehole interval at high enough pressure for formation of a fracture. Continued pumping caused the fracture to propagate away from the borehole. Following fracturing the packer elements were deflated and raised to the next pumping depth. This process continued until all fractures were completed in the borehole. This method is the bottom up approach and ensures that discrete fractures are emplaced at each depth.

The network of created sand fractures provided permeable flow pathways for the subsequent LactOil® injection into the surrounding soils.

During all fracturing events at the site, pressure and pump rate data was monitored and recorded.

4.2 Mapping of Subsurface Fractures

Tiltmeter geophysics was used to map the distribution of sand proppant emplaced by hydraulic fracturing, as well as the distribution of LactOil® solution emplaced by pneumatic fracturing. The tiltmeter mapping helps verify the final distribution of sand and LactOil® in the subsurface.

Prior to pumping the fractures, ten biaxial ES model 700 tiltmeter sensors were placed in two concentric circular arrays (inner and outer) around the fracture borehole location to monitor the micro-movements in the ground surface in response to each fracturing event.

For the hydraulic fracturing, the radial distance of the tiltmeters in the inner array ranged from 14.5 to 15.5 ft and in the outer array ranged from 22 to 25.25 ft. For the pneumatic fracturing, the radial distance of the tiltmeters in the inner array ranged from 11.75 to 12.75 ft and in the outer array ranged from 22.75 to 25 ft.

Tiltmeters were set on prepared locations and leveled to read a tilt angle of approximately zero degrees. During each hydraulic fracturing event, signal data was collected and stored in the memory modules of dataloggers at a collection frequency of 1 tilt data signal every 10 seconds. During each pneumatic fracturing event collection frequency was 1 tilt data signal every 3 seconds. Upon the completion of fracturing at each depth interval, the tiltmeter sensors were leveled again in preparation for the next fracturing event. This process was repeated until all fractures at the borehole were completed.

Geophysical data were analyzed using inverse parameter modeling to determine fracture geometry (modeled as planar disc features) defined by length, width, thickness, asymmetry, orientation, and angle of ascent from horizontal (measured in degrees). In addition to tilt signal, fracture volumes and times were considered in the interpretation of tiltmeter data.

4.3 Injection Well Installation

Following sand fracturing, an injection well was installed by Plains with oversight by CDM. It was completed on March 25, 2016. On March 26, 2016 the injection well was developed to remove any sediment present in the injection well sand pack.

4.4 LactOil® Injection

The LactOil® injection operations commenced on March 26, 2016. The LactOil® solution was formulated by mixing potable water with LactOil® to create a solution that ranged in concentration from 3% to 19% (volume LactOil® to volume of water).

A wellhead assembly was installed on the well. The assembly included connections for hoses with dedicated shut off valves and a pressure gauge. The solution was pumped into the well using Geo Tactical's EFI2000 injection unit. The injection unit operator monitored flow and pressure readings during injection, these readings were displayed and stored by the on-board data acquisition system.

5.0 Results

5.1 Hydraulic Fracturing

The sand fracturing program was conducted between March 21 and 25th, 2016. A total of 12 individual sand fractures were initiated and propagated from four fracture borehole locations at the site (Table 5-1). Fracture initiation intervals ranged from 16 to 30 ft bgs. The total volume of sand slurry emplaced was approximately 1,592 gal and contained approximately 11,250 lbs of sand proppant.

TABLE 5-1
Summary of Fracture Emplacement Results

Borehole I.D.	Fracture Depth Range (ft)	Number of Fracture Depths	Slurry Volume Emplaced (gal)	Sand Mass Emplaced (lbs)
HIW-01	16 – 32	5	727	5,220
HIW-02	18 – 30	4	456	2,785
HIW-03	29.5	1	251	1,995
HIW-04	25	1	158	1,250
SITE TOTAL		***11***	***1,592***	***11,250***

Direct push drilling was used to advance the fracture tool at three locations: HIW-01, HIW-02 and HIW-04. A straddle packer with inflatable sealing elements was used at fracture borehole HIW-03. At HIW-03 only one fracture was successfully emplaced as a borehole seal could not be maintained when attempting to initiate fractures at other depths.

Sand fracturing was completed at four borehole locations instead of the planned single borehole. This change was required due to fluid surfacing that occurred during each pumping event. This adjustment to the design was also made in order to ensure the desired sand mass was emplaced in the work area. Approximately 4% of the fluid volume pumped came to surface. As a result of time delays from fluid surfacing and equipment problems, only 70% of the designed mass of sand was pumped during the field program. Table 1 shows the results of the sand emplacement at each of the borehole locations.

Analysis of operational pressure-time curve and flow rate data (Appendix I) indicated that average pressures for initiating fractures (i.e. "Break Pressures"), including pressure required to overcome friction losses from pumping high viscosity slurry, ranged from 70 to 1,155 psi. The average propagation pressure ranged from 47 to 400 psi with an average pump rate during fracturing from 15 to 110 gal/min (gpm). Pressure time curves with fracture summary sheets are depicted in Appendix I.

5.2 Injection Well Installation

Installation of the injection well was completed on March 25, 2016. A location (Contingency-1) was selected north of HIW-01 for the injection well location (Figure 3). Subsurface debris was found at 4 ft bgs while attempting to drill at Contingency-1, so a well could not be installed. A second location (Contingency-2) was selected west of HIW-01 (Figure 3). This location did not intersect any sand fractures, so the injection well was not installed. HIW-03 was then selected as the location for the injection well because it is upgradient of the groundwater flow direction and had a sand fracture connected to it.

The pneumatic fracturing borehole was not completed as an injection well because no sand proppant was emplaced during pneumatic fracturing.

5.3 LactOil® Injection

Injection of LactOil® into HIW-03 started on March 26, 2016. A total of 1,876 gal of LactOil® solution was injected and contained 101 gal of LactOil®.

The injection flow rate into HIW-03 ranged from 0.6 to 10 gpm. The first 528 gal of LactOil® solution was injected at 10 gpm, with the wellhead pressure ranging from 10 to 25 psi. Surfacing of the LactOil® solution occurred from the well casing after the 528 gal was injected. The pump rate was then initially reduced to 4 gpm, further reductions were required as pumping continued, finishing with 0.6 gpm. The average pump rate during the injection was 5 gpm. The LactOil® concentration was increased to ensure the planned mass was emplaced without significantly extending injection time. The average solution concentration was 5.5%. The injection data is summarized in Table 5-2 below and details for each tank pumped are presented in Table 2 attached.

Table 5-2
Summary of Injection Results

Injection Well I.D.	LactOil® Volume (gal)	Solution Volume (gal)	Time to Pump (min)	Solution Concentration (%)
HIW-03	101	1,876	965	3.0 to 19.0

The fluid surfacing that occurred around the injection well was contained and then re-injected into HIW-03. This allowed over 99% of the LactOil® solution to be successfully injected.

5.4 Hydraulic Sand Fractures Tiltmeter Mapping Results

Six fractures initiated from HIW-01 were mapped using tiltmeter geophysics. An analysis of the tiltmeter data was made to determine the geometry of the fractures. The size and orientation of the fractures are summarized in Table 5-3 below. A more detailed report of the tiltmeter analysis containing graphical depictions is appended in Appendix II and Appendix III.

TABLE 5-3
Hydraulic Sand Fractures – Summary of Tiltmeter Geophysical Results

Fracture I.D.	Depth of Fracture Initiation[1] (ft)	Fracture Thickness (inches)	Fracture Width[2] (ft)	Fracture Length[3] (ft)	Fracture Azimuth[4] (°)	Fracture Dip Angle[5] (°)
HIW-01-1	18	0.336	30.0	12.0	306	46
HIW-01-2	21	0.180	22.0	8.0	298	44
HIW-01-3	26	0.030	25.0	12.0	193	49
HIW-01-3b	26	0.720	33.0	19.0	306	45
HIW-01-4	30	0.660	25.0	12.2	327	21
HIW-01-5	32	0.228	26.0	12.0	48	27

Notes: 1. Depth measured from ground surface to the ports on the fracture tool.
2. Width – fracture dimension measured along dip.
3. Length – fracture dimension measured along azimuth.
4. Fracture Azimuth – describes the compass bearing when looking along a line perpendicular to dip direction (strike), with the fracture dipping down to right.
5. Dip Angle – Angle of fracture inclination from horizontal.

In general, the indicated fracture thickness of the hydraulic fractures during propagation ranged from 0.030 inches at HIW-01-3 to 0.720 inches at HIW-01-3b, with an average thickness of 0.359 inches.

The width of fractures was compared to their length to determine the average fracture aspect ratio. The average width of fractures was 26.8 ft and the average length was 12.5 ft. Thus, the average aspect ratio of HIW-01 was above 1.0, meaning that the dimension along dip is larger than the dimension along azimuth. Fractures generally have some component of asymmetry, and fracture aspect ratios greater or less than 1.0 are common.

The four shallowest hydraulic fractures (18 – 26 ft depth) all dip at or nearly 45°, while the two deeper fractures (30 and 32 ft depth) dip at 21° and 27°.

5.5 Pneumatic LactOil® Fractures Tiltmeter Mapping Results

Five pneumatic fractures and subsequent solution pumping from PIW-03 were mapped using tiltmeter geophysics. An analysis of the fracture mapping results was made to determine the configurations of fracture geometry.

Fracture characteristics could not be determined based on the tilt signals from initiation and propagation of the pneumatic fractures. Tiltmeter analysis was conducted on the tilt signals collected during post LactOil® injection. The tilt signal is generated when pumping stops and the fracture closes. The fracture closes as the fluid propping the fracture open permeates into the surrounding soil matrix (leak-off).

The size and orientation of the fractures are summarized in Table 5-4 below. A more detailed report of the tiltmeter analysis containing graphical depictions is appended in Appendix II and Appendix III.

TABLE 5-4
Pneumatic LactOil® Fractures – Summary of Tiltmeter Geophysical Results

Fracture I.D.	Depth of Fracture Initiation[1] (ft)	Fracture Thickness (inches)	Fracture Width[2] (ft)	Fracture Length[3] (ft)	Fracture Azimuth[4] (°)	Fracture Dip Angle[5] (°)
PIW-03-1	33.5	0.120	35.0	14.0	335	9
PIW-03-2	30.5	0.095	46.9	15.0	305	42
PIW-03-3	27.5	0.120	26.1	15.0	256	35
PIW-03-4	24.5	0.144	27.8	12.7	282	49
PIW-03-5	21.5	0.024	28.4	23.3	38	55

Notes:
1. Depth measured from ground surface to the center of the straddle packer isolation interval.
2. Width – fracture dimension measured along dip.
3. Length – fracture dimension measured along azimuth.
4. Fracture Azimuth – describes the compass bearing when looking along a line perpendicular to dip direction (strike), with the fracture dipping down to right.
5. Dip Angle – Angle of fracture inclination from horizontal.

In general, the indicated fracture thickness of the pneumatic fractures ranged from 0.024 inches at PIW-03-5 to 0.144 inches at PIW-03-4, with an average thickness of 0.101 inches.

The width of fractures was compared to their length to determine the average fracture aspect ratio. The average width of fractures was 32.8 ft and the average length was 16 ft. Thus, the average aspect ratio of PIW-03 was above 2.0, meaning that the dimension along dip is larger than the dimension along azimuth.

The four shallowest hydraulic fractures (21.5 – 30.5 ft depth) all dipped 35° or greater, while the one deeper fracture (33.5 ft depth) dipped at 9°.

6.0 Discussion

Analysis of operational pressure-time data indicate that the mode of sand emplacement into subsurface soils was by hydraulic fracturing, with twelve fractures initiated and propagated from four boreholes.

Fluid surfacing occurred during sand fracturing at the site, requiring three additional fracture boreholes from the original single borehole design. The fluid surfacing was caused by high angle fractures and is likely a result of disturbed subsurface soils. Due to the high angle nature of the fractures, in the future smaller volumes of sand fractures could be used in this area of the site to limit the amount of surfacing on site. Additional boreholes with reduced sand slurry volumes would allow for similar coverage while reducing the chances of fluid surfacing.

During the LactOil® injection the pump rate was limited due to fluid surfacing around the cement seal of the injection well casing. Allowing more time for the cement seal to set would likely have limited the fluid surfacing around the injection well.

The average thickness of the sand propped fractures was 0.36 inches. This thickness is expected to provide longevity of the fractures as high permeable pathways for subsequent injections as required.

The tiltmeter field data was regarded as good to very good with high signal to noise ratios, providing modeling results that were generally of good to excellent quality. All six hydraulic fractures showed excellent fits between recorded and modeled tilt vectors. Of the five pneumatic fractures modeled, four had very good fits, while the remaining fracture had an excellent fit.

All 11 fractures were modeled as single planar structures, although fractures may be more complex than interpreted due to effects that include leak off into more permeable or naturally occurring fractures in bedrock or soils encountered, fluid losses through existing subsurface disturbances (e.g. existing boreholes, excavations, etc.), and possible excessive curvatures of fractures emplaced.

Tiltmeter geophysical results for the hydraulic fractures show that 67% of the fractures had a preferential azimuth orientation towards the northwest which may be the result of preferential pathways in the subsurface. These results showed very little variation in fluid leak off across the site with the majority of analyses showing fracture efficiencies of greater than 86%.

7.0 Conclusion

Hydraulic fracturing was successful in emplacing 70% of the total sand fracture design mass at the site. A total of approximately 11,250 lbs of sand was fractured into four boreholes as 12 independent fractures. A total volume of 1,876 gals of LactOil® solution containing 101 gals of LactOil® was injected into the installed injection well HIW-03. The fracture network emplaced at the site is expected to increase the hydraulic conductivity in the area of the fracture network and allow for increased injection volumes and reduced injection time for future injection events.

The results of fracturing and tiltmeter geophysics demonstrated the vertical and lateral extensiveness of the fracture network of sand and LactOil® across portions of the impacted subsurface sediments. The hydraulically connected network of sand fractures is anticipated to provide significant contact with impacted bedrock and groundwater.

8.0 Closure

Geo Tactical has extensive experience in advanced, in situ fracture and permeation emplacement of a wide variety of treatment amendments. However, Geo Tactical does not warrant or guarantee the long-term success of enhanced in situ remediation using any treatment amendment provided by third party vendors. Geo Tactical guarantees that the quality of its work is of the highest standard using our best practices and technical protocols. Operational sites, or sites where past environmental impacts have been documented, may pose a continuous and ongoing risk of contaminant leakage and/or contaminant migration. Geo Tactical will not be held responsible for achieving any standard of remediation in consideration of the potential for ongoing or future contaminant releases at the site.

We trust that this report meets your requirements. Should you have any questions or comments, please contact the undersigned. Thank you for retaining Geo Tactical on this innovative remedial project.

Yours truly,
Geo Tactical Remediation Ltd.

Cole R. Kaiser, B.A.
Operations Manager

Heather A. Sturm, P.Eng.
Environmental Engineer

Gordon T. Guest, P.Geol.
Principal

9.0 References

CDM Smith. 2015. Demonstration Plan for ESTCP ER-201430

Arcadis. 2006. Final NECOU Remedial Investigation/Feasibility Study. Lake City Army Ammunition Plant. Independence, Missouri. May.

FIGURES

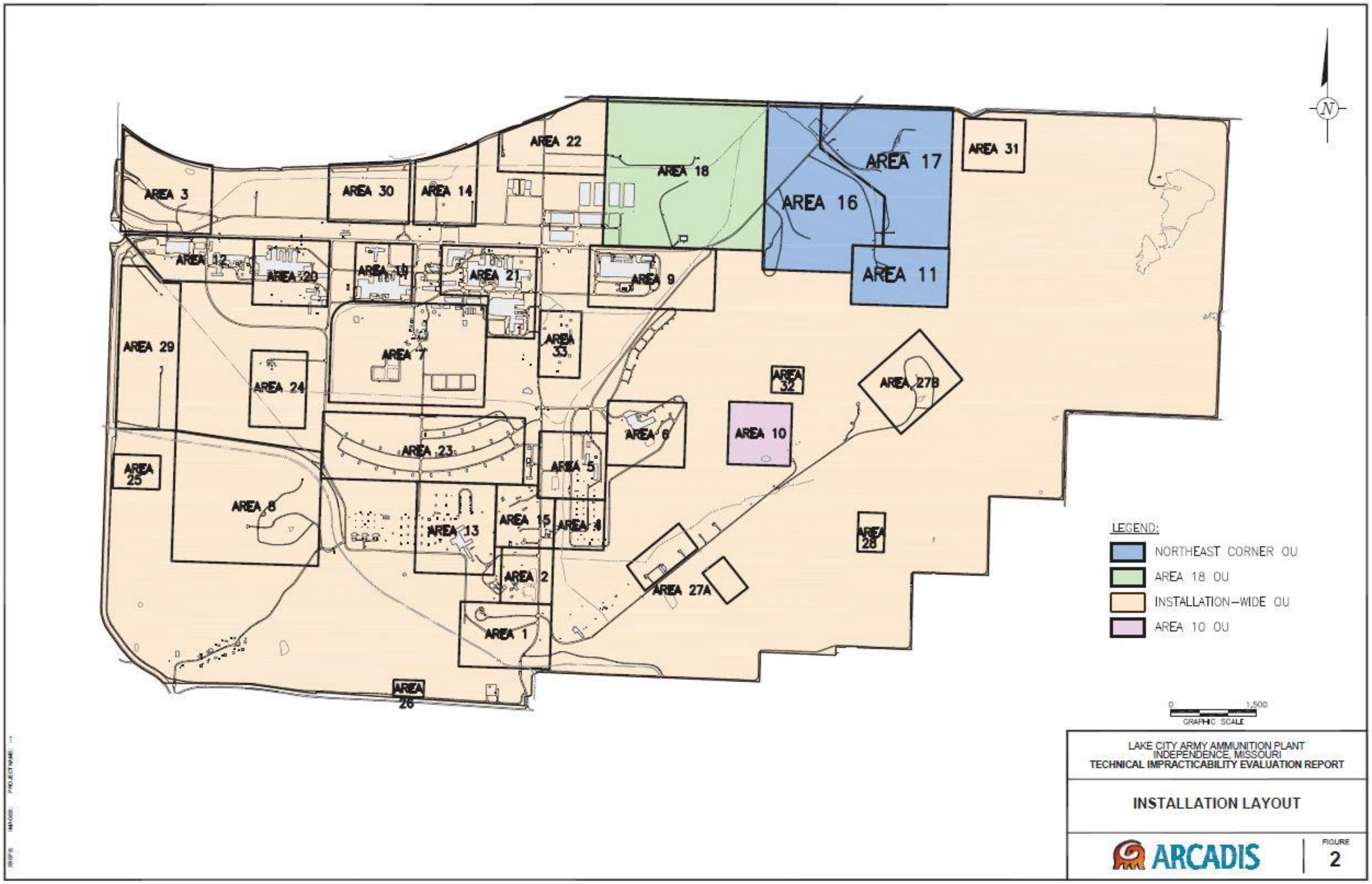


FIGURE 1 – Lake City Army Ammunition Plant Site Map (provided by CDM Smith Inc.)

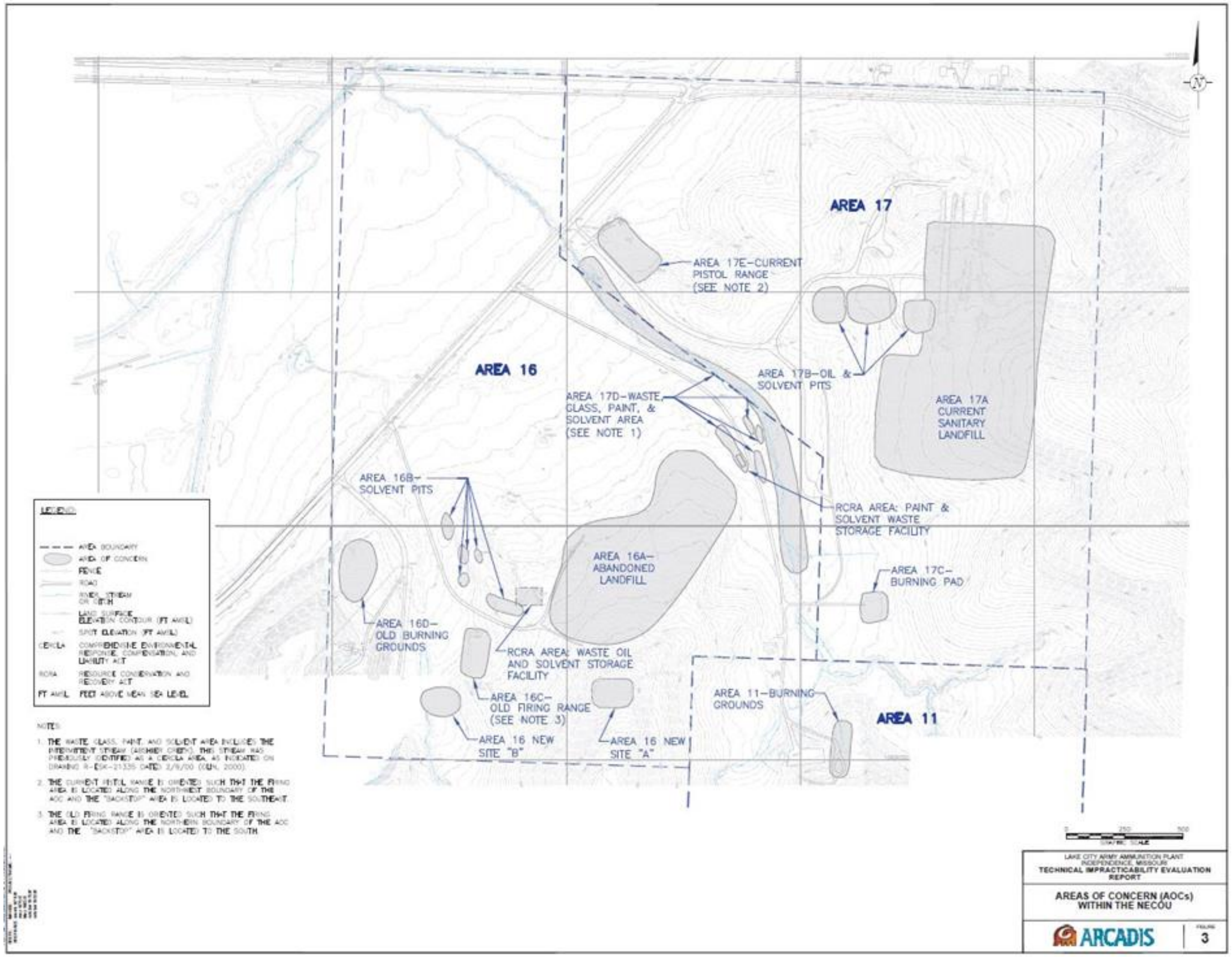


FIGURE 2 – Area 17D Site Map (provided by CDM Smith Inc.)

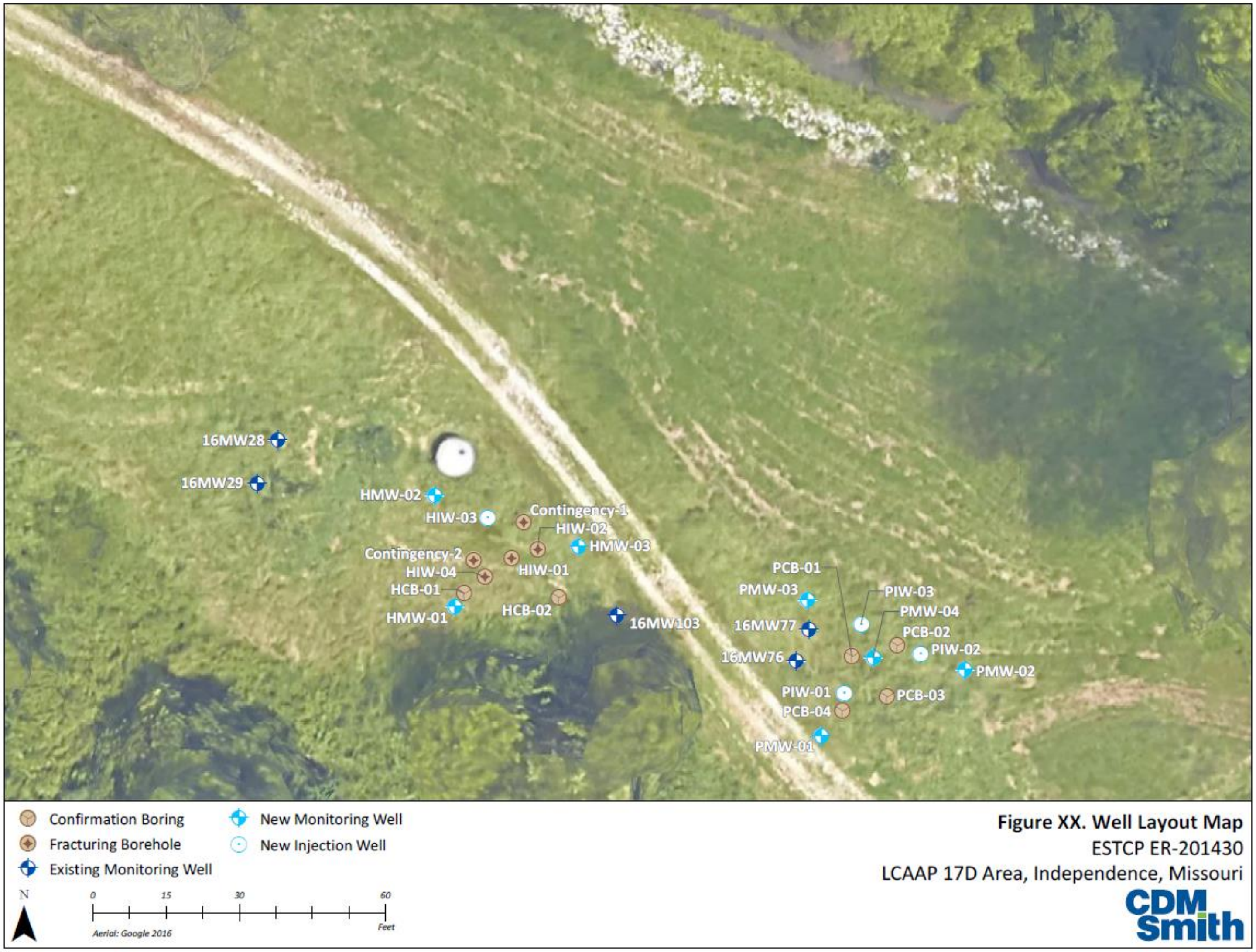


FIGURE 3 – Site Plan (provided by CDM Smith Inc.)

TABLES

TABLE 1
Sand Proppant Fracture Emplacement Results

Fracture Borehole	*Fracture I.D.*	*Depth (ft bgs)*	*Date Emplaced*	*Slurry Volume Pumped (gal)*	*Sand Mass Pumped (lbs)*	*Fluid Surfacing Volume (gal)*	*Slurry Volume Emplaced (gal)*	*Sand Mass Emplaced (lbs)*	Emplacement Efficiency (%)
HIW-01	HIW-01-1	16	21-Mar-16	174	1,275	5	169	1,240	97.1
	HIW-01-2	21	21-Mar-16	21	155	3	18	135	85.7
	HIW-01-3A	26	21-Mar-16	91	670	7	84	620	92.3
	HIW-01-3B	26	21-Mar-16	301	2,100	24	277	1,935	92.0
	HIW-01-4	30	21-Mar-16	144	1,040	8	136	980	94.4
	HIW-01-5	32	21-Mar-16	48	345	5	43	310	89.6
HIW-01 Total				*779*	*5,585*	*52*	*727*	*5,220*	*93.3*
HIW-02	HIW-02-1	18	23-Mar-16	132	475	1	131	470	99.2
	HIW-02-2	22	23-Mar-16	13	50	3	10	40	76.9
	HIW-02-3	26	23-Mar-16	53	190	1	52	185	98.1
	HIW-02-4	30	23-Mar-16	264	2,100	1	263	2,090	99.6
HIW-02 Total				*462*	*8,400*	*6*	*456*	*2,785*	*98.7*
HIW-03	HIW-03-1	29.5	23-Mar-16	264	2,100	13	251	1,995	95.1
HIW-04	HIW-04-1	25	25-Mar-16	159	1,260	1	158	1,250	99.4
SITE TOTAL				***1,664***	***17,345***	***72***	***1,592***	***11,250***	***95.7***

bgs below ground surface

TABLE 2
LactOil® Injection Results at HIW-03

Tank #	LactOil® Volume (gal)	Solution Volume (gal)	Time to Pump (min)	Average Pump Rate (gpm)	Solution Concentration (%)
1	4	132	13	10.2	3
2	4	132	11	12	3
3	4	132	10	13.2	3
4	4	132	9	14.7	3
5	4	132	35	3.8	3
6	4	132	40	3.3	3
7	4	132	33	4	3
8	4	132	39	3.4	3
9	4	132	61	2.2	3
10	8	119	87	1.4	6.7
11	8	119	110	1.1	6.7
12	8	106	115	0.9	7.5
13	8	106	114	0.9	7.5
14	8	106	76	1.4	7.5
15	25	132	212	0.6	19
Total	***101***	***1,876***	***965***		

APPENDIX I

PRESSURE TIME CURVES AND FRACTURE SUMMARY SHEETS

FRACTURED BOREHOLE SUMMARY SHEET

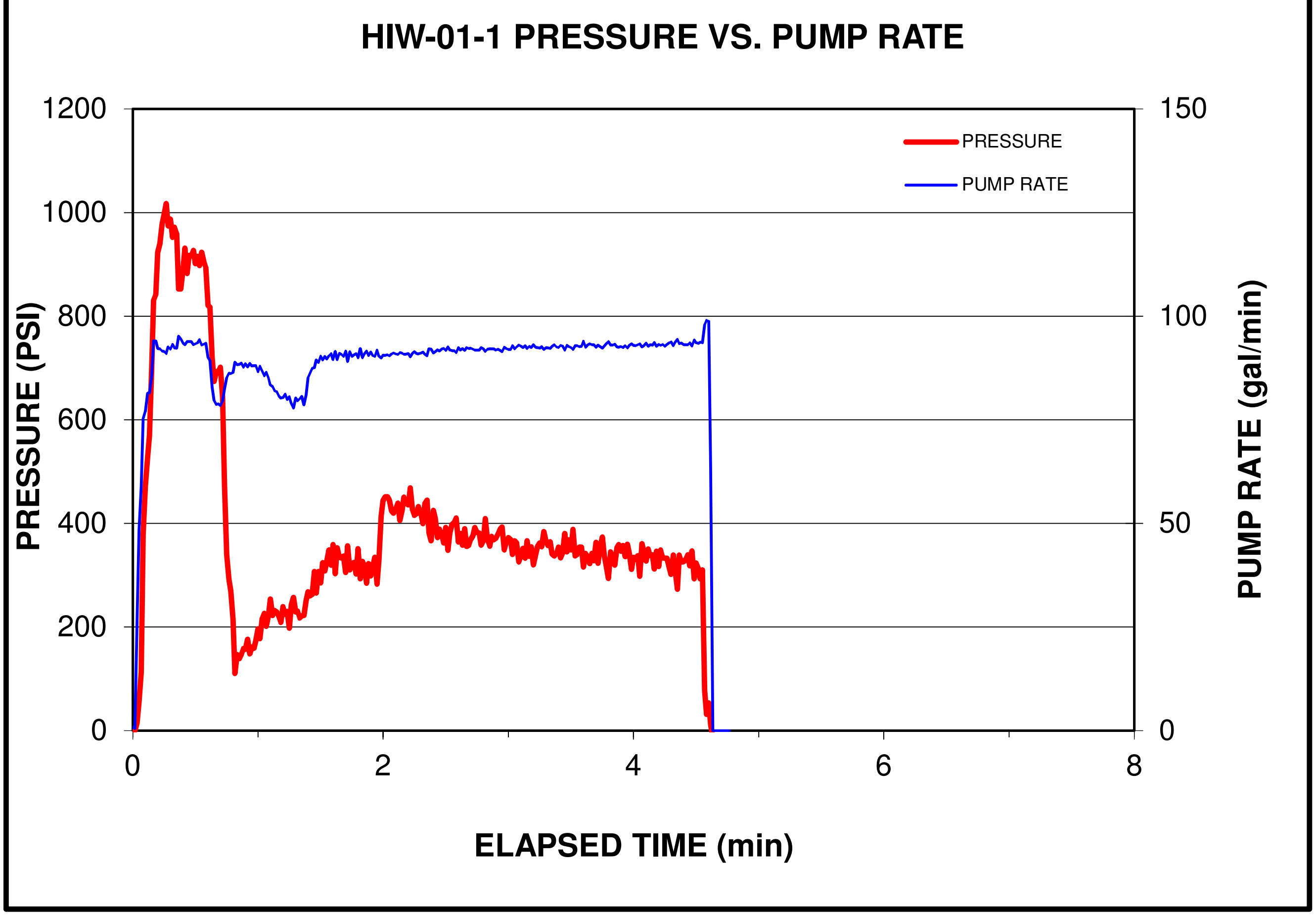
PROJECT NUMBER: J1604 DATE: March 21, 2016

FRACTURE BOREHOLE ID: HIW-01

FRACTURE ID:	HIW-01-1	HIW-01-2	HIW-01-3A	HIW-01-3B	HIW-01-4	HIW-01-5
DEPTH (ft.)	16	21	26	26	30	32
SOIL TYPE	Silty Clay	Silty Clay	Silty Clay	Silty Clay	Silty Clay	Silty Clay
PROPPANT TYPE	20/40 sand	20/40 sand	20/40 sand	20/40 sand	20/40 sand	20/40 sand
PROPPANT SLURRY VOL PUMPED (gal)	175	20	90	300	145	50
GEL PAD VOL (gal)	13	13	13	20	13	26
GEL FLUSH VOL (gal)	13	0	28	42	20	0
PROPPANT MASS PUMPED (lbs.)	1275	155	670	2100	1040	345
PROPPANT LOADING (lbs./gal)	7	8	7	7	7	7
VENT/LOSS (gal)	5	3	7	24	8	5
VENT/LOSS TYPE	Remote	Remote	Remote	Remote	Remote	Remote
PLACEMENT EFFICY. (%)	97	87	93	92	95	89
PROPPANT MASS EMPLACED (lbs.)	1235	135	620	1935	985	310
PEAK PRESSURE (PSI)	1017	521	1156	637	265	129
AVERAGE PRESSURE (PSI)	402	48	72	390	218	47
BREAK PRESSURE (PSI)	1017	464	625	637	228	79
PEAK PUMP RATE (gal/min)	99	119	121	118	95	118
AVERAGE PUMP RATE (gal/min)	89	16	65	110	89	98
PUMP RATE AT BREAK (gal/min)	81	64	46	106	93	96
REMARKS	Vent 5 ft South of HIW-01, approximately 5 gal	Vent 5 ft South of HIW-01, approximately 3 gal	Vent 5 ft South of HIW-01, approximately 7 gal	Vent 5 ft East of HIW-01, approximately 24 gal	Vent 5 ft East of HIW-01, approximately 8 gal	Vent 10 ft East of HIW-01, approximately 5 gal Low pump efficiency, pumping paused at 4 min to gel flush pump

ND - Not Determined NA - Not Applicable

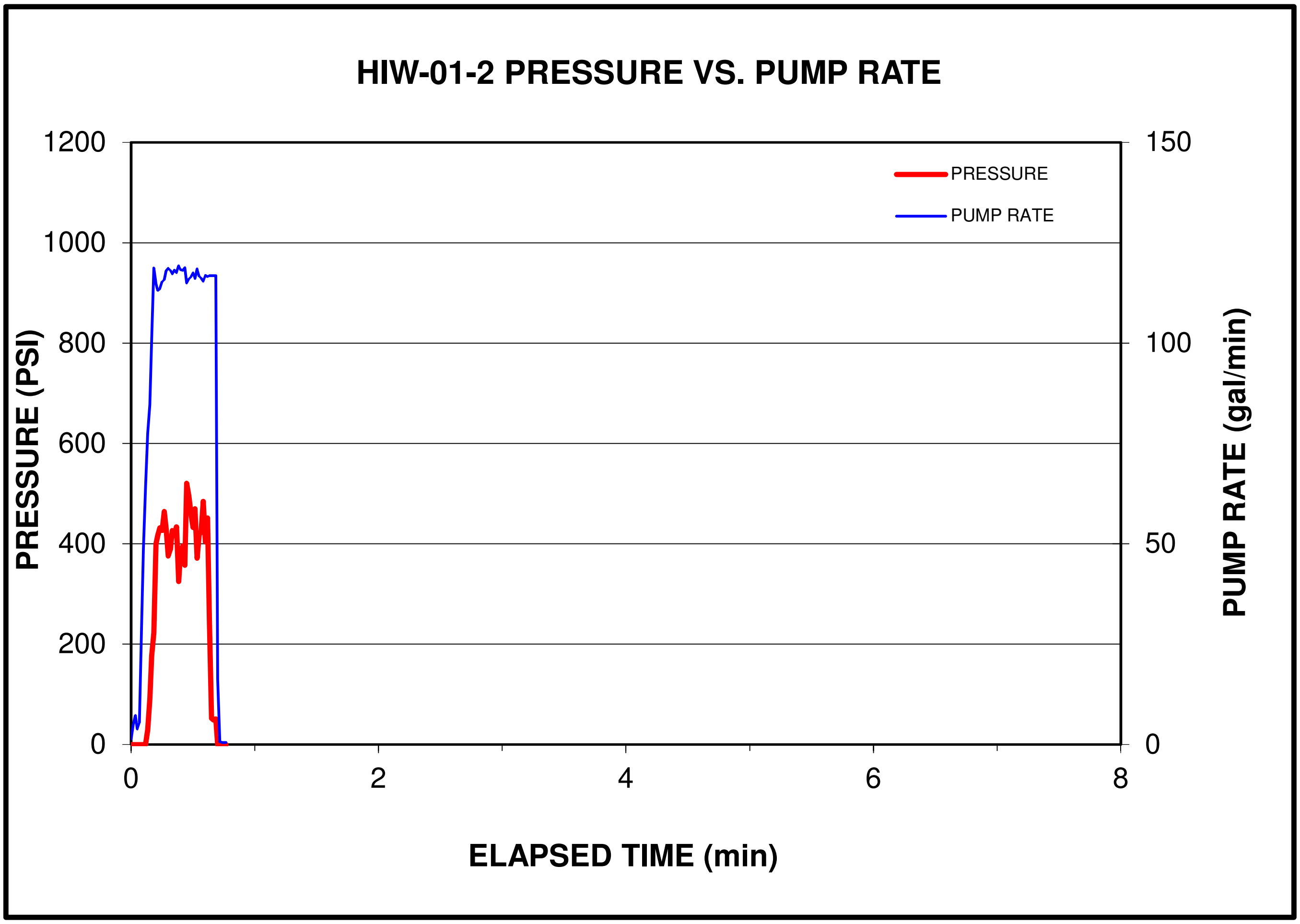
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	21 March 2016	
FRACTURE NO.:	HIW-01-1		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	16.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	175	(gal)	PLACEMENT EFFICIENCY:	97	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	1275	(lbs.)
BREAK PRESSURE:	1017	(PSI)	AVERAGE PUMP RATE:	89	(gal/min)

REMARKS: Vent 5 ft South of HIW-01, approximately 5 gal

FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	21 March 2016	
FRACTURE NO.:	HIW-01-2		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	21.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	20	(gal)	PLACEMENT EFFICIENCY:	87	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	155	(lbs.)
BREAK PRESSURE:	464	(PSI)	AVERAGE PUMP RATE:	16	(gal/min)

REMARKS: Vent 5 ft South of HIW-01, approximately 3 gal

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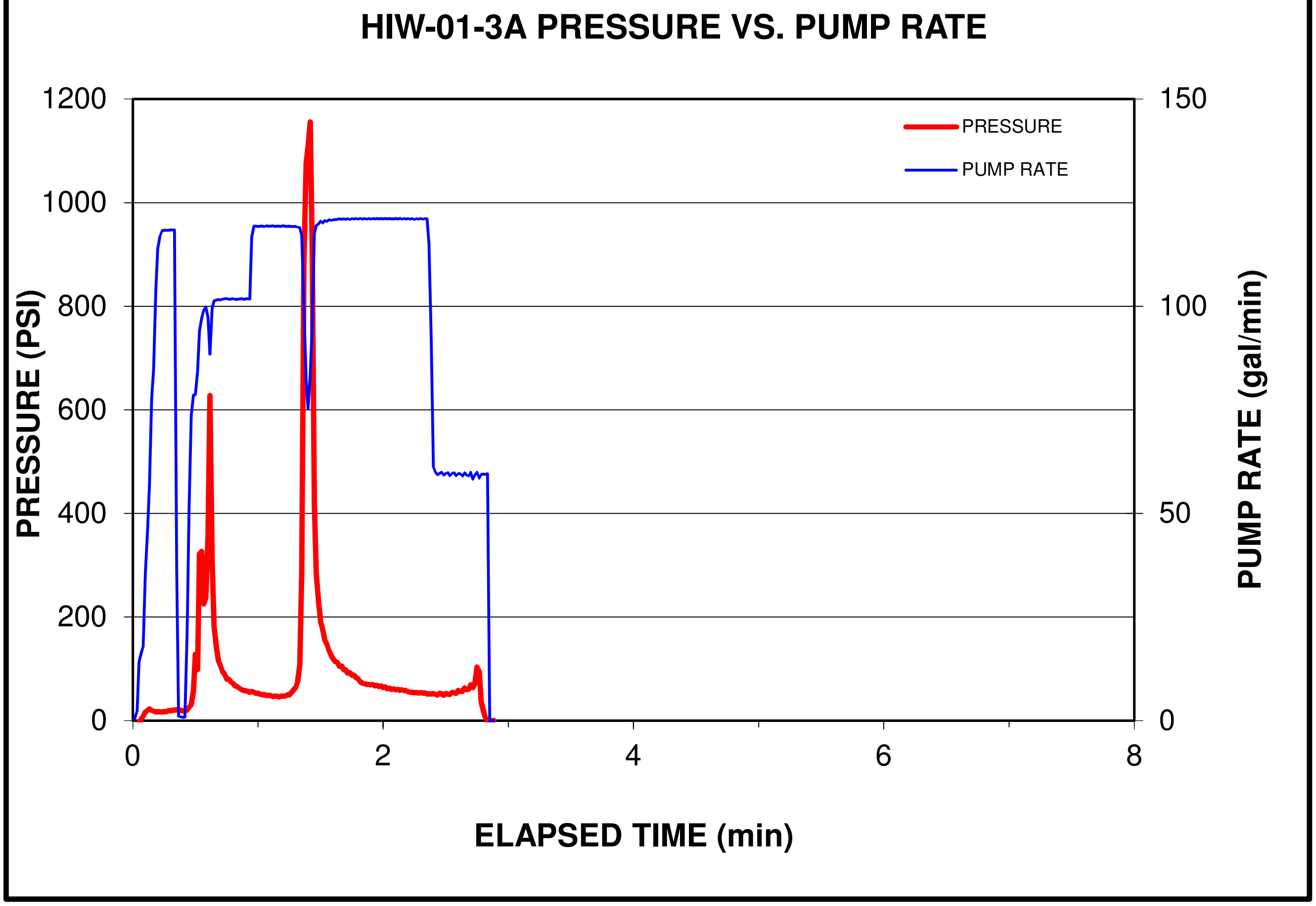
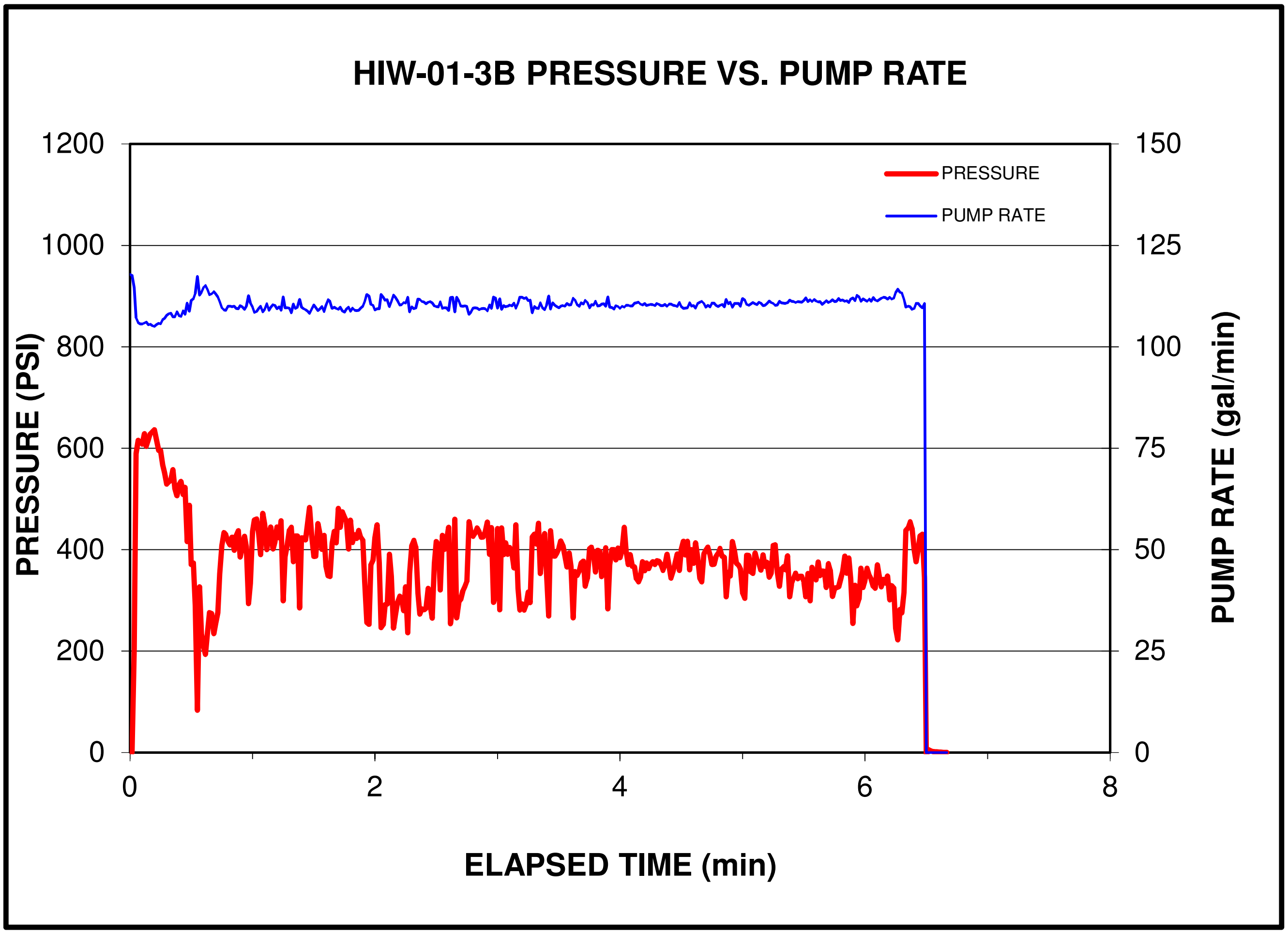
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	21 March 2016	
FRACTURE NO.:	HIW-01-3A		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	26.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	90	(gal)	PLACEMENT EFFICIENCY:	93	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	670	(lbs.)
BREAK PRESSURE:	625	(PSI)	AVERAGE PUMP RATE:	65	(gal/min)

REMARKS: Vent 5 ft South of HIW-01, approximately 7 gal

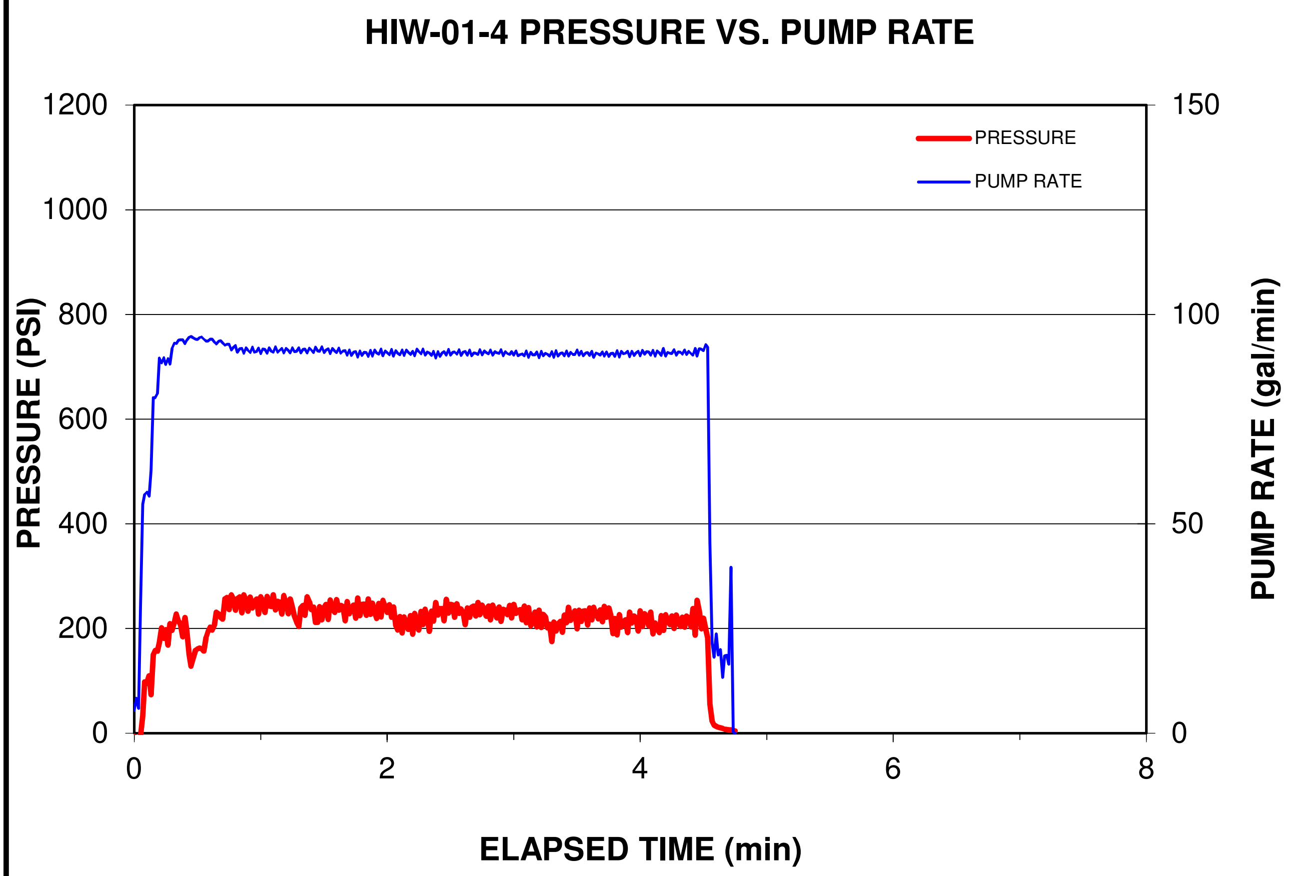
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	22 March 2016	
FRACTURE NO.:	HIW-01-3B		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	26.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	300	(gal)	PLACEMENT EFFICIENCY:	92	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	2100	(lbs.)
BREAK PRESSURE:	637	(PSI)	AVERAGE PUMP RATE:	110	(gal/min)

REMARKS: Vent 5 ft East of HIW-01, approximately 24 gal

FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	22 March 2016	
FRACTURE NO.:	HIW-01-4		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	30.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	145	(gal)	PLACEMENT EFFICIENCY:	95	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	1040	(lbs.)
BREAK PRESSURE:	228	(PSI)	AVERAGE PUMP RATE:	89	(gal/min)

REMARKS: Vent 5 ft East of HIW-01, approximately 8 gal

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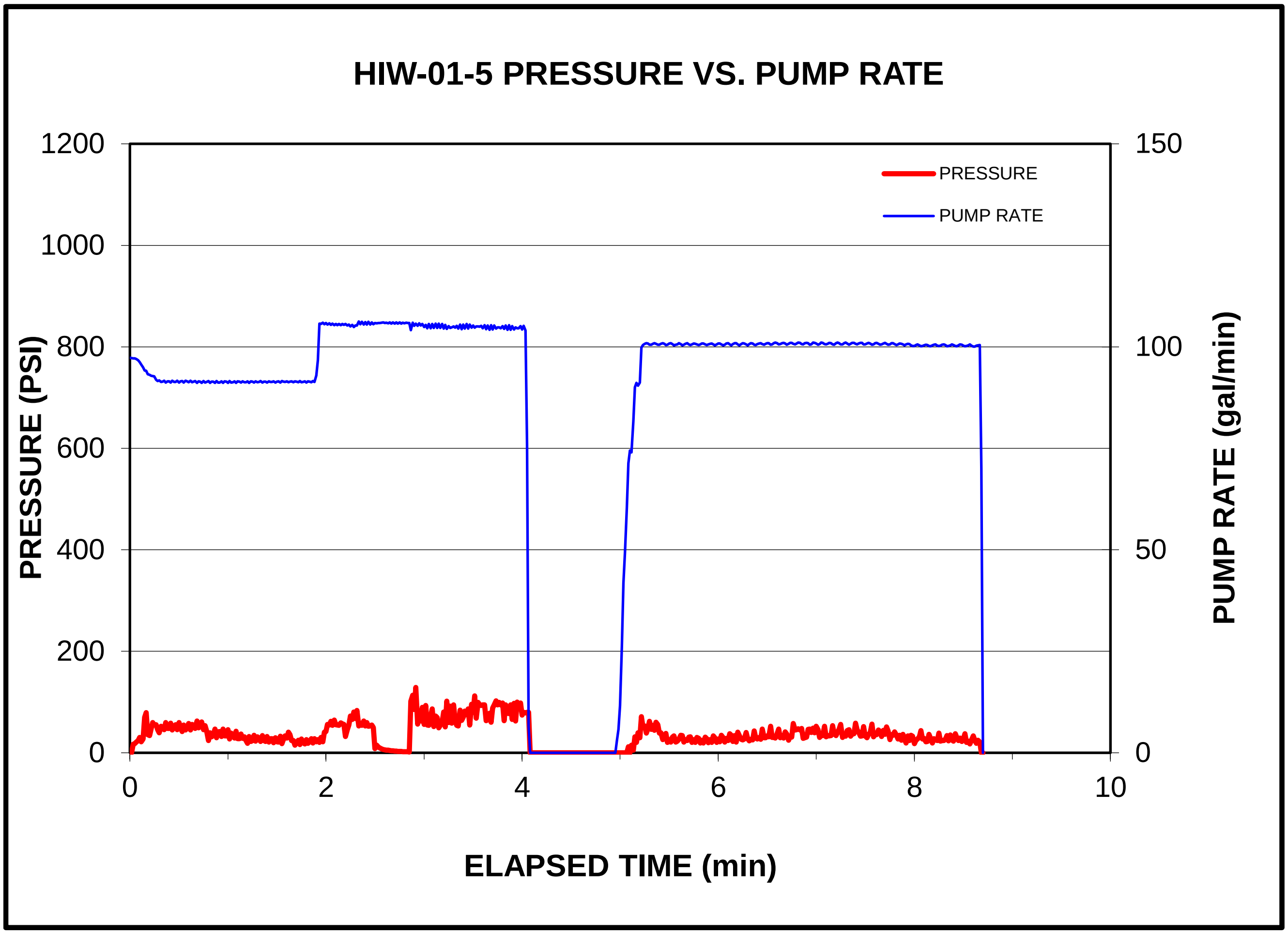
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	22 March 2016	
FRACTURE NO.:	HIW-01-5		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	32.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	50	(gal)	PLACEMENT EFFICIENCY:	89	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	345	(lbs.)
BREAK PRESSURE:	79	(PSI)	AVERAGE PUMP RATE:	96	(gal/min)

REMARKS: Vent 10 ft East of HIW-01, approximately 5 gal Low pump efficiency, pumping paused at 4 min to gel flush pump

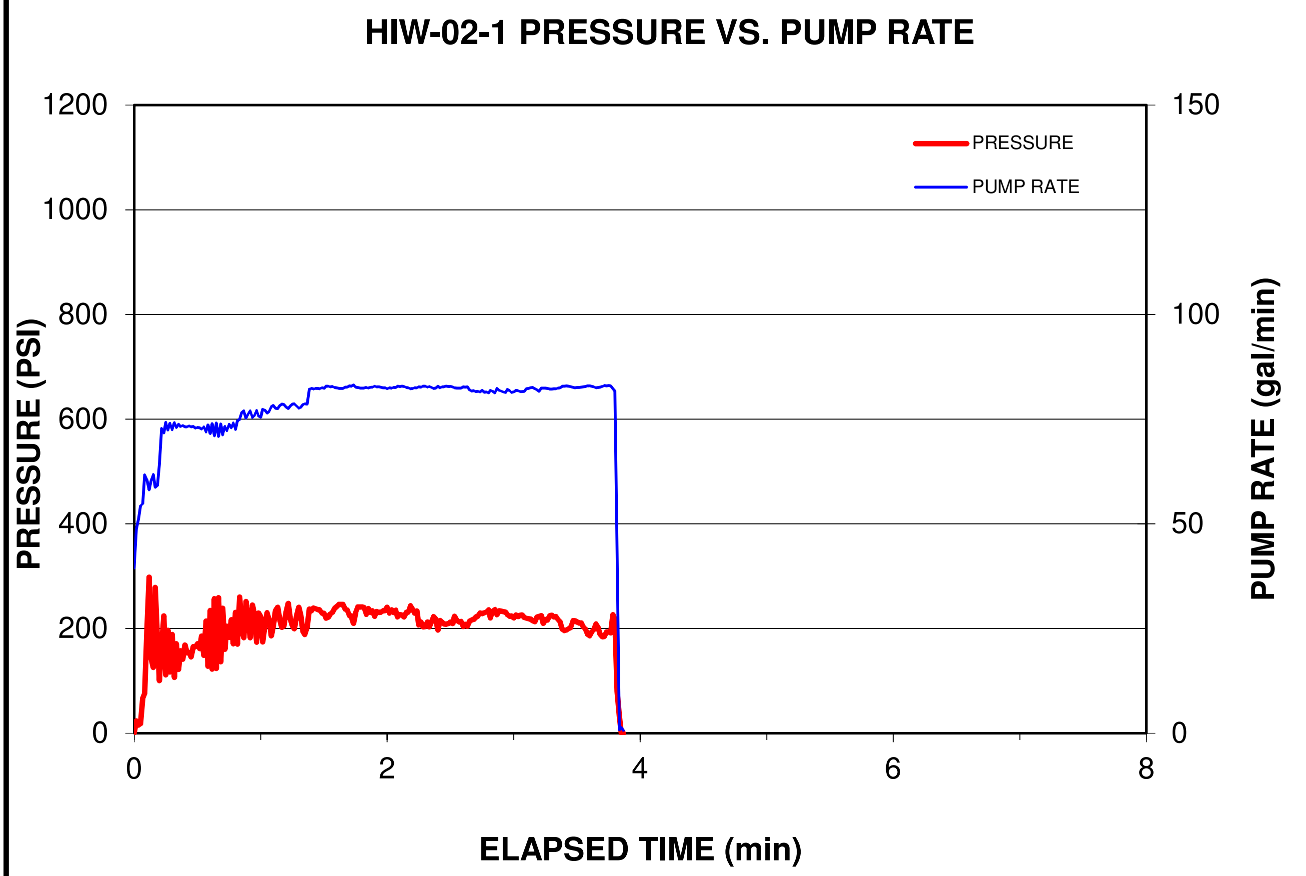
FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1604 DATE: March 23, 2016

FRACTURE BOREHOLE ID: HIW-02

FRACTURE ID:	HIW-02-1	HIW-02-2	HIW-02-3	HIW-02-4
DEPTH (ft.)	18.0	22.0	26.0	30.0
SOIL TYPE	Silty Clay	Silty Clay	Silty Clay	Silty Clay
PROPPANT TYPE	20/40 sand	20/40 sand	20/40 sand	20/40 sand
PROPPANT SLURRY VOL PUMPED (gal)	130	15	55	265
GEL PAD VOL (gal)	7	0	0	7
GEL FLUSH VOL (gal)	7	0	0	7
PROPPANT MASS PUMPED (lbs.)	475	50	190	2100
PROPPANT LOADING (lbs./gal)	7	7	7	7
VENT/LOSS (gal)	1	3	1	1
VENT/LOSS TYPE	Remote	Remote	Remote	Remote
PLACEMENT EFFICY. (%)	99.0	82.4	97.6	99.5
PROPPANT MASS EMPLACED (lbs.)	470	41	185	2090
PEAK PRESSURE (PSI)	298	358	247	408
AVG. PRESSURE (PSI)	203	33	68	303
BREAK PRESSURE (PSI)	298	358	247	408
PEAK RATE (gal/min)	83	81	76	85
AVG. RATE (gal/min)	78	15	28	76
RATE AT BREAK (gal/min)	58	57	36	30
REMARKS	Vent 3 ft North of HIW-02, approximately 1 gal	Vent 3 ft North of HIW-02, approximately 3 gal	Vent 3 ft North of HIW-02, approximately 1 gal	Vent 3 ft North of HIW-02, approximately 1 gal

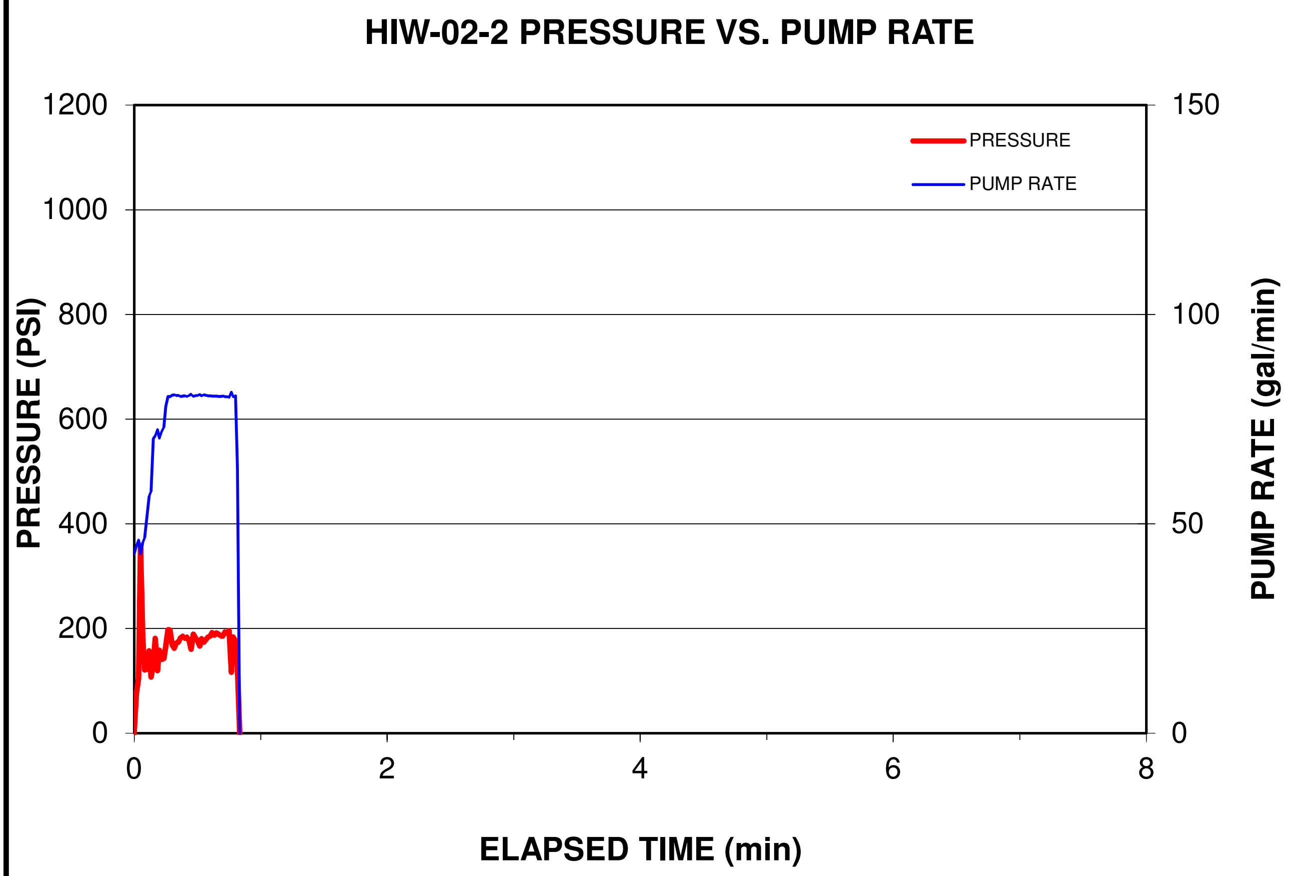
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	23 March 2016	
FRACTURE NO.:	HIW-02-1		FRACTURE BOREHOLE:	HIW-02	
FRACTURE DEPTH:	18.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	99	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	475	(lbs.)
BREAK PRESSURE:	298	(PSI)	AVERAGE PUMP RATE:	78	(gal/min)

REMARKS: Vent 3 ft North of HIW-02, approximately 1 gal

FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	23 March 2016	
FRACTURE NO.:	HIW-02-2		FRACTURE BOREHOLE:	HIW-02	
FRACTURE DEPTH:	22.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	15	(gal)	PLACEMENT EFFICIENCY:	82	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	50	(lbs.)
BREAK PRESSURE:	358	(PSI)	AVERAGE PUMP RATE:	15	(gal/min)

REMARKS: Vent 3 ft North of HIW-02, approximately 3 gal

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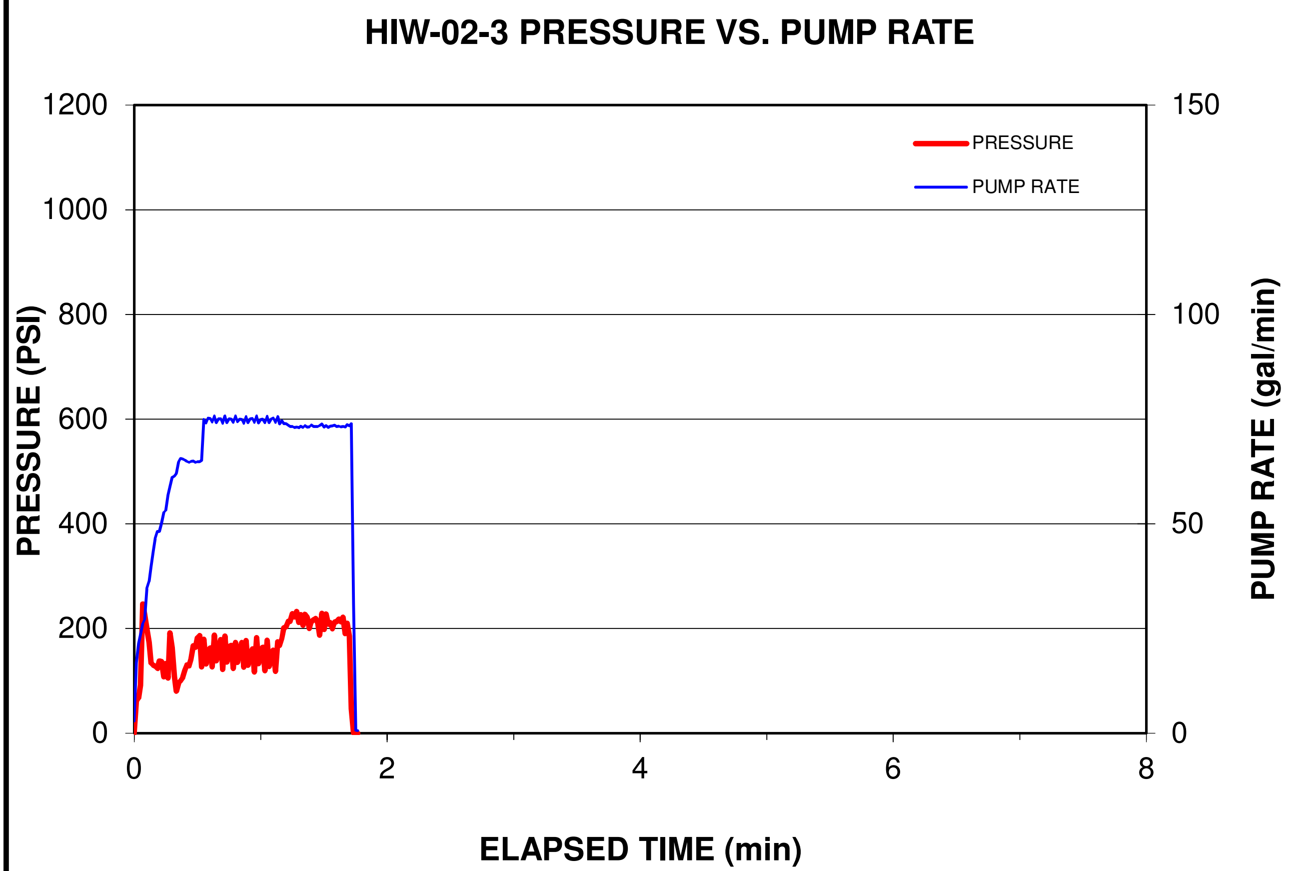
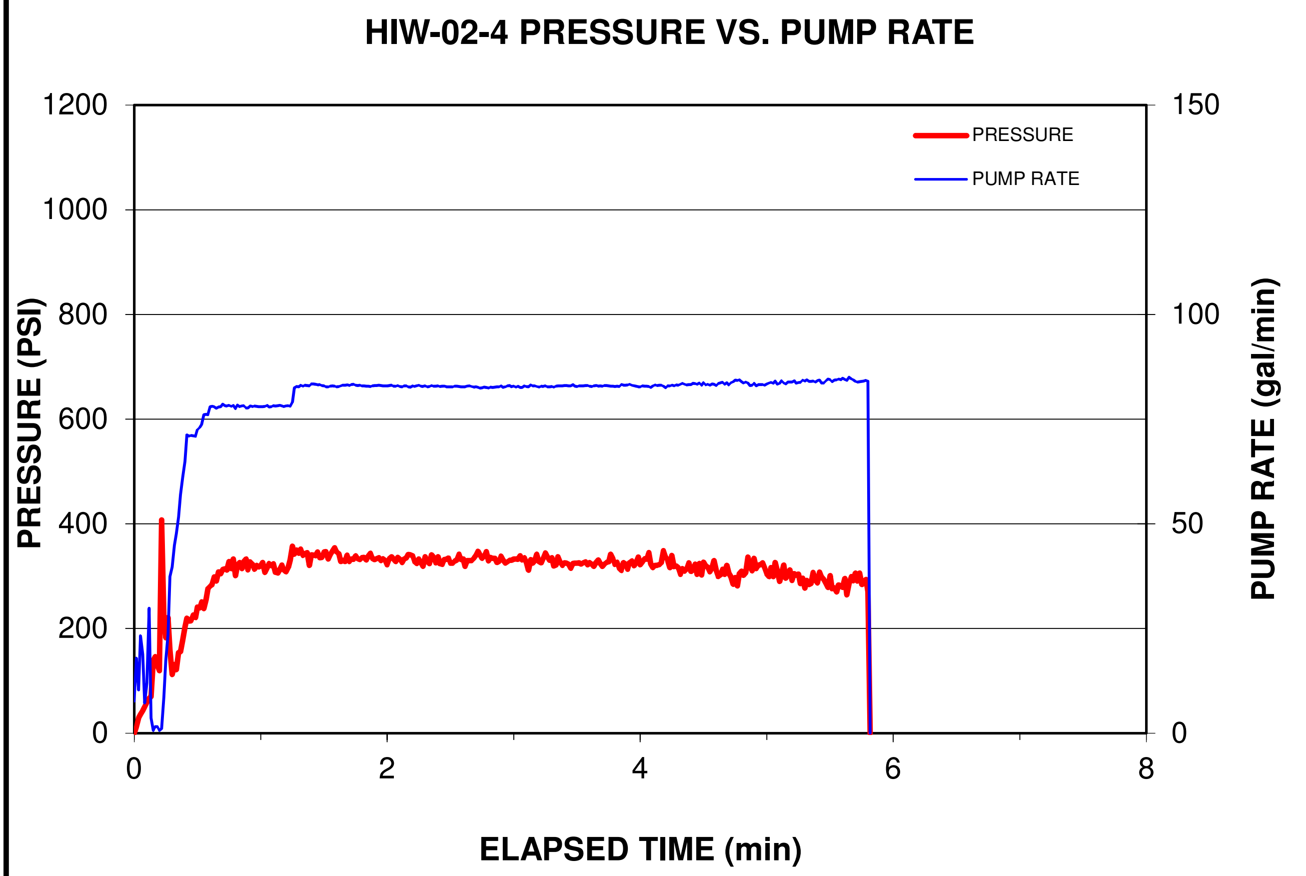
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	23 March 2016	
FRACTURE NO.:	HIW-02-3		FRACTURE BOREHOLE:	HIW-02	
FRACTURE DEPTH:	26.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	55	(gal)	PLACEMENT EFFICIENCY:	98	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	190	(lbs.)
BREAK PRESSURE:	247	(PSI)	AVERAGE PUMP RATE:	28	(gal/min)

REMARKS: Vent 3 ft North of HIW-02, approximately 1 gal

FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	23 March 2016	
FRACTURE NO.:	HIW-02-4		FRACTURE BOREHOLE:	HIW-02	
FRACTURE DEPTH:	30.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	265	(gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	2100	(lbs.)
BREAK PRESSURE:	408	(PSI)	AVERAGE PUMP RATE:	76	(gal/min)

REMARKS: Vent 3 ft North of HIW-02, approximately 1 gal

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FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1604

DATE: March 23, 2016

FRACTURE BOREHOLE ID: HIW-03

FRACTURE ID:	HIW-03-1
DEPTH (ft.)	29.5
SOIL TYPE	Silty Clay
PROPPANT TYPE	20/40 sand
PROPPANT SLURRY VOL PUMPED (gal)	265
GEL PAD VOL (gal)	20
GEL FLUSH VOL (gal)	20
PROPPANT MASS PUMPED (lbs.)	2100
PROPPANT LOADING (lbs./gal)	7
VENT/LOSS (gal)	13
VENT/LOSS TYPE	Remote
PLACEMENT EFFICY. (%)	95.0
PROPPANT MASS EMPLACED (lbs.)	1995
PEAK PRESSURE (PSI)	329
AVG. PRESSURE (PSI)	246
BREAK PRESSURE (PSI)	ND
PEAK RATE (gal/min)	96
AVG. RATE (gal/min)	91
RATE AT BREAK (gal/min)	70
REMARKS	Vent 5 ft East of HIW-03, approximately 13 gal

ND - Not Determined   NA - Not Applicable

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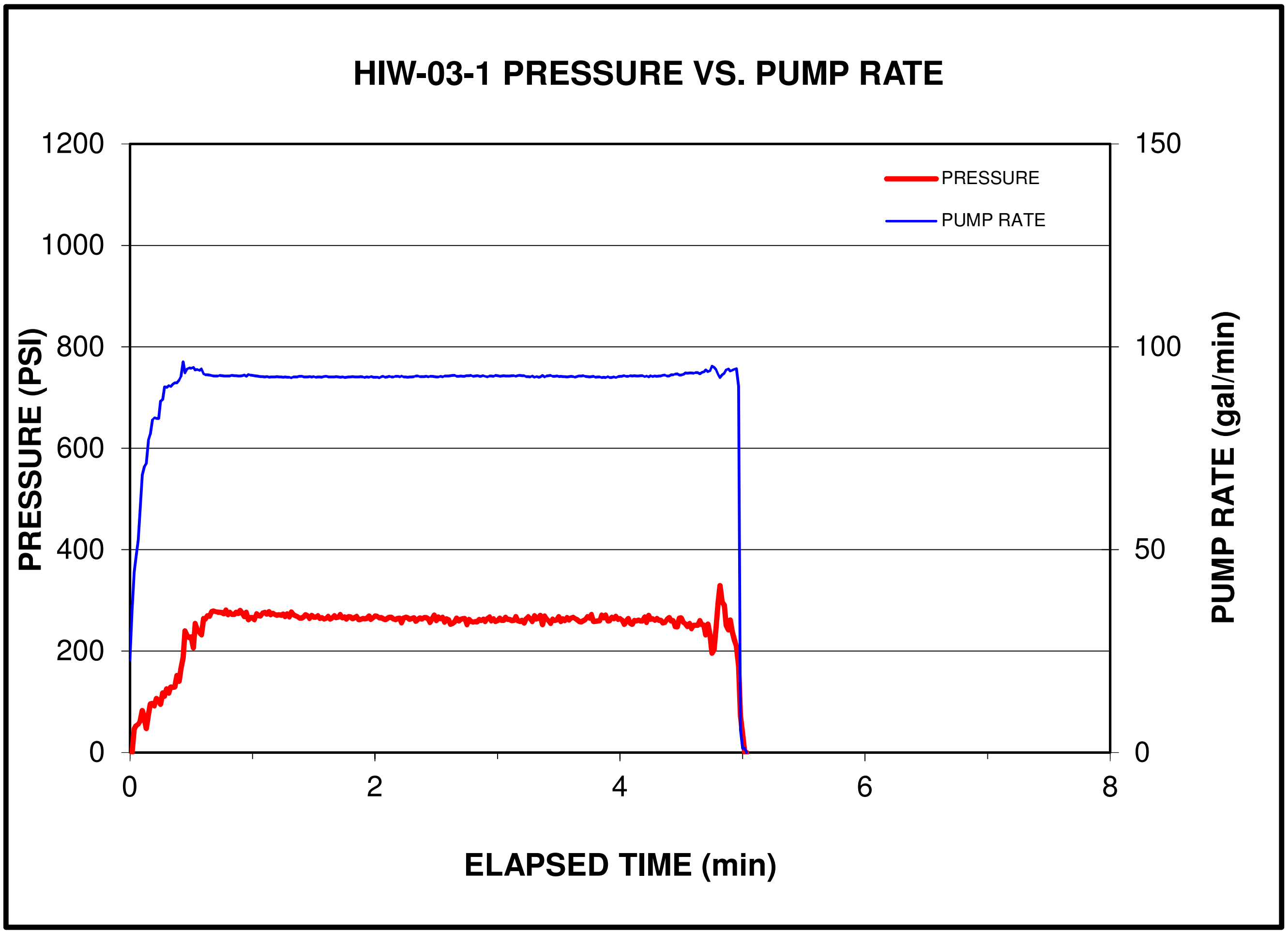
FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	23 March 2016	
FRACTURE NO.:	HIW-03-1		FRACTURE BOREHOLE:	HIW-03	
FRACTURE DEPTH:	29.5	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	265	(gal)	PLACEMENT EFFICIENCY:	95	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	2100	(lbs.)
BREAK PRESSURE:	ND	(PSI)	AVERAGE PUMP RATE:	91	(gal/min)

REMARKS: Vent 5 ft East of HIW-03, approximately 13 gal

Geo Tactical Remediation Ltd.

FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1604 DATE: March 25, 2016

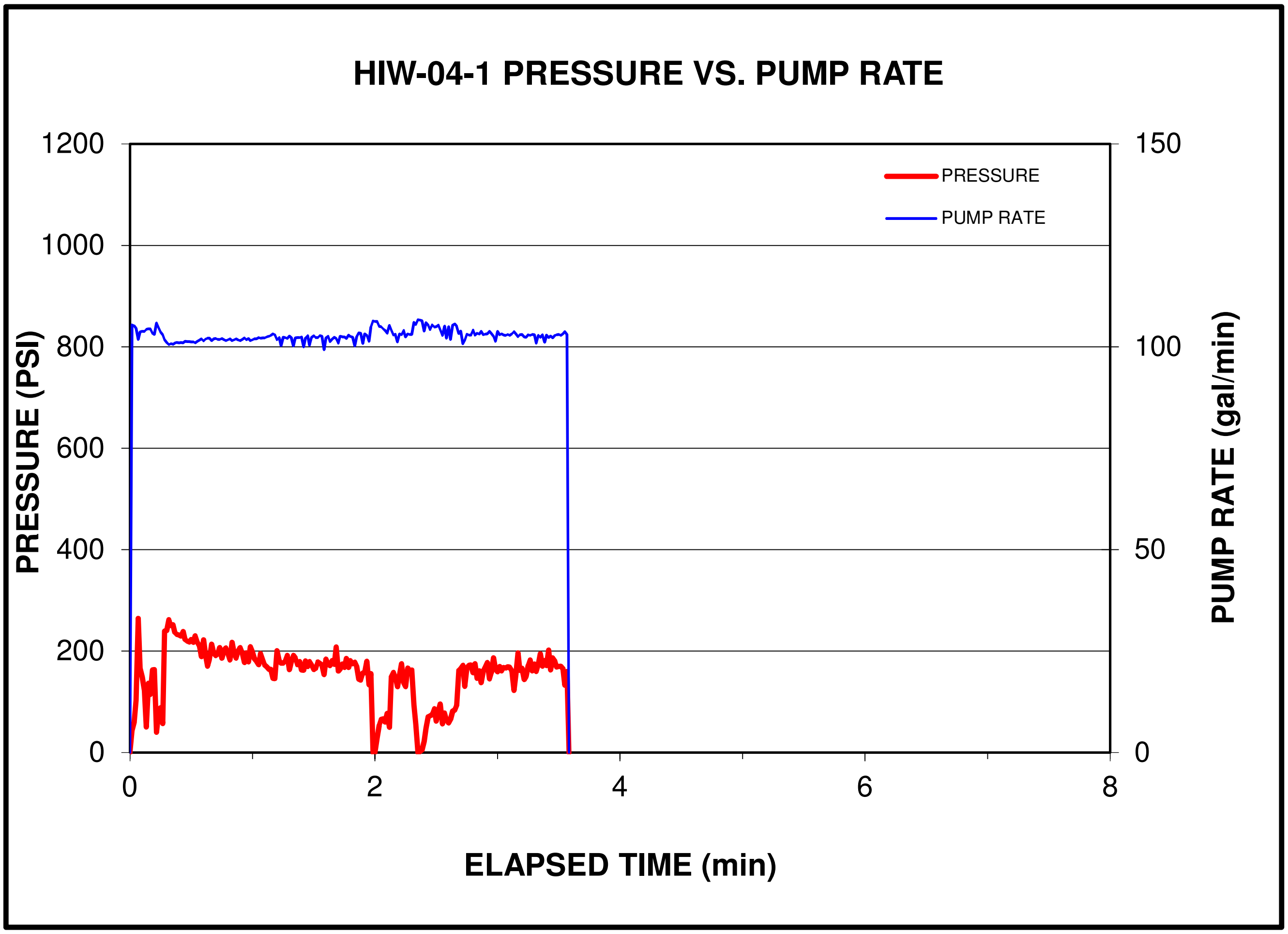
FRACTURE BOREHOLE ID: HIW-04

FRACTURE ID:	HIW-04-1
DEPTH (ft.)	25.0
SOIL TYPE	Silty Clay
PROPPANT TYPE	20/40 sand
PROPPANT SLURRY VOL PUMPED (gal)	160
GEL PAD VOL (gal)	13
GEL FLUSH VOL (gal)	7
PROPPANT MASS PUMPED (lbs.)	1255
PROPPANT LOADING (lbs./gal)	7
VENT/LOSS (gal)	1
VENT/LOSS TYPE	Remote
PLACEMENT EFFICY. (%)	99.6
PROPPANT MASS EMPLACED (lbs.)	1250
PEAK PRESSURE (PSI)	265
AVG. PRESSURE (PSI)	133
BREAK PRESSURE (PSI)	265
PEAK RATE (gal/min)	107
AVG. RATE (gal/min)	88
RATE AT BREAK (gal/min)	104
REMARKS	Vent 5 ft East of HIW-04, approximately 1 gal

ND - Not Determined NA - Not Applicable

Geo Tactical Remediation Ltd.

FRACTURE DATA



PROJECT NUMBER:	J1604		DATE:	25 March 2016	
FRACTURE NO.:	HIW-04-1		FRACTURE BOREHOLE:	HIW-04	
FRACTURE DEPTH:	25.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	160	(gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	20/40 sand		PROPPANT MASS PUMPED:	1250	(lbs.)
BREAK PRESSURE:	265	(PSI)	AVERAGE PUMP RATE:	88	(gal/min)

REMARKS: Vent 5 ft East of HIW-04, approximately 1 gal

APPENDIX II

TILTMETER GEOPHYSICAL REPORT

Tiltmeter Monitoring of

Hydraulic Fracture Injections

Lake City Army Ammunition Plant Site 17D

Lake City, Missouri

Prepared by:

Geo Tactical Remediation Ltd.

Calgary, Alberta, Canada

August 2017

SUMMARY

During the days of March 21 through March 22, 2016, six hydraulic fractures in one boring and five pneumatic fractures in a different boring were monitored with surface tiltmeters at a field site in Lake City, Missouri. The purpose of the hydraulic fractures was to emplace sand proppant into the subsurface to facilitate the remediation of contaminated soils. The purpose of the pneumatic fractures was to emplace LactOil™ solution to remediate the contaminated subsoils.

The hydraulic fractures were initiated at depths ranging from 18.0 to 32.0 ft below ground surface. The pneumatic fractures were initiated at depths ranging from 20.0 to 35.0 ft below ground surface. All fractures were monitored using Geo Tactical's proprietary tiltmeter mapping system. The recorded data quality was generally very good to excellent with high signal to noise ratios.

Analysis of the tiltmeter data indicated that the hydraulic fractures were moderately to strongly ascending, with inclination angles from horizontal ranging from 21 to 49°. The pneumatic fractures were moderately to strongly ascending, with one fracture near horizontal. The angle of inclination from horizontal for the pneumatic fractures ranged from 9 to 55°.

Data analysis of the hydraulic fractures indicated limited fluid leakoff during the fracturing process with nearly all of the injected fluid remaining in the propped fractures. The pneumatic fractures indicated high leakoff during the fracturing process.

Results of the tiltmeter analyses are summarized in Table 1.

UNITS, DEFINITIONS, AND SIGN CONVENTION FOR FRACTURE DESCRIPTION

Except where explicitly stated otherwise, the following units are used in this report:

Length – feet
Volume – cubic feet
Pressure – psi
Fracture angle – degrees
Tilt angle – microradians
RMS error – nanoradians
Normalized vector error – dimensionless

One microradian is the angle subtended by an arc of length 1 mm at a radius of 1 km.

RMS error is the root mean squared difference between observed and theoretical tilt vectors on completion of a non-robust chi-square optimization.

Normalized vector error is a normalized measure of the difference between the observed and theoretical tilt vectors. This error is normalized for comparison between analyses of different fracture models. A value less than 0.4 is considered a good fit of modeled to observed tilt, a value less than 0.3 is considered very good, and a value less than 0.2 is considered an excellent fit.

Each fracture is described by one or more rectangular dislocations with location and geometry specified as follow:

- The location in space is defined by the (x,y,z) coordinates of the mid-point of the rectangular fracture, where x and y are the magnetic eastings and northings with respect to the injection well, and z is the depth below ground surface.
- Fracture orientation is defined by azimuth and dip using the right hand rule, where azimuth is the direction of strike clockwise from magnetic north, and dip is the angle from horizontal at a right angle from the azimuth. For example, a fracture with an azimuth of 45° and a dip of 45° strikes northeast-southwest and dips to the southeast; a fracture with an azimuth of 225° and a dip of 45° strikes southwest-northeast and dips to the northwest.

Fracture geometry is specified by length along azimuth, height along the direction of dip, and width between the fracture faces.

SUMMARY OF THE TILTMETER MAPPING SYSTEM

Many subsurface processes result in small but measurable movements at the Earth's surface. The shape of these surface deformations will depend on the processes which caused them. Geo Tactical's tiltmeter mapping system measures these surface deformations, and a model is created of subsurface processes which caused the deformation.

Various man made processes can result in measurable deformations at the Earth's surface. Long term processes such as production of oil and gas, or production of water from an aquifer, can result in subsidence of several feet over a period of years. Shorter term processes such as injection or production tests, or hydraulic fracturing produce correspondingly smaller deformations, but with suitably sensitive instrumentations these can be measured and analyzed.

The surface of the Earth is also continuously deforming due to natural processes. These include the tidal effects of the Sun and Moon, and thermal effects as the ground heats up during the day and cools down at night. While these effects are very small, they may be on a similar scale to the effects of the processes being monitored. However, the effects of these natural processes can be predicted and removed from data.

The process of hydraulic fracturing creates a dislocation in the subsurface with a characteristic deformation. A horizontal fracture (dip=0°) causes an uplift or dome at the surface. A vertical fracture (dip=90°) causes subsidence at the surface oriented along the azimuth of the fracture with a slight uplift outside the subsidence.

If a point on the Earth's surface is uplifted relative to another point, there will be a change in slope of the surface between the two points. The tiltmeter system continuously records changes in slope, or tilt. The change in tilt at a particular tiltmeter location is measured in two orthogonal directions, and the vector sum of these two measurements yields the magnitude and direction of the change in tilt at that location. The surface deformation due to a subsurface process may then be characterized by measuring the change in tilt an array of tiltmeter locations around an area of interest.

Numerical models and optimization schemes are then used to determine a best fit between observed and theoretical deformations.

DATA ACQUISITION

Tiltmeter data was collected to monitor six hydraulic fractures in one boring and five pneumatic fractures at a different boring at the site on March 21 through March 23, 2016. An array of model 700 tiltmeters was deployed to monitor the fracture treatments. Tilt data was collected at a 3 and 10 second sample interval during the fracture injections.

DATA QUALITY

Data quality was generally very good to excellent with high signal to noise ratios for each fracture.

DATA ANALYSIS

All eleven fractures were modeled as single planar structures. The results were optimized on the parameters for azimuth, dip, length, height, width, depth and offset from the borehole. The fit of the theoretical to observed tilt from the planar fracture models was excellent for all six hydraulic fracture analyses. Of the five pneumatic fractures, one had excellent fit and the other four had fits classified as very good. Figure 1 shows the overall statistical distribution of the fit of theoretical to observed tilt.

DISCUSSION

Results of the tiltmeter analyses of both the hydraulic and pneumatic fractures are summarized in Table 1. Maps of the modeled fractures with real and theoretical tilt vectors for the fractures are shown in Appendix A. Analysis of the fracture parameters was based primarily on the tilt data with limited information of the local geologic structure and stratigraphy.

Analyses of the tiltmeter data indicated planar fractures dipping from sub-horizontal to 55 degrees from horizontal. The overall statistical distribution of the fracture dip values for both the hydraulic and pneumatic fractures is shown in Figure 2.

The analyses of the hydraulic fractures indicated that three of the fractures (HIW-01-3B, HIW-01-4, and HIW-01-5) appear to have migrated uphole from the initiation depth.

Data analyses of the hydraulic fracture tiltmeter data indicated limited fluid leakoff during the hydraulic fracture operations and higher leakoff during pneumatic fracturing. Fracture efficiency for the individual fracture analyses are shown on the plots in Appendix A.

TABLE 1
Tiltmeter Results Summary

Fracture I.D.	Date	Azimuth (deg)	Dip (deg)	Width (ft)	Length (ft)	Height (ft)	Z (ft)	Vector Error	RMS Error (nRad)	Modeled Frac Volume (ft^3)	X (ft)	Y (ft)
HIW-01-1	21-Mar	306	46	0.028	12.0	30.0	18.0	0.063	7.67E+04	10.1	-3.7	-5.0
HIW-01-2	21-Mar	298	44	0.015	8.0	22.0	21.0	0.052	1.31E+04	2.6	-3.4	-5.9
HIW-01-3	21-Mar	193	49	0.003	12.0	25.0	26.0	0.197	3.60E+05	0.8	3.6	-7.2
HIW-01-3b	22-Mar	306	45	0.060	19.0	33.0	16.3	0.073	2.83E+05	37.6	-0.6	-7.9
HIW-01-4	22-Mar	327	21	0.055	12.2	25.0	12.6	0.049	1.50E+05	16.8	-1.3	-7.5
HIW-01-5	22-Mar	48	27	0.019	12.0	26.0	6.0	0.102	8.42E+04	5.9	-3.1	-3.0
PIW-03-1	23-Mar	335	9	0.010	14.0	35.0	30.0	0.260	2.60E+04	4.9	2.4	0.1
PIW-03-2	23-Mar	305	42	0.008	15.0	46.9	29.0	0.232	2.53E+04	5.6	5.4	0.9
PIW-03-3	23-Mar	256	35	0.010	15.0	26.1	26.0	0.127	1.80E+04	3.9	3.6	-5.5
PIW-03-4	23-Mar	282	49	0.012	12.7	27.8	23.0	0.214	2.80E+04	4.2	1.6	-5.5
PIW-03-5	23-Mar	38	55	0.002	23.3	28.4	20.0	0.232	1.01E+04	1.3	-2.4	5.5

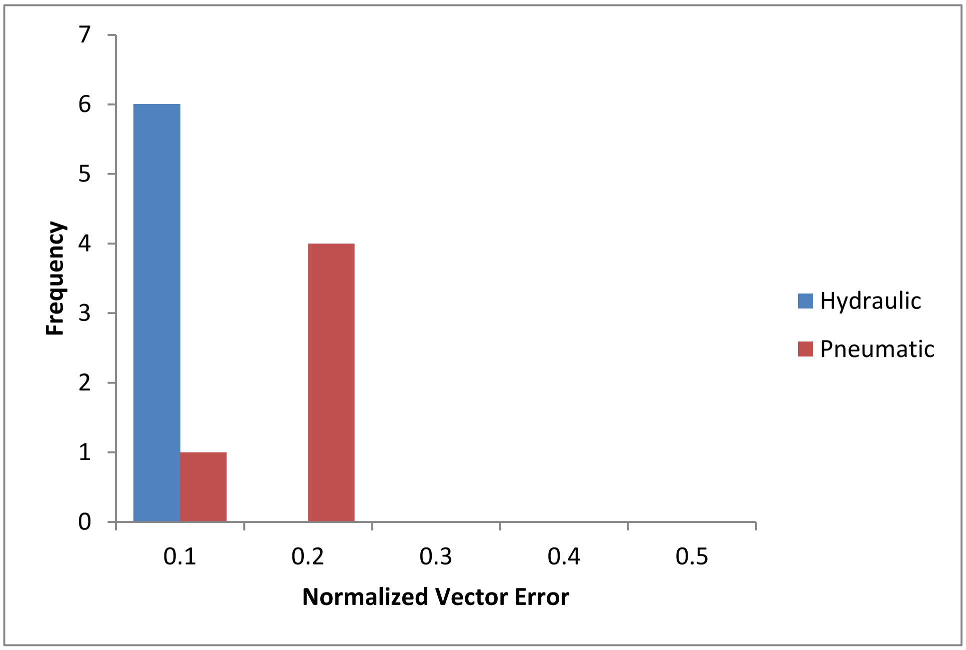


Figure 1 – Statistical Distribution of Normalized Vector Error

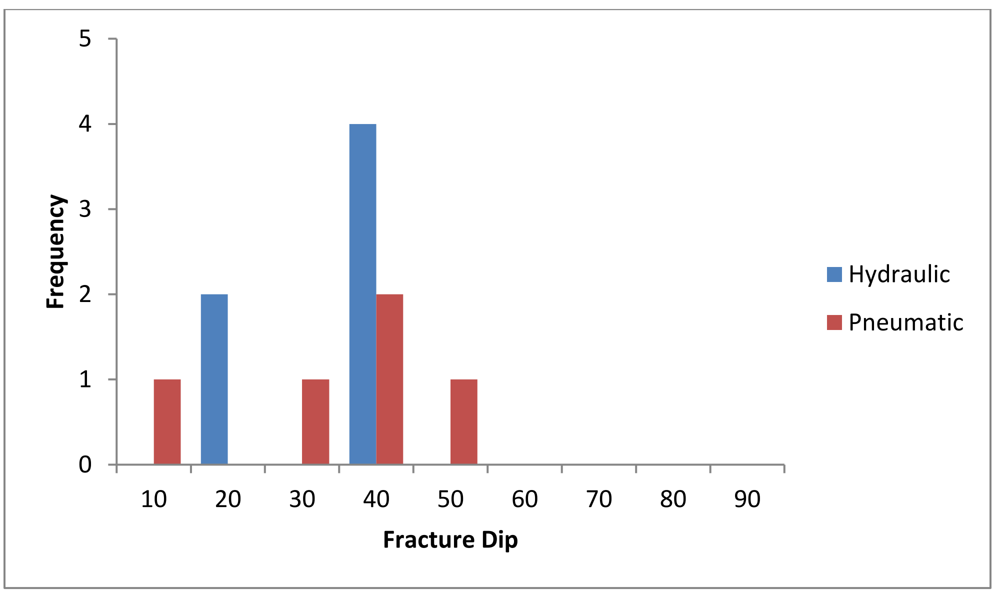
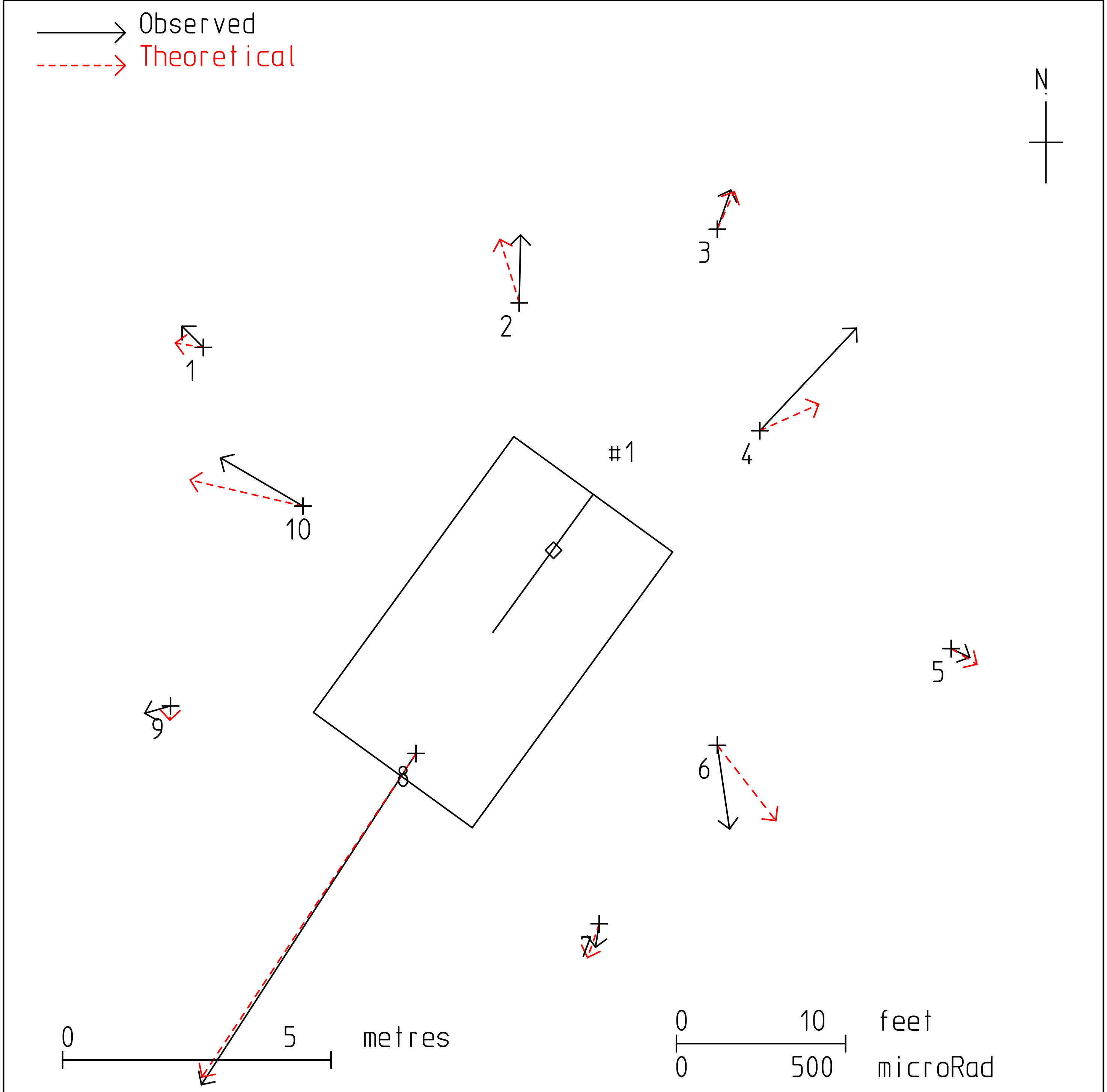


Figure 2 – Statistical Distribution of Fracture Dip

APPENDIX A

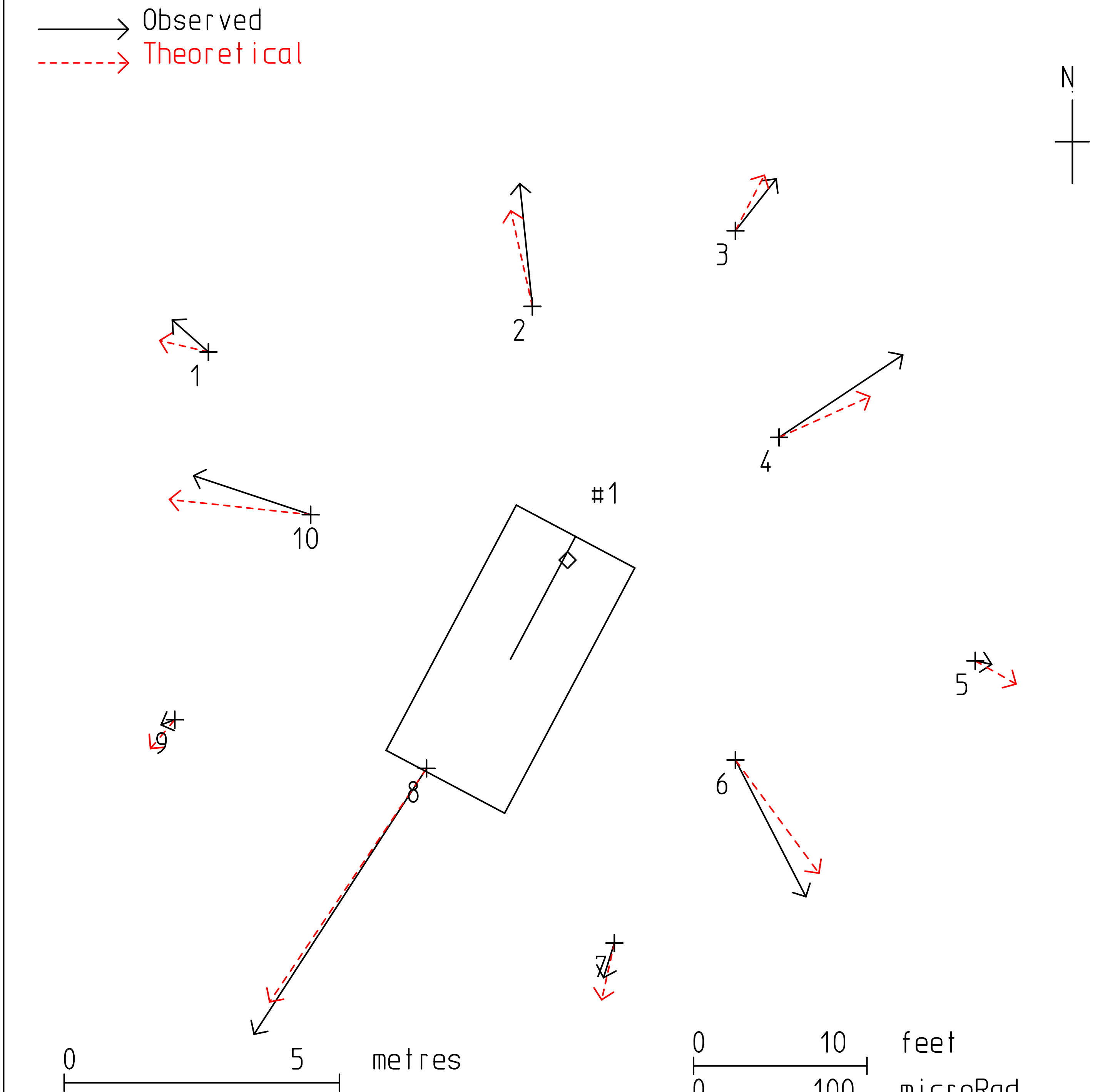


WELL: HIW-01 Frac 1
DATE: 3/21/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	306	46	18	4.14	2	43%

Length = 12 ft, Height = 30 ft, Width = 0.028 ft
Normalized Vector Error = 0.063, RMS Error = 7.67E04

GeoTactical 2016

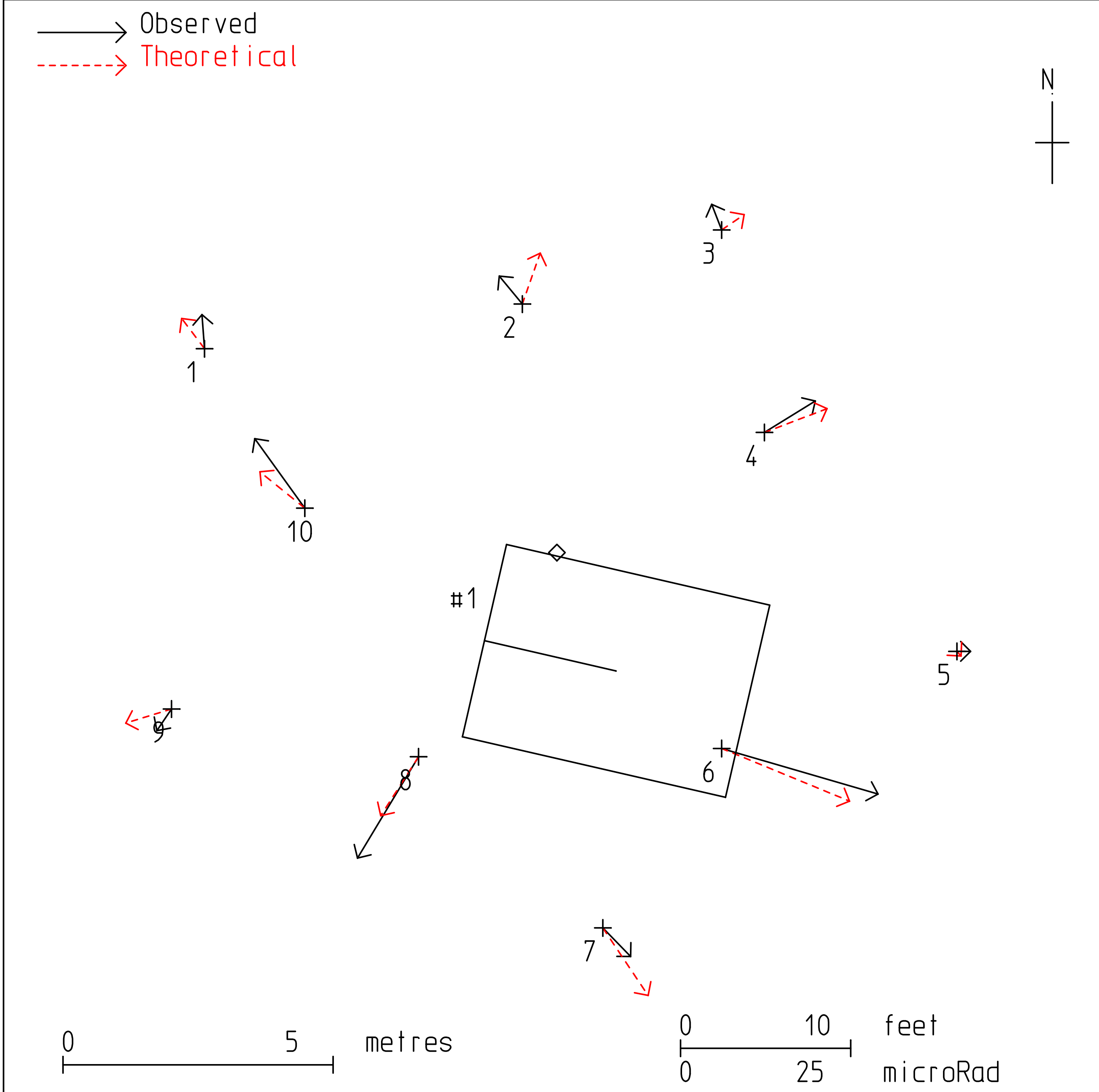


WELL: HIW-01 Frac 2
DATE: 3/21/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	298	44	21	0.5	0	98%

Length = 8 ft, Height = 12 ft, Width = 0.015 ft
Normalized Vector Error = 0.052, RMS Error = 1.31E04

GeoTactical 2016

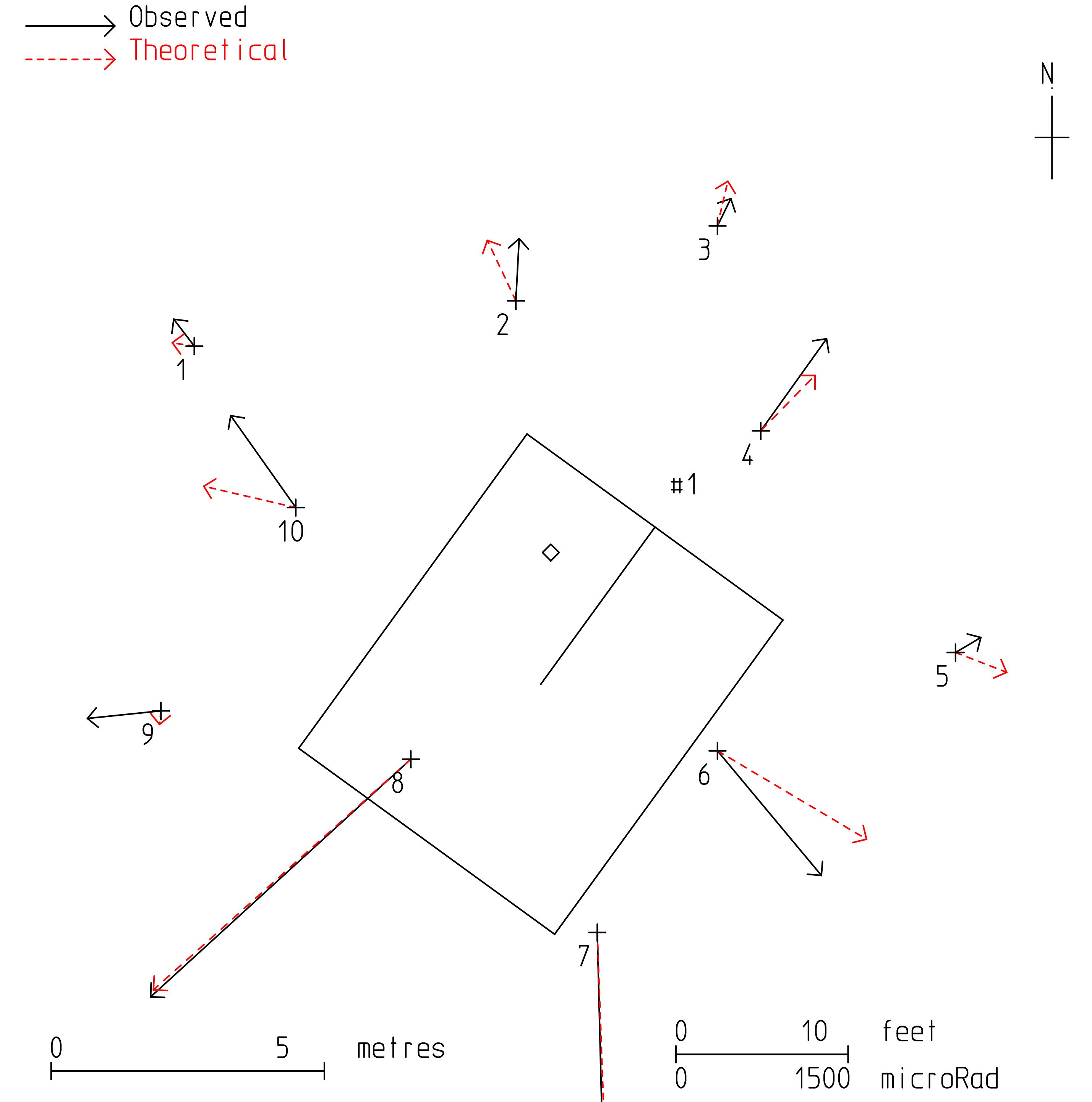


WELL: HIW-01 Frac 3
DATE: 3/21/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	193	49	26	2.52	0	5%

Length = 12 ft, Height = 25 ft, Width = 0.0025 ft
Normalized Vector Error = 0.197, RMS Error = 3.60E05

GeoTactical 2016

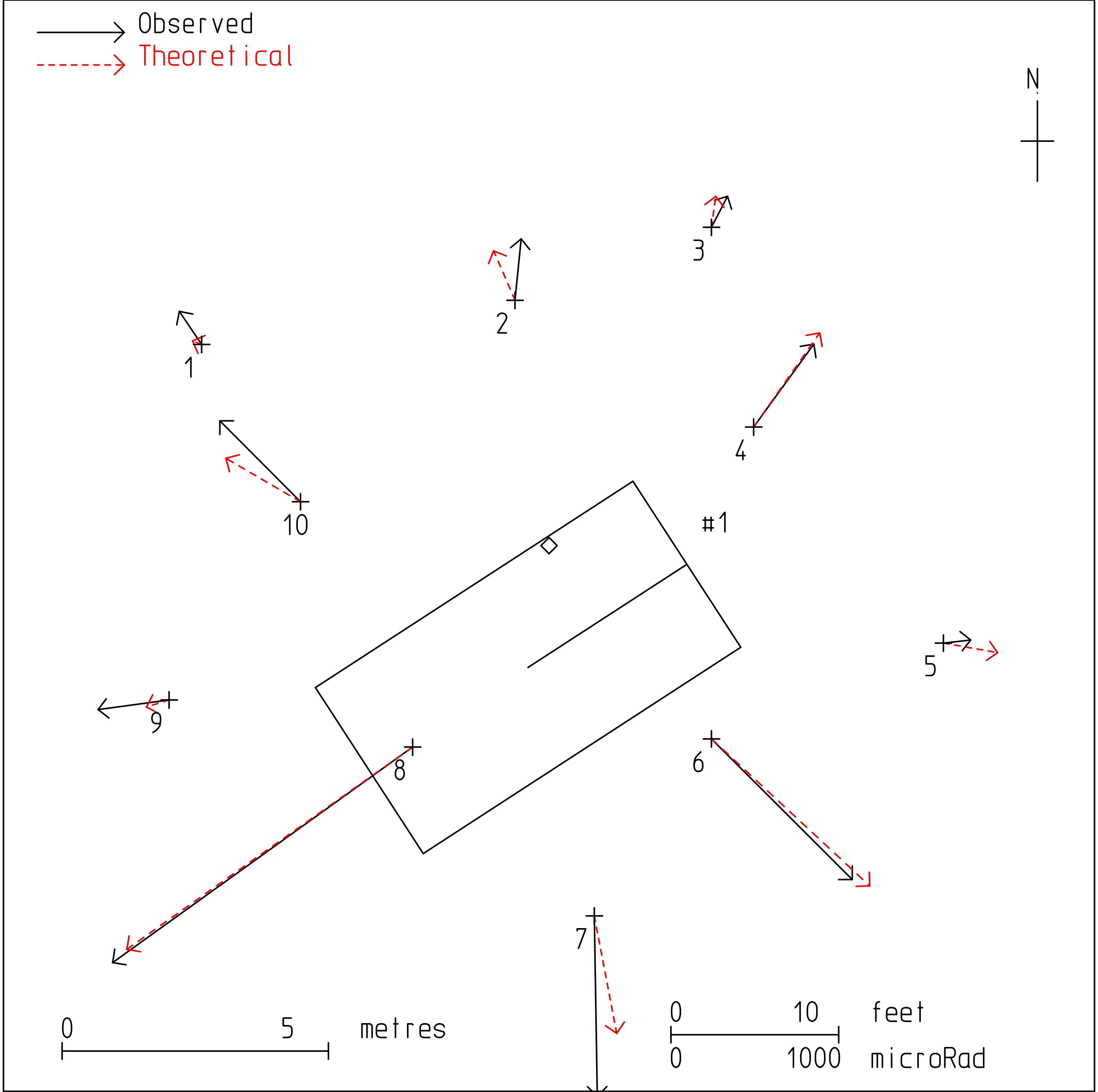


WELL: HIW-01 Frac 3b
DATE: 3/22/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	306	45	16.3	6.9	7	97%

Length = 19 ft, Height = 33 ft, Width = 0.06 ft
Normalized Vector Error = 0.073 RMS Error = 2.83E05

ESI 1996

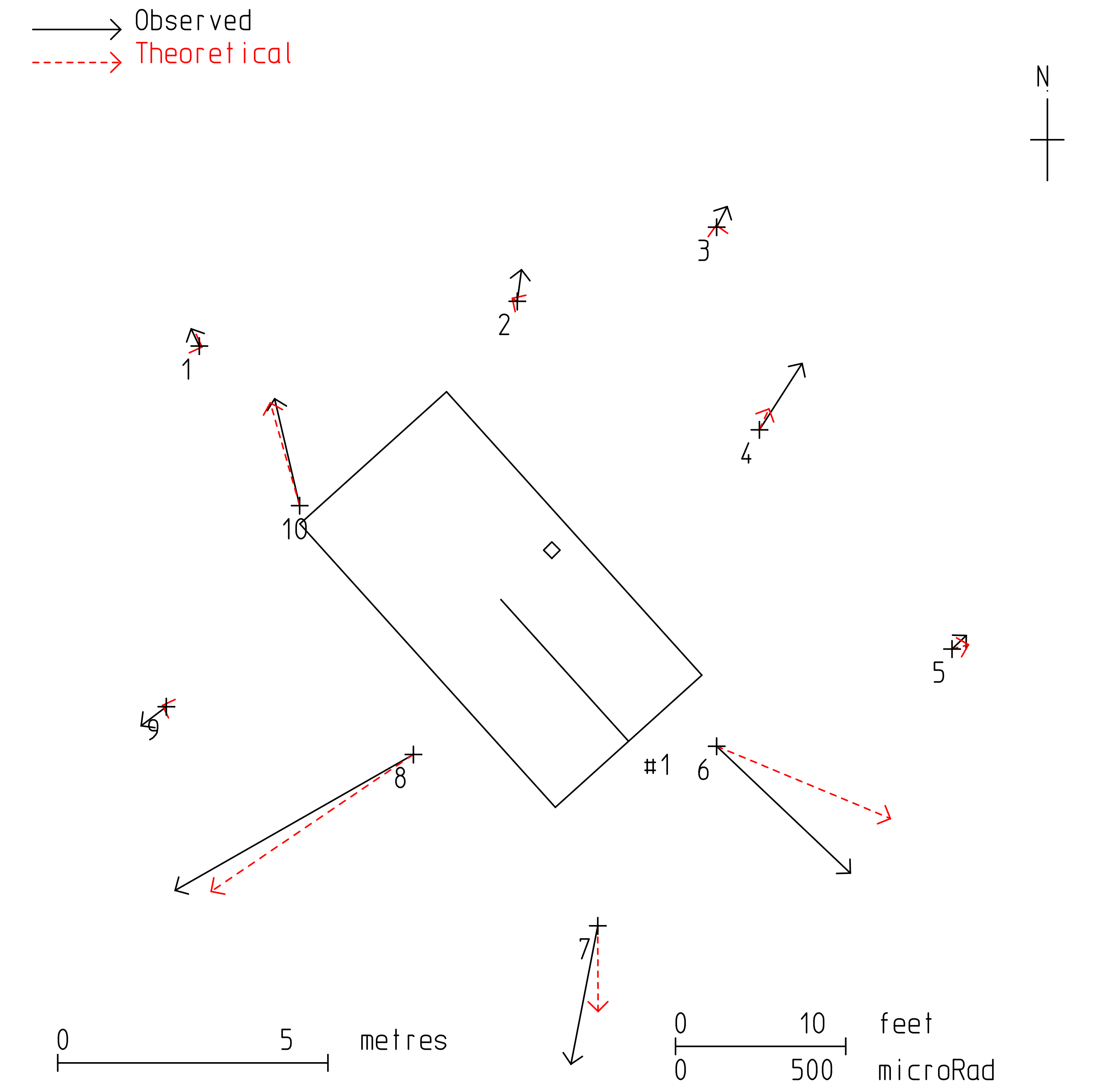


WELL: HIW-01 Frac 4
DATE: 3/22/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	327	21	12.6	3.43	3	87%

Length = 12.2 ft, Height = 25 ft, Width = 0.055 ft
Normalized Vector Error = 0.049, RMS Error = 1.50E05

GeoTactical 2016

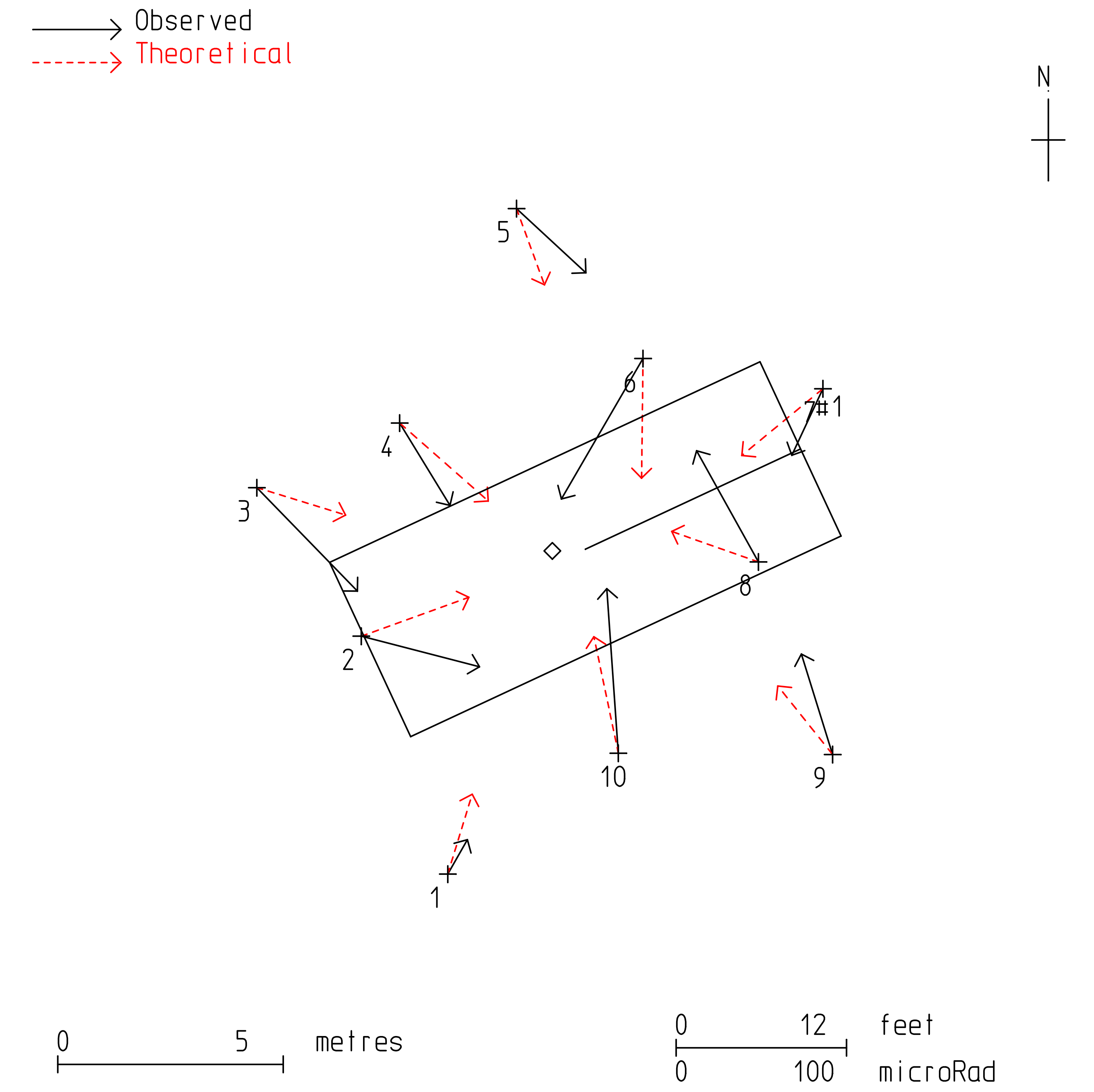


WELL: HIW-01 Frac 5
DATE: 3/22/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	48	27	6	1.14	1	93%

Length = 12 ft, Height = 26 ft, Width = 0.019 ft
Normalized Vector Error = 0.102, RMS Error = 8.42E04

GeoTactical 2016

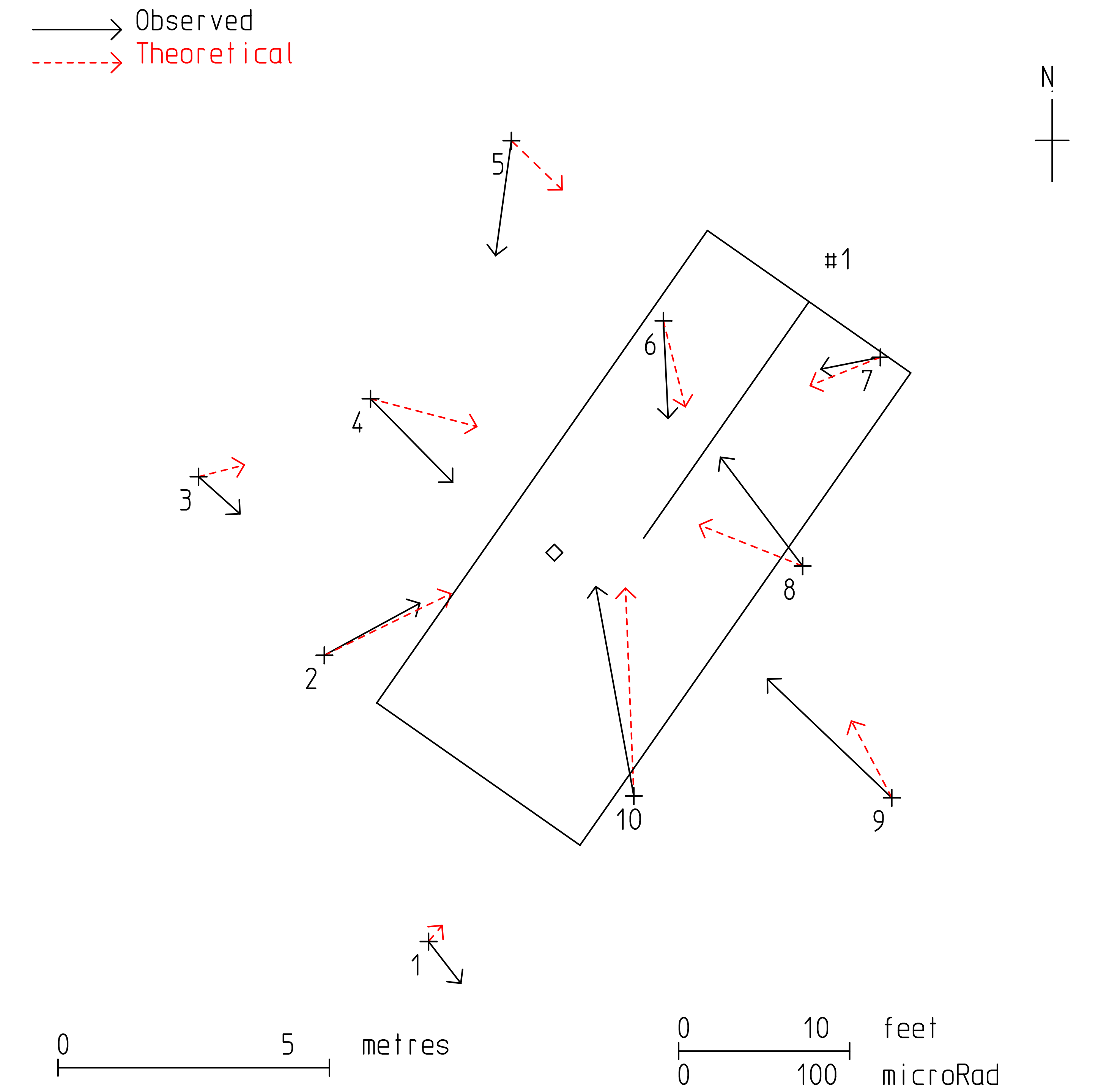


WELL: PIW-03 Injection 1 Shut-in
DATE: 3/23/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	335	9	30	4.76	1	18%

Length = 14 ft, Height = 35 ft, Width = 0.01 ft
Normalized Vector Error = 0.260 RMS Error = 2.60E04

GeoTactical 2016

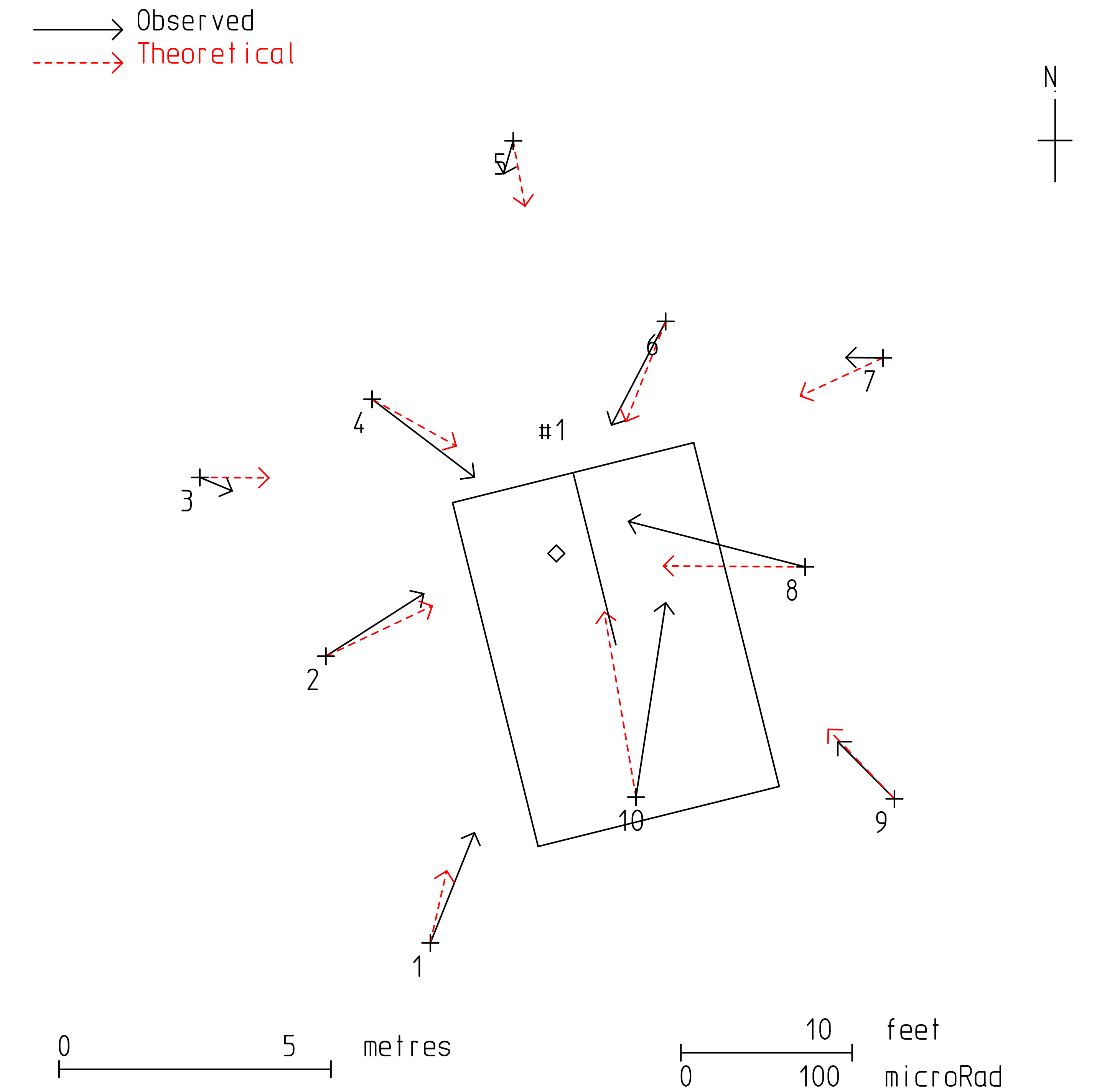


WELL: PIW-03 Injection 2 Shut-in
DATE: 3/23/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	305	42	29	4.76	1	21%

Length = 15 ft, Height = 46.9 ft, Width = 0.0079 ft
Normalized Vector Error = 0.232, RMS Error = 2.53E04

GeoTactical 2016

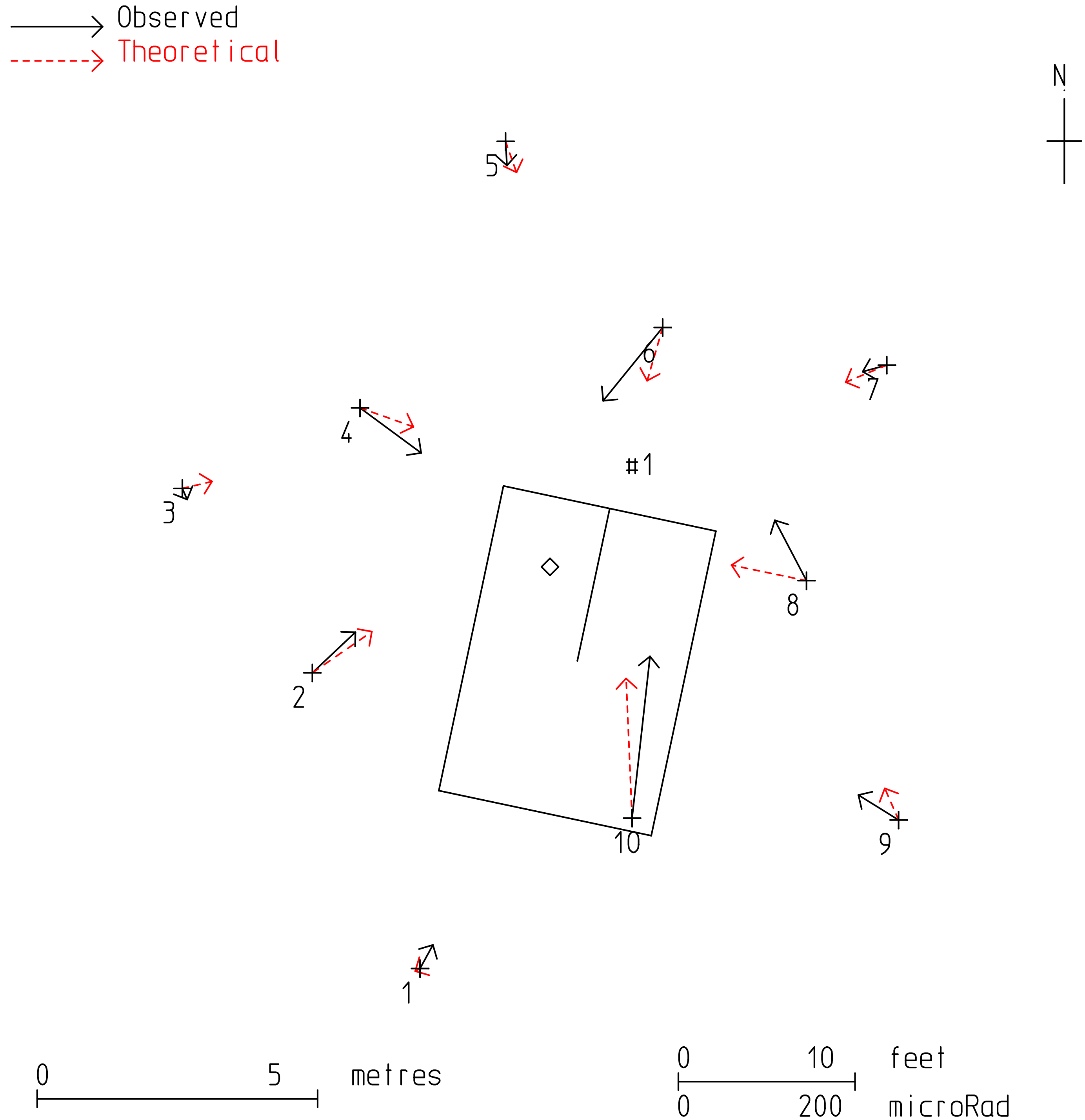


WELL: PIW-03 Injection 3 Shut-in
DATE: 3/23/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	256	35	26	4.76	1	15%

Length = 15 ft, Height = 26.1 ft, Width = 0.01 ft
Normalized Vector Error = 0.127, RMS Error = 1.80E04

GeoTactical 2016;
PU;PA6409,4876;LB0

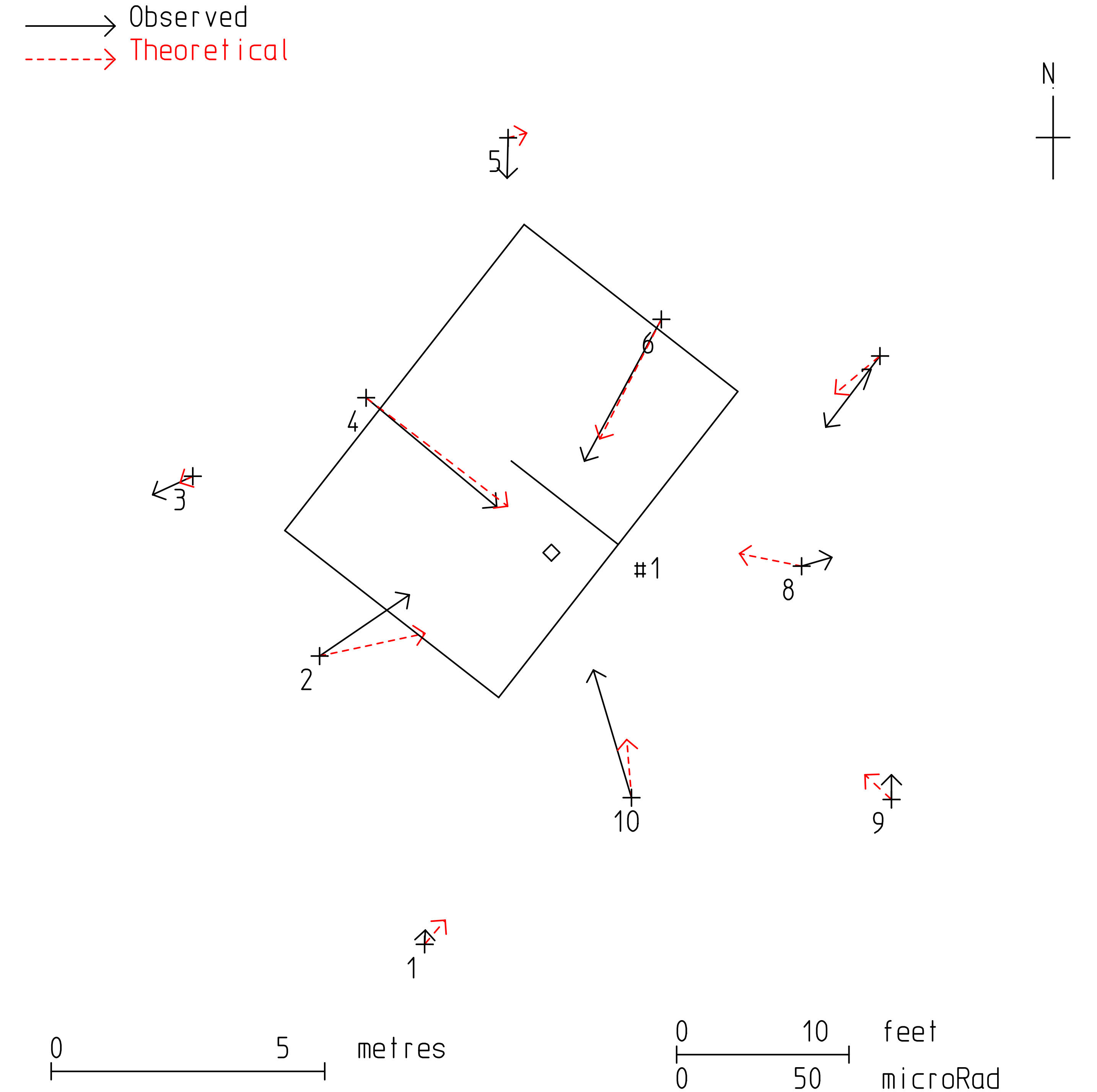


WELL: PIW-03 Injection 4 Shut-in
DATE: 3/23/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	282	49	23	4.76	1	16%

Length = 12.7 ft, Height = 27.8 ft, Width = 0.012 ft
Normalized Vector Error = 0.214, RMS Error = 2.80E04

GeoTactical 2016



WELL: PIW-03 Injection 5 Shut-in
DATE: 3/23/16

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	38	55	20	4.76	0	5%

Length = 23.3 ft, Height = 28.4 ft, Width = 0.002 ft
Normalized Vector Error = 0.232, RMS Error = 1.01E04

GeoTactical 2016

APPENDIX III

SUBSURFACE DISTRIBUTION OF SAND FRACTURES AND LACTOIL® FRACTURES

Hydraulic Fracture Borehole HIW-01

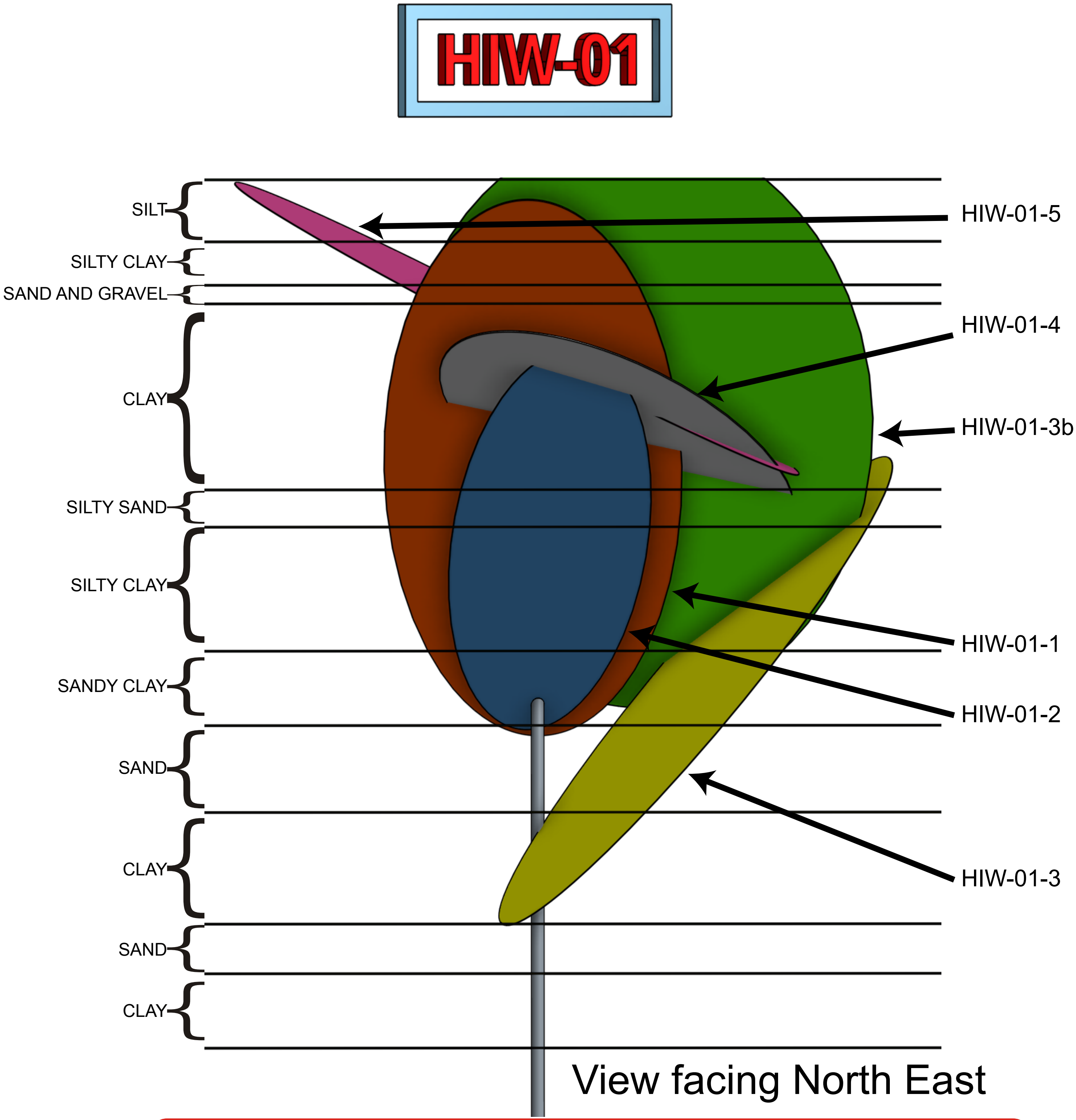
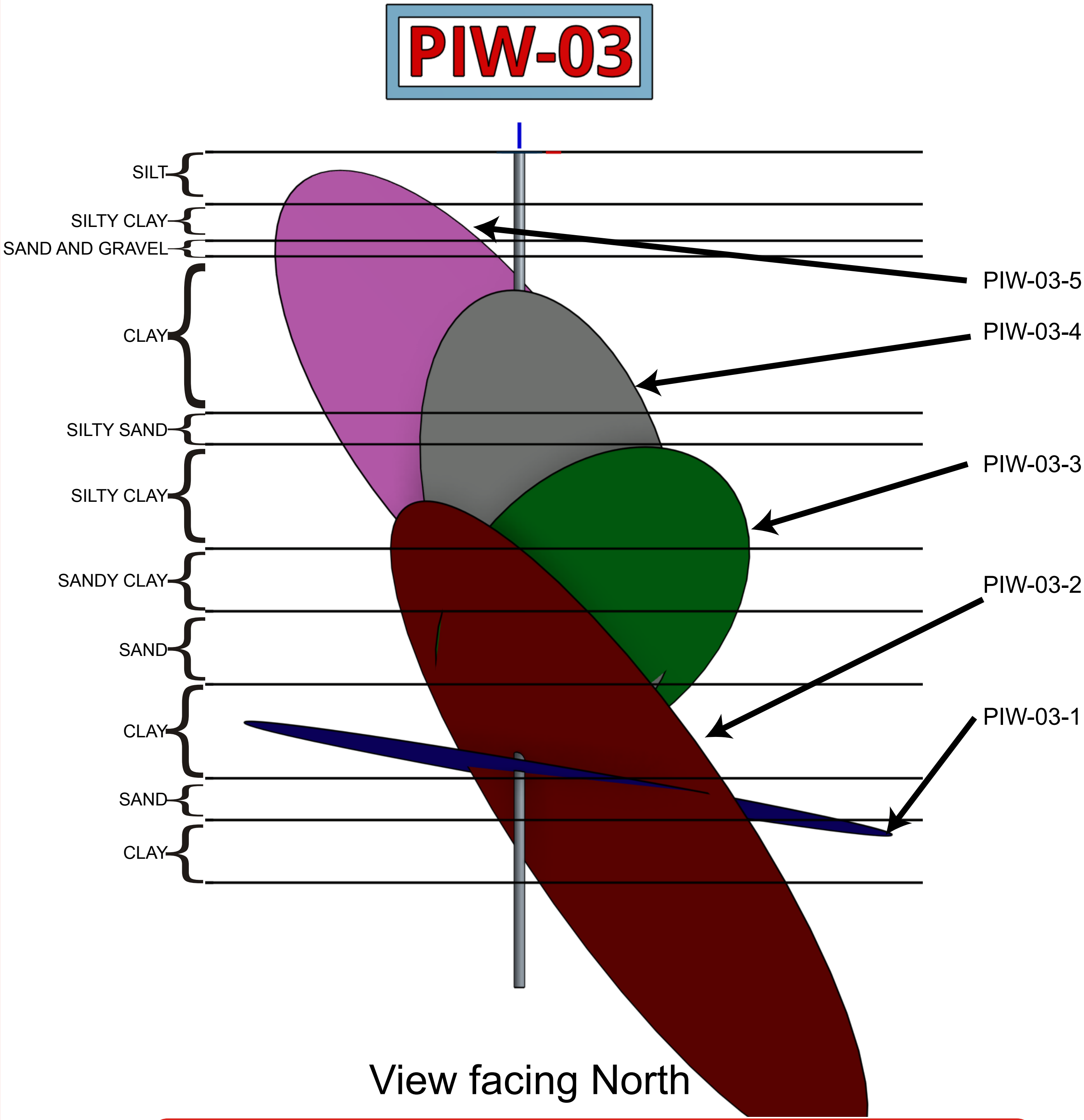


Figure III-1

Three-dimensional representation of Silica sand in Subsoils at HIW-01

GEOTACTICAL REMEDIATION

Pneumatic Fracture Borehole PIW-03



View facing North

Figure III-2

Three-dimensional representation of Lactoil in subsoils at PIW-03

GEOTACTICAL REMEDIATION

Report on the Emplacement of a Remediation Amendment Using Environmental Hydraulic Fracturing Techniques

Camp Pendleton Marine Corps Base
Site 1115
Camp Pendleton, California

September 2017

Prepared for:
CDM Federal Programs Corporation
3201 Jermantown Road
Suite 400
Fairfax, VA 22030

Prepared by:
Geo Tactical Remediation Ltd.
#2, 4416 5 Street NE
Calgary, Alberta
T2E 7C3

On Behalf of:
Frac Rite Remediation Inc.

Subcontract No. 6446-001-005-SI
J1607

Executive Summary

Geo Tactical Remediation Ltd. was retained by Frac Rite Remediation Inc. on behalf of CDM Federal Programs Corporation (CDM) to: emplace sand propped permeable pathways using environmental hydraulic fracturing; and inject an oxidizing remediation amendment into the permeable pathways, at the Camp Pendleton Site 1115 (the site) in the Camp Pendleton Marine Corps Base, California. The work was a part of the Environmental Security Technology Certification Program (ESTCP).

ESTCP Project Number ER-201430 involves the demonstration and validation of hydraulic and pneumatic fracturing technologies to enhance the delivery of remediation amendments to low permeability zones and using tiltmeter monitoring technology to quantify the emplaced fracture networks (CDM Smith Inc., 2015).

The program was conducted between August 22 and September 1, 2016 according to the design and scope of work developed by CDM.

The hydraulic fracturing work consisted of emplacing silica sand proppant as discrete fractures to enhance the formation permeability, followed by the injection of a solution of sodium persulfate activated with sodium hydroxide into the sand propped fractures.

A total of six individual sand fractures were successfully initiated and propagated from one fracture borehole location. Fracture initiation depths ranged from 32 to 50 ft bgs. The total mass of sand slurry emplaced was approximately 2,939 gal and it contained 20,830 lbs of sand. The fracture emplacement efficiency was 99%.

An injection well was installed in the fracture borehole. Approximately 3,215 gal of solution containing 3,200 lbs of sodium persulfate and 200 lbs of sodium hydroxide was injected into this well. The entire solution volume was successfully injected into the subsurface.

The six sand fractures were mapped with tiltmeter monitoring technology. The tiltmeter data was analyzed and modelled for five of the six fractures. The analysis indicated that discrete planar features were created in each instance. Of the five analyzed fractures, one was modelled as a conjugate and the other four as single planar features.

Table of Contents

1.0 Introduction

Geo Tactical Remediation Ltd. (Geo Tactical) was retained by Frac Rite Remediation Ltd. (Frac Rite) on behalf of CDM Federal Programs Corporation (CDM) to emplace permeable pathways for injection of remediation amendment, at the Camp Pendleton Site 1115 (the site) in the Camp Pendleton Marine Corps Base, California. The work was a part of the Environmental Security Technology Certification Program (ESTCP).

ESTCP Project Number ER-201430 involves the demonstration and validation of hydraulic and pneumatic fracturing technologies to enhance the delivery of remediation amendments to low permeability zones and using tiltmeter monitoring technology to quantify the emplaced fracture networks (CDM Smith Inc., 2015).

The work consisted of emplacing sand proppant as discrete fractures to enhance the formation permeability, followed by permeation injection of alkaline activated persulfate into the sand propped fractures. Sand fracture emplacement was mapped with tiltmeter monitoring technology. The program was conducted at the site between August 22 and September 1, 2016 according to the design and scope of work developed by CDM.

2.0 Background

Camp Pendleton Marine Corps Base is located roughly 41 miles north of San Diego, California (Figure 1). The base was established in 1942, and is still in use. The area selected for demonstration, site 1115, is located on the eastern portion of Camp Pendleton, and is approximately 14.5 acres in size (Figure 2). The site was used as a motor pool for vehicle maintenance, and as a repair, painting, washing, and fuel service station for the base. All buildings and a total of nine underground storage tanks (USTs) used on site have been removed or closed. Currently, the site is paved with asphalt and utilized for vehicle and equipment staging (Parsons, 2012).

The Santiago formation - present throughout the site - consists primarily of interbedded, low permeability, lightly cemented siltstone, sandstone and mudstone (CDM Smith Inc., 2015). The groundwater flow in the shallow zone is multi-directional, generally flowing south and southwest beneath the western and southern portion of the site, west beneath the east-central portion, and north and northeast in the northern portion of the site. In the lower aquifer, the groundwater flows generally to the south and southwest (Parsons, 2012).

Previous investigations have shown a widespread groundwater contaminant plume from three distinct source areas. As of 2015, the plumes stemming from the three source areas had migrated several hundred feet (Parsons, 2012).

The contaminants of concern consist of 1,2-dichloroethane, 1,2-dibromoethane, arsenic, benzene, carbon tetrachloride, cis-1,2-dichloroethene (cis-1,2-DCE), ethylbenzene, methylene chloride, methyl tertiary butyl ether (MTBE), naphthalene, toluene, trichloroethene (TCE), and vinyl chloride (VC). These contaminants are mostly found in the vicinities of the former USTs. Benzene is the main groundwater contaminant in the northwestern part of the site (near UST 1), and fuel-related compounds and chlorinated solvents can be found on the eastern and central portions of the site (Parsons, 2012). Diesel and gasoline range petroleum hydrocarbons ranged from non-detect to 14,000 mg/kg in a soil investigation completed in 2009. Figure 3 shows the contaminant plume extent (Parsons, 2012).

3.0 Objectives

The overall objectives of this project were to:

- Demonstrate the capability of environmental hydraulic fracturing to create high permeability sand propped pathways in low permeability soils.
- Demonstrate the effectiveness of the pathways for distribution of solution amendment.
- Demonstrate and validate the use of tiltmeter monitoring as a high-resolution, and non-invasive mapping technique to aid in evaluating the performance of environmental fracturing.
- Demonstrate the efficacy of permeation injection of alkaline activated persulfate in treating contaminants present on site.

4.0 Field Program

4.1 Hydraulic Fracture Emplacement of Sand Proppant

Fracture emplacement of sand commenced at the site on August 23, 2016 using Geo Tactical's EF9300 skid-mounted fracturing unit (Photo 1), downhole fracturing equipment, and high viscosity fracture fluid system.

Cascade Drilling, L.P. ("Cascade") provided drilling for fracturing operations. Drilling was completed using a sonic drill rig (Photo 2).

The sand slurry was batch mixed aboard the fracturing unit using potable water and Geo Tactical's GTR Enviro high viscosity fracturing fluid system. The high viscosity slurry carries the sand in suspension for even distribution throughout the fracture.

A straddle packer with inflatable sealing elements was used at the fracture borehole, HIW-01. The straddle packer system uses upper and lower inflatable sealing elements connected by an interval pipe (Photo 3). Sand slurry is pumped through ports in the interval pipe into the open borehole between the sealing elements to initiate and propagate the sand fracture. The interval is isolated by expanding the packer sealing elements by inflating them with water. This forms a seal between the packer sealing elements and the borehole above and below the target fracture interval, preventing slurry from entering the borehole above or below the selected interval.

Cascade drilled an open borehole for the straddle packer assembly. Their rig was used to lower Geo Tactical's inflatable straddle packer assembly to the first (deepest) fracture initiation depth. When the packers were set and inflated, the sand slurry was pumped into the open borehole interval at high enough pressure for the formation of a fracture. Continued pumping caused the fracture to propagate away from the borehole. Following fracturing, the packer elements were deflated and raised to the next pumping depth. This process continued until all fractures were completed in the borehole. This method is the bottom up approach and it ensures that discrete fractures are emplaced at each depth.

The network of sand fractures created provided permeable flow pathways for the subsequent alkaline activated persulfate injection into the surrounding soils.

During all fracturing events at the site, pressure and pump rate data was monitored and recorded.

4.2 Mapping of Subsurface Fractures

Tiltmeter geophysics was used to map the distribution of sand proppant emplaced by hydraulic fracturing at HIW-01 (Photo 4). The tiltmeter analysis helps verify the final distribution of sand in the subsurface.

Prior to pumping the fractures, ten biaxial ES model 700 tiltmeter sensors were placed in two concentric circular arrays (inner and outer) around the fracture borehole location to monitor the micro-movements in the ground surface in response to each fracturing event. The radial distance of the tiltmeters in the inner array ranged from 24.75 to 30 ft., and the radial distance of the tiltmeters in the outer array ranged from 35 to 45.25 ft.

Tiltmeters were set on prepared locations and leveled to read a tilt angle of approximately zero degrees. During each hydraulic fracturing event, signal data was collected and stored in the memory modules of dataloggers at a collection frequency of 1 tilt data signal every 10 seconds. Upon the completion of fracturing at each depth interval, the tiltmeter sensors were leveled again in preparation for the next fracturing event. This process was repeated until all fractures at the borehole were completed.

Geophysical data was analyzed using inverse parameter modeling to determine fracture geometry (modeled as planar disc features) defined by length, width, thickness, asymmetry, orientation, and angle of ascent from horizontal (measured in degrees). In addition to tilt signal, fracture volumes and times were considered in the interpretation of tiltmeter data.

4.3 Injection Well Installation

Following sand fracturing, an injection well was installed by Cascade with oversight by CDM. The injection well was installed on August 26, 2016. The well was developed prior to the permeation injection to remove any sediment and residual guar from the sand pack.

4.4 Alkaline Activated Persulfate Permeation Injection

The alkaline activated persulfate permeation injection commenced and was completed on August 30, 2016. The solution was formulated by mixing potable water with granular sodium persulfate and sodium hydroxide beads. The sodium persulfate was mixed at concentrations that ranged from 13 to 15% (mass of sodium persulfate to solution volume). The sodium hydroxide was mixed at concentrations ranging from roughly 7 to 10% (mass of sodium hydroxide to solution volume).

A wellhead assembly was installed on the injection well. The assembly included connections for hoses with dedicated shut off valves and a pressure gauge. The solution was pumped into the well using Geo Tactical's EFI2000 injection unit (Photo 5). The injection unit operator monitored flow and pressure readings during injection, these readings were displayed by the on-board data acquisition system.

5.0 Results

5.1 Hydraulic Fracturing

The sand fracturing program was conducted on August 23 and 24, 2016. A total of six individual sand fractures were initiated and propagated from one fracture borehole location at the site (Table 5-1). Fracture initiation intervals ranged from 32 to 50 ft bgs. The total volume of sand slurry emplaced was approximately 2,939 gal and contained approximately 20,830 lbs of sand proppant.

TABLE 5-1
Summary of Fracture Emplacement Results

Borehole I.D.	Fracture Depth Range (ft)	Number of Fracture Depths	Slurry Volume Emplaced (gal)	Sand Mass Emplaced (lbs)
HIW-01	32 - 50	6	2,939	20,830
SITE TOTAL		***6***	***2,939***	***20,830***

A straddle packer with inflatable sealing elements was used to initiate and propagate all six boreholes at HIW-01. Surfacing of the sand slurry occurred from the annular space of the borehole while pumping at the first depth, HIW-01-1, so only 36% of the planned volume was emplaced at this fracture interval. To make up for the remainder of the volume designed for HIW-01-1, two separate fractures were initiated and propagated at the second fracture depth interval, HIW-01-2a and HIW-01-2b. Immediate annular fluid surfacing occurred at the third proposed fracture depth interval, HIW-01-3.

Analysis of operational pressure-time curve and flow rate data (Appendix I) indicated that average pressures for initiating fractures (i.e. "Break Pressures"), including pressure required to overcome friction losses from pumping high viscosity slurry, ranged from 163 to 288 psi. The average propagation pressure ranged from 157 to 228 psi with an average pump rate during fracturing from 92 to 115 gal/min (gpm). Pressure time curves with fracture summary sheets are depicted in Appendix I.

5.2 Injection Well Installation

Installation of the injection well was completed on August 26, 2016 in HIW-01. The injection well was installed according to the original design. The injection well was screened from 30 to 50 ft bgs. The screened interval spans from the center of the deepest fracture initiation interval depth to 2 ft above the shallowest fracture initiation depth.

5.3 Alkaline Activated Persulfate Permeation Injection

Injection of the solution containing sodium persulfate activated with sodium hydroxide was completed on August 30, 2016. A total of 3,215 gal of solution was injected into HIW-01. The solution contained a total of approximately 3,200 lbs of sodium persulfate and 200 lbs of sodium hydroxide. The injection data is summarized in Table 5-2 below and details for each tank pumped are presented in Table 2 attached.

Table 5-2
Summary of Injection Results

Injection Well I.D.	Sodium Persulfate Mass (lbs)	Sodium Hydroxide Mass (lbs)	Solution Volume (gal)	Time to Pump (min)	Sodium Persulfate Concentration (%)	Sodium Hydroxide Concentration (%)
HIW-01	3,197	200	3,215	897	13 to 15	7 to 10

The injection flow rate ranged from 0.5 to 9.7 gpm. Approximately 90% of the total volume injected was carried out as a co-injection of sodium hydroxide solution (264 gal) and sodium persulfate solution using (2,629 gal) separate pumps for each solution. Due to a problem with one of pumps, the remaining 10% as 58 gal of sodium hydroxide and sodium persulfate solution, and 264 gal of only sodium persulfate solution was injected with a single pump.

No fluid surfacing occurred during the permeation injection of sodium persulfate solution activated with sodium hydroxide. The injection was completed per the original plan.

5.4 Hydraulic Sand Fractures Tiltmeter Mapping Results

Six fractures initiated from HIW-01 were mapped using tiltmeter geophysics. An analysis of the fracture mapping results was made to determine the geometry of the fractures. The size and orientation of the fractures are summarized in Table 5-3 below. A more detailed report of the tiltmeter analysis containing graphical depictions is appended in Appendices II and III.

TABLE 5-3
Hydraulic Sand Fractures – Summary of Tiltmeter Geophysical Results

Fracture I.D.	Depth of Fracture Initiation[1] (ft)	Fracture Thickness (inches)	Fracture Width[2] (ft)	Fracture Length[3] (ft)	Fracture Azimuth[4] (°)	Fracture Dip Angle[5] (°)
HIW-01-1	50	0.336	20.0	20.0	38	42
HIW-01-1 (conjugate[6])	50	0.276	24.0	30.0	269	37
HIW-01-2b	46	0.444	30.0	70.0	313	22
HIW-01-4	40	0.360	34.5	75.0	50	6
HIW-01-5	36	0.428	30.0	75.0	282	2
HIW-01-6	32	0.300	33.6	87.7	106	26

Notes:
1. Depth measured from ground surface to the ports on the fracture tool.
2. Width – fracture dimension measured along dip.
3. Length – fracture dimension measured along azimuth.
4. Fracture Azimuth – describes the compass bearing when looking along a line perpendicular to dip direction (strike), with the fracture dipping down to right.
5. Dip Angle – Angle of fracture inclination from horizontal.
6. Conjugate – A conjugate fracture is when a secondary fracture formed during pumping. The fracture is then modeled as a dual planar feature (a fracture and a conjugate).

In general, the indicated fracture thickness of the hydraulic fractures during propagation ranged from 0.28 to 0.44 inches, with an average thickness of 0.36 inches.

The width of fractures was compared to their length to determine the average fracture aspect ratio. The average width of fractures was 28.7 ft and the average length was 59.6 ft. Thus, the average aspect ratio of HIW-01 was below 1.0, meaning that the dimension along dip is smaller than the dimension along azimuth. Fractures generally have some component of asymmetry, and fracture aspect ratios greater or less than 1.0 are common.

The dip angles of the fractures ranged from 2° at HIW-01-5 (36 ft depth) to 42° (50 ft depth).

6.0 Discussion

Analysis of operational pressure-time data indicate that the mode of sand emplacement into subsurface soils was by hydraulic fracturing, with six fractures initiated and propagated from one borehole.

Hydraulic fracturing emplacement as the mode of emplacement is further supported by analysis of the tiltmeter data collected and analyzed during five of the six pumping events. The five analyzed pumping events were modeled as planar features as is consistent with hydraulic fractures.

Surfacing of sand slurry occurred from the annular space of the borehole while pumping at HIW-01-1. The fluid surfacing was likely a result of the straddle packer assembly not maintaining seal in the borehole. This may have happened due to inconsistencies in the borehole walls that eventually allowed the fracture fluid to travel past the upper packer into annular space above. The fluid surfacing at HIW-01-3 occurred as soon as pumping began, this is indicative of a loss of seal with the upper packer. Fracture HIW-01-4 was initiated 2 ft above HIW-01-3 to ensure that the new fracture interval would not have any overlap with the fracture interval planned for HIW-01-3.

The fractures emplaced at the site are expected to increase the bulk hydraulic conductivity in the area of the fracture network and allow for increased injection volumes and reduced injection time for future injection events into the injection well.

The permeation injection of sodium persulfate solution activated with sodium hydroxide was completed according to the initial design. No fluid surfacing occurred during the injection. This is likely because the surfacing that occurred during the sand proppant fracturing occurred due to borehole seals, not because of remote pathways created to the surface. This indicates that the treatment pathways were likely contained within the contaminated zone.

The tiltmeter field data was regarded as good to very good with high signal to noise ratios, providing modeling results that were generally of good to excellent quality. Of the five hydraulic fractures modeled, one had a good fit, one had a very good fit, while the remaining three fractures had excellent fits.

The average thickness of the sand propped fractures was 0.36 inches. This thickness is expected to provide longevity of the fractures as high permeable pathways for subsequent injections as required.

Four of the five modeled fractures were depicted as single planar structures, and one as a conjugate fracture. A conjugate fracture is a secondary fracture feature formed during pumping, resulting in a dual planar feature being modeled. Fractures may be more complex than interpreted due to effects that include leak off into more permeable or naturally occurring fractures in bedrock or soils encountered, fluid losses through existing subsurface disturbances (e.g. existing boreholes, excavations, etc.) and possible excessive curvatures of fractures emplaced.

Tiltmeter geophysical results for the hydraulic fractures showed very little variation in fluid leak off across the site with the analyses showing fracture efficiencies of greater than 95%.

Table 5-3 shows that the fracture dip angles are relatively flat, ranging from 2 to 42°. This is a good indication that the sodium persulfate solution activated with sodium hydroxide likely targeted the planned treatment zone.

The modeled fractures display an average length of 59.6 ft, with four of the lengths ranging from 70.0 to 87.7 ft. The 3D depiction of the fractures (Appendix III) shows that they provide a good treatment area around the borehole, as well as to the northwest, northeast, and east of the borehole.

7.0 Conclusion

The following conclusions were made based on: observations made in the field, analysis of the tiltmeter data, and analysis of pressure/pump rate data.

- 21,000 lbs of sand was distributed into the soils from six fractures at one borehole location using hydraulic fracturing as a mode of emplacement.
- Good vertical and lateral extent was achieved around the fracture borehole. The six fractures are expected to enhance the bulk hydraulic conductivity in the vicinity of the borehole.
- 3,215 gal of solution containing approximately 3,200 lbs of sodium persulfate activated with 200 lbs of sodium hydroxide was successfully injected into the injection well HIW-01.
- The tiltmeter field data collected and analyzed was found to be very good to excellent providing modeling results that were mostly of excellent quality.

8.0 Closure

Geo Tactical has extensive experience in advanced, in situ fracture and permeation emplacement of a wide variety of treatment amendments. However, Geo Tactical does not warrant or guarantee the long-term success of enhanced in situ remediation using any treatment amendment provided by third party vendors. Geo Tactical guarantees that the quality of its work is of the highest standard using our best practices and technical protocols.
Operational sites, or sites where past environmental impacts have been documented, may pose a continuous and ongoing risk of contaminant leakage and/or contaminant migration. Geo Tactical will not be held responsible for achieving any standard of remediation in consideration of the potential for ongoing or future contaminant releases at the site.

We trust that this report meets your requirements. Should you have any questions or comments, please contact the undersigned. Thank you for retaining Geo Tactical on this innovative remedial project.

Yours truly,

Geo Tactical Remediation Ltd.

Andreea Mogos B.Sc., Geol.I.T.
Environmental Geologist

Gord T. Guest, P.Geol.
Principal

9.0 References

CDM Smith Inc. May 2015. Draft Technology Demonstration Plan, A Rigorous Demonstration of Environmental Fracturing in Low Permeability Media, ESTCP Project Number ER-201430

Parsons. March 2012. Final Site 1115 Groundwater Pilot Study Technical Memorandum. Prepared for Naval Facilities Engineering Command – Southwest Division.

FIGURES

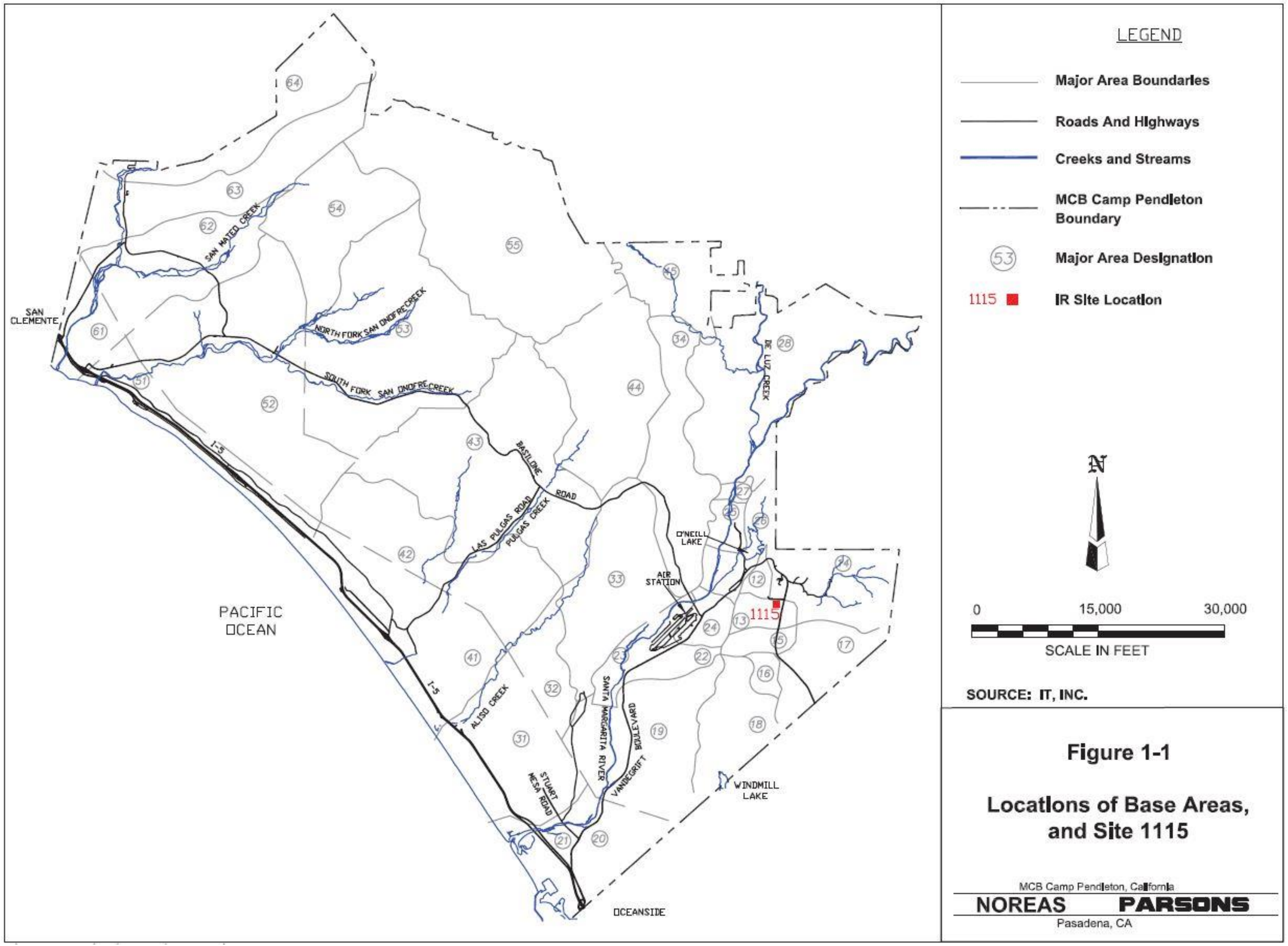


FIGURE 1 – Site Location Map (provided by CDM Smith Inc.)

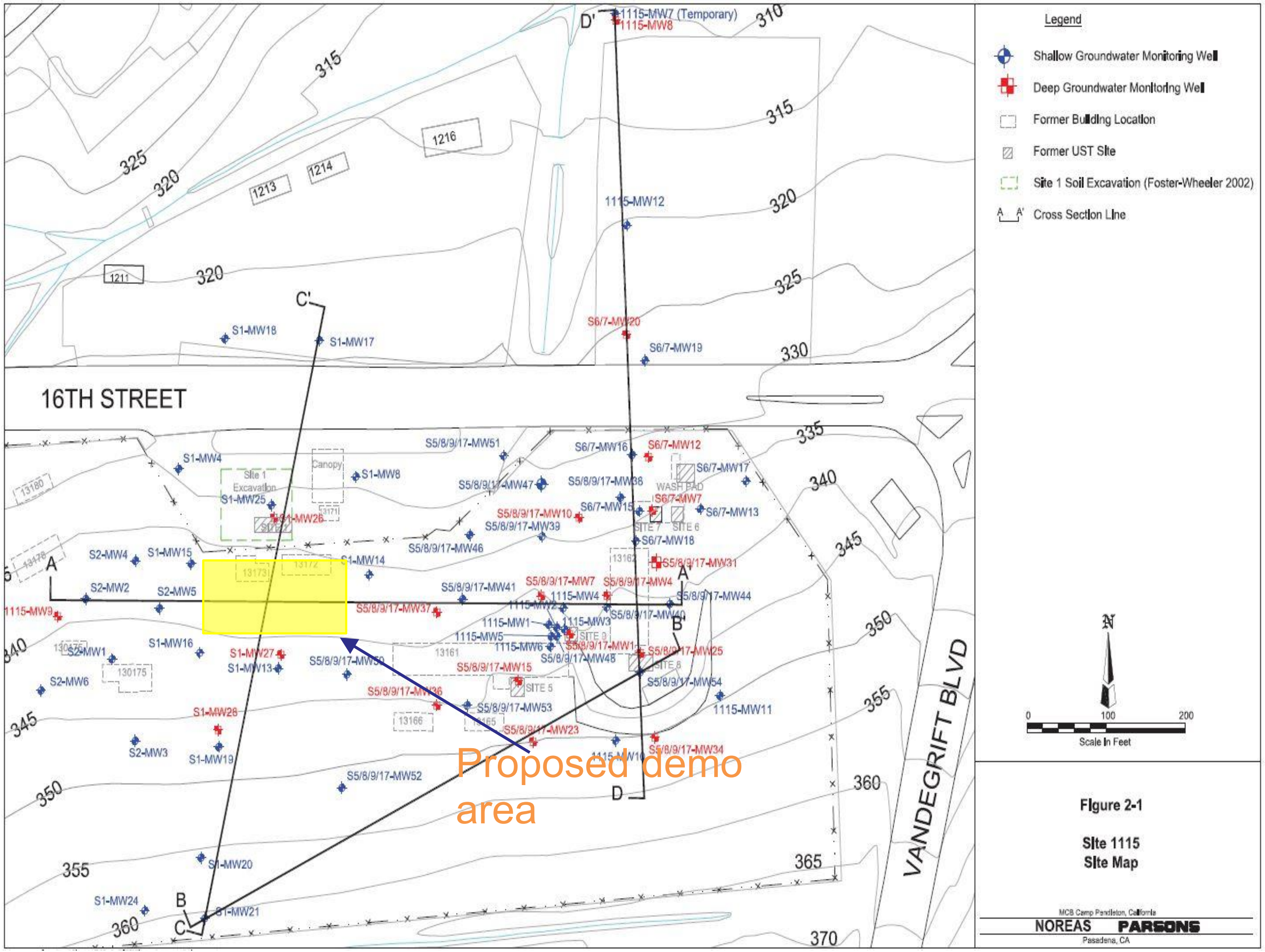


FIGURE 2 – Site Plan (provided by CDM Smith Inc.)

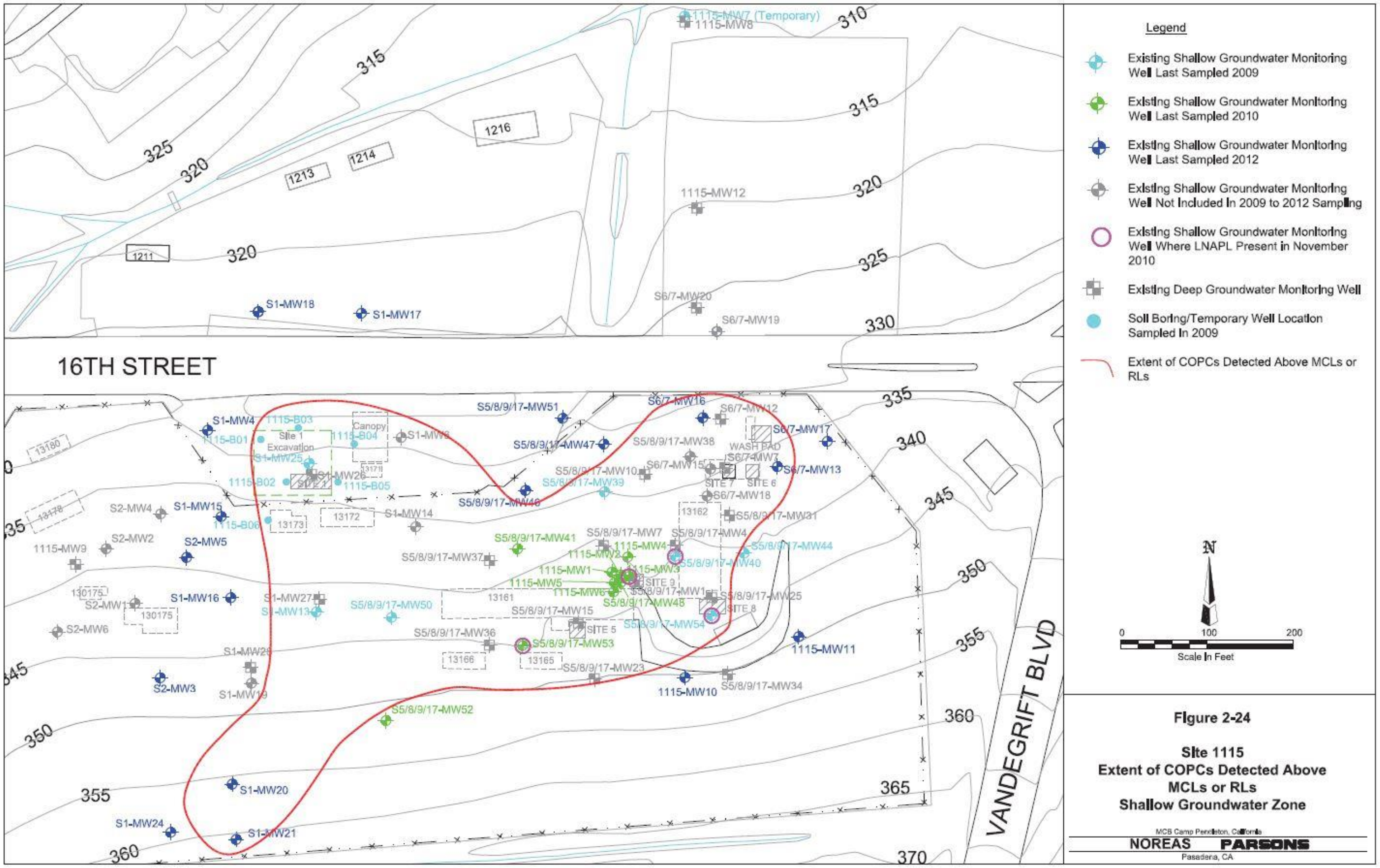


FIGURE 3 – Contaminant Plume (provided by CDM Smith Inc.)

TABLES

TABLE 1
Sand Proppant Fracture Emplacement Results

Fracture Borehole	*Fracture I.D.*	*Depth (ft bgs)*	*Date Emplaced*	*Slurry Volume Pumped (gal)*	*Sand Mass Pumped (lbs)*	*Fluid Surfacing Volume (gal)*	*Slurry Volume Emplaced (gal)*	*Sand Mass Emplaced (lbs)*	Emplacement Efficiency (%)
HIW-01	HIW-01-1	50	23-Aug-16	238	1,510	26	212	1,340	89.1
	HIW-01-2A	46	23-Aug-16	383	2,690	0	383	2,690	100.0
	HIW-01-2B	46	23-Aug-16	581	4,200	0	581	4,200	100.0
	HIW-01-3	42	23-Aug-16	5	0	5	0	0	0.0
	HIW-01-4	40	23-Aug-16	581	4,200	0	581	4,200	100.0
	HIW-01-5	36	24-Aug-16	601	4,200	0	601	4,200	100.0
	HIW-01-6	32	24-Aug-16	581	4200	0	581	4,200	100.0
TOTAL				***2,970***	***21,000***	***31***	***2,939***	***20,830***	***99.0***

bgs below ground surface

TABLE 2
Injection Results at HIW-01

Tank #	Sodium Persfulate Mass (lbs)	Sodium Hydroxide Mass (lbs)	Solution Volume (gal)	Time to Pump (min)	Average Pump Rate (gpm)	Sodium Persulfate Concentration (%)	Sodium Hydroxide Concentration (%)
1	0	75.0	132.1	260	0.5	0.0	6.8
2	143	0.0	118.9	32	3.7	14.4	0.0
3	143	0.0	132.1	23	5.7	13.0	0.0
4	143	0.0	132.1	23	5.7	13.0	0.0
5	143	0.0	132.1	23	5.7	13.0	0.0
6	143	0.0	132.1	23	5.7	13.0	0.0
7	143	0.0	132.1	22	6.0	13.0	0.0
8	143	0.0	132.1	22	6.0	13.0	0.0
9	143	0.0	132.1	21	6.3	13.0	0.0
10	143	0.0	132.1	20	6.6	13.0	0.0
11	143	0.0	132.1	20	6.6	13.0	0.0
12	0	75.0	132.1	178	0.7	0.0	6.8
13	143	0.0	132.1	19	7.0	13.0	0.0
14	143	0.0	132.1	20	6.6	13.0	0.0
15	143	0.0	132.1	18	7.3	13.0	0.0
16	143	0.0	132.1	19	7.0	13.0	0.0
17	143	0.0	132.1	19	7.0	13.0	0.0
18	143	0.0	132.1	20	6.6	13.0	0.0
19	143	0.0	132.1	23	5.7	13.0	0.0
20	143	0.0	132.1	18	7.3	13.0	0.0
21	143	0.0	132.1	16	8.3	13.0	0.0
22	143	0.0	132.1	15	8.8	13.0	0.0
23	0	24.9	29.1	3	9.7	0.0	10.3
24	165	0.0	132.1	16	8.3	15.0	0.0
25	0	24.9	29.1	5	5.8	0.0	10.3
26	165	0.0	132.1	19	7.0	15.0	0.0
TOTAL	***3,197***	***200***	***3,215***	***897***			

SITE PHOTOGRAPHS

Photo 1 – EF9300 Fracturing Unit with Ancillaries

Photo 2 – Cascade's Track Mounted Sonic Drilling Rig

Photo 3 – Straddle Packer Assembly Being Lowered in HIW-01

Photo 4 – Tiltmeters Placed Around HIW-01

Photo 5 – EFI2000 Mixing and Pumping Unit with Ancillaries

APPENDIX I

PRESSURE TIME CURVES AND FRACTURE SUMMARY SHEETS

FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1607 DATE: August 23 & 24, 2016

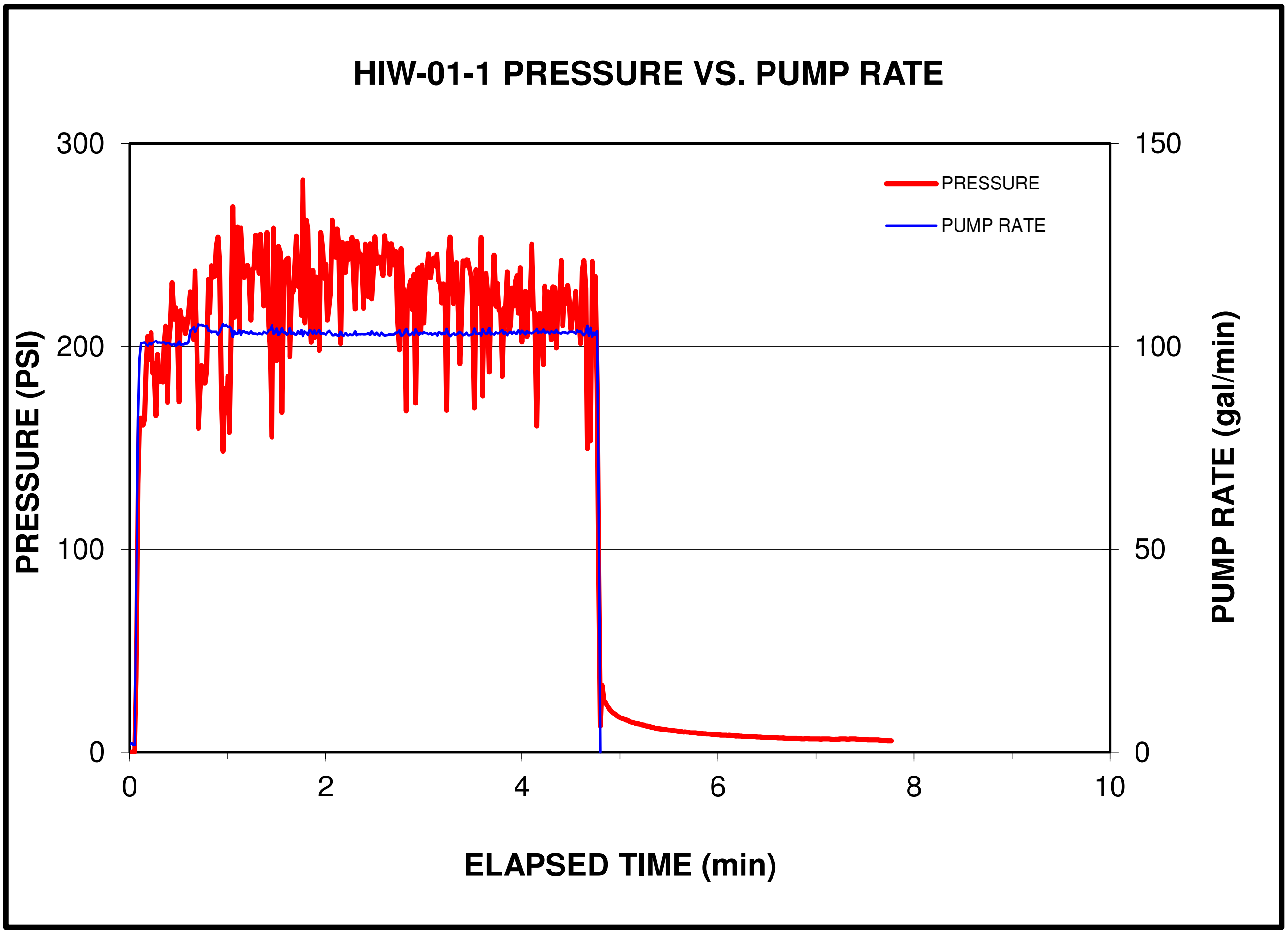
FRACTURE BOREHOLE ID: HIW-01

FRACTURE ID:	HIW-01-1	HIW-01-2a	HIW-01-2b	HIW-01-3	HIW-01-4	HIW-01-5	HIW-01-6
DEPTH (ft.)	50.0	46.0	46.0	42.0	40.0	36.0	32.0
SOIL TYPE	Silt	Silt	Silt	Silt	Silt	Silt	Silt
PROPPANT TYPE	SIL 20/45	SIL 20/45	SIL 20/45	SIL 20/45	SIL 20/45	SIL 20/45	SIL 20/45
PROPPANT SLURRY VOL PUMPED (gal)	238	383	581	0	581	601	581
GEL PAD VOL (gal)	13	13	0	0	0	13	13
GEL FLUSH VOL (gal)	13	13	20	0	20	20	20
PROPPANT MASS PUMPED (lbs.)	1510	2690	4200	0	4200	4200	4200
PROPPANT LOADING (lbs./gal)	6	7	7	7	7	7	7
VENT/LOSS (gal)	26	0	0	5	0	0	0
VENT/LOSS TYPE	Borehole	None	None	Borehole	None	None	None
PLACEMENT EFFICY. (%)	88.9	100.0	100.0	0.0	100.0	100.0	100.0
PROPPANT MASS EMPLACED (lbs.)	1340	2690	4200	0	4200	4200	4200
PEAK PRESSURE (PSI)	282	277	288	0	254	192	259
AVG. PRESSURE (PSI)	220	228	157	0	168	159	203
BREAK PRESSURE (PSI)	207	263	288	0	254	163	242
PEAK RATE (gal/min)	106	96	119	0	110	118	109
AVG. RATE (gal/min)	103	92	107	0	108	115	107
RATE AT BREAK (gal/min)	101	64	115	0	106	116	97
REMARKS	No distinct frac break pressure.			Immediate annular surfacing of fluid.		No distinct frac break pressure.	

Note:	Stratigraphy based on information received from CDM Smith Inc.

ND - Not Determined NA - Not Applicable

FRACTURE DATA

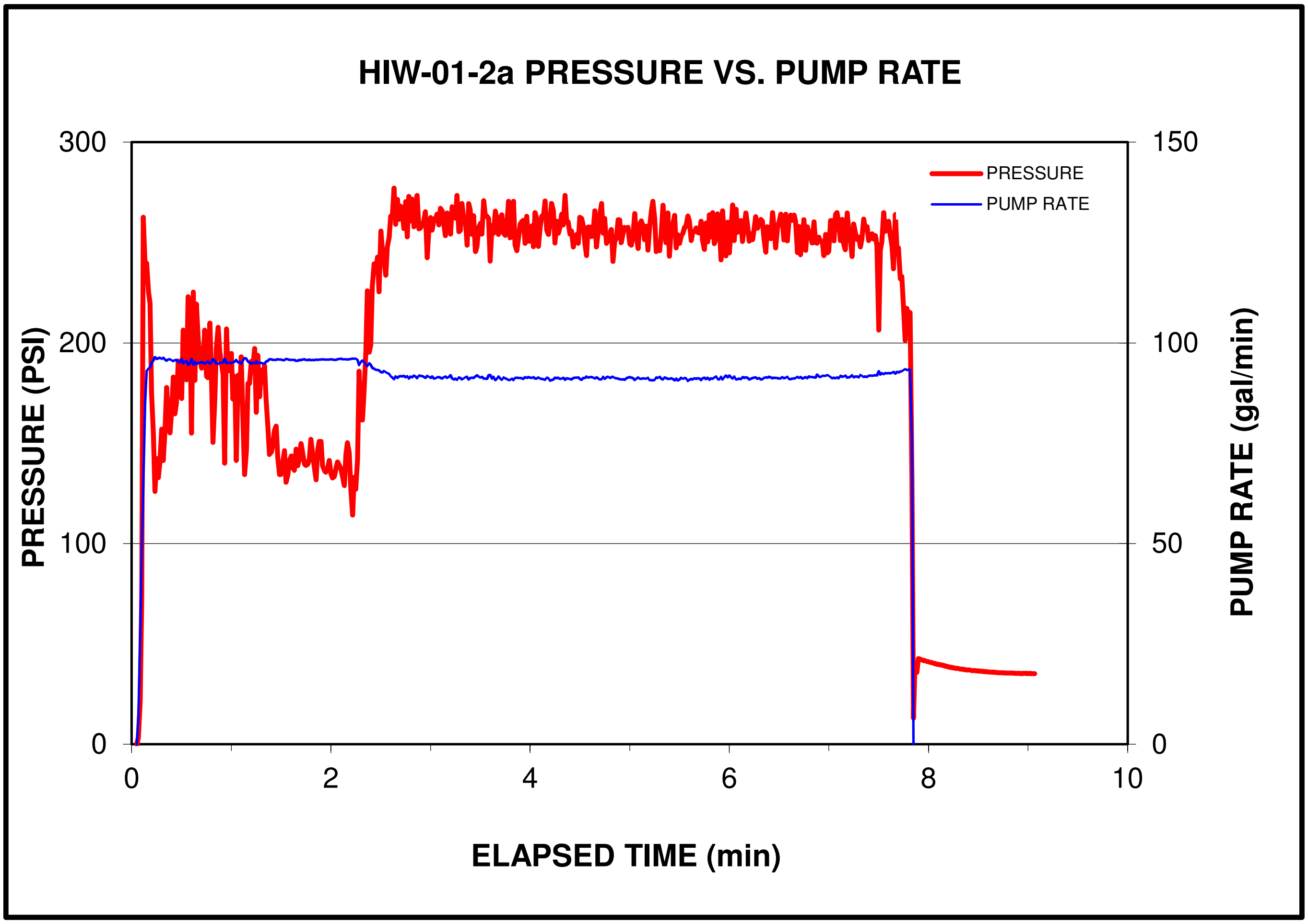


PROJECT NUMBER:	J1607		DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-1		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	50.0	(ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	238	(gal)	PLACEMENT EFFICIENCY:	89	(%)
PROPPANT TYPE:	SIL 20/45		PROPPANT MASS PUMPED:	1510	(lbs.)
BREAK PRESSURE:	207	(PSI)	AVERAGE PUMP RATE:	103	(gal/min)

REMARKS: No distinct frac break pressure.

NOTE: Stratigraphy based on information received from CDM Smith Inc.

FRACTURE DATA

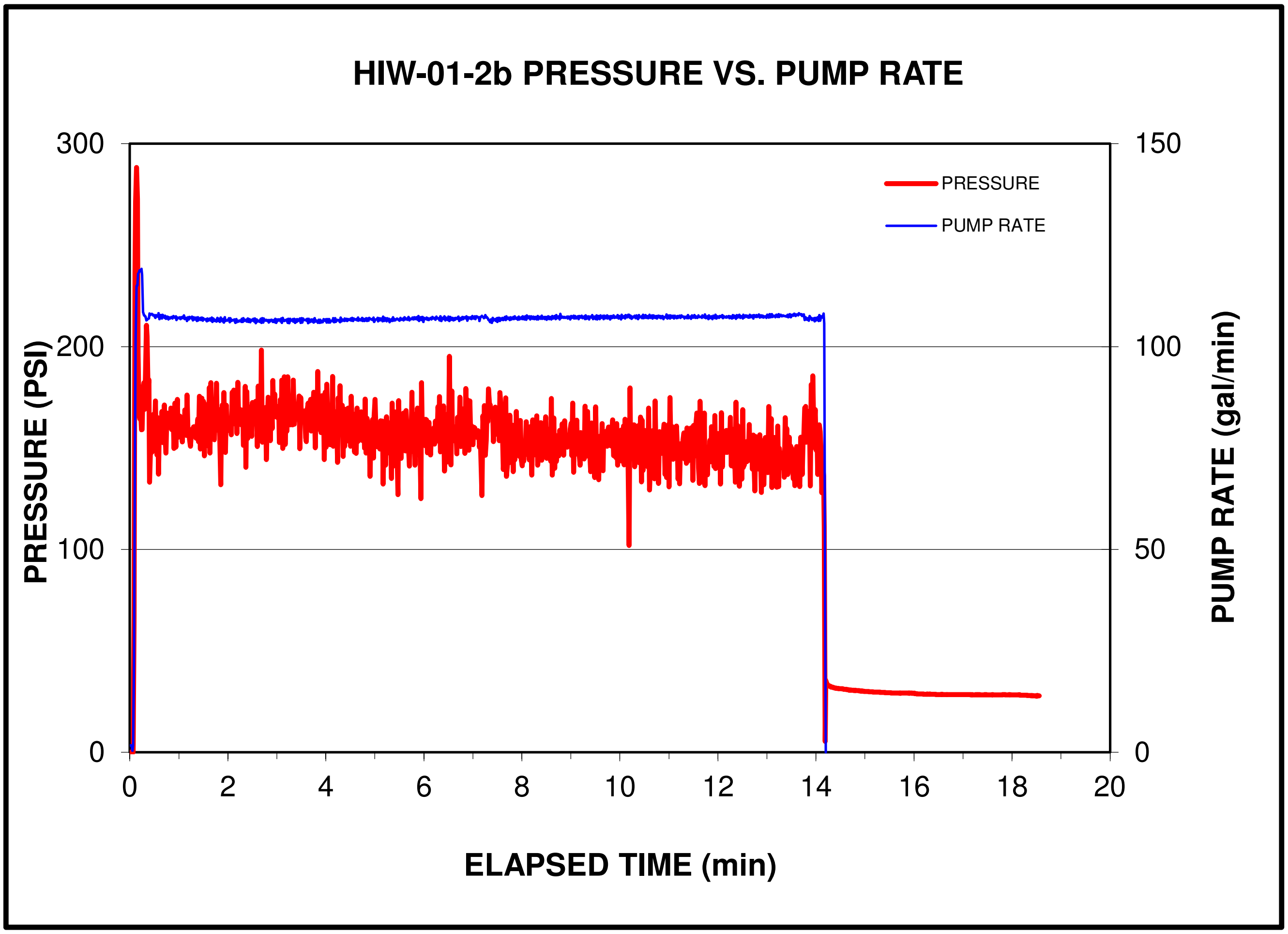


PROJECT NUMBER:	J1607		DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-2a		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	46.0	(ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	383	(gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	SIL 20/45		PROPPANT MASS PUMPED:	2690	(lbs.)
BREAK PRESSURE:	263	(PSI)	AVERAGE PUMP RATE:	92	(gal/min)

REMARKS:

NOTE: Stratigraphy based on information received from CDM Smith Inc.

FRACTURE DATA

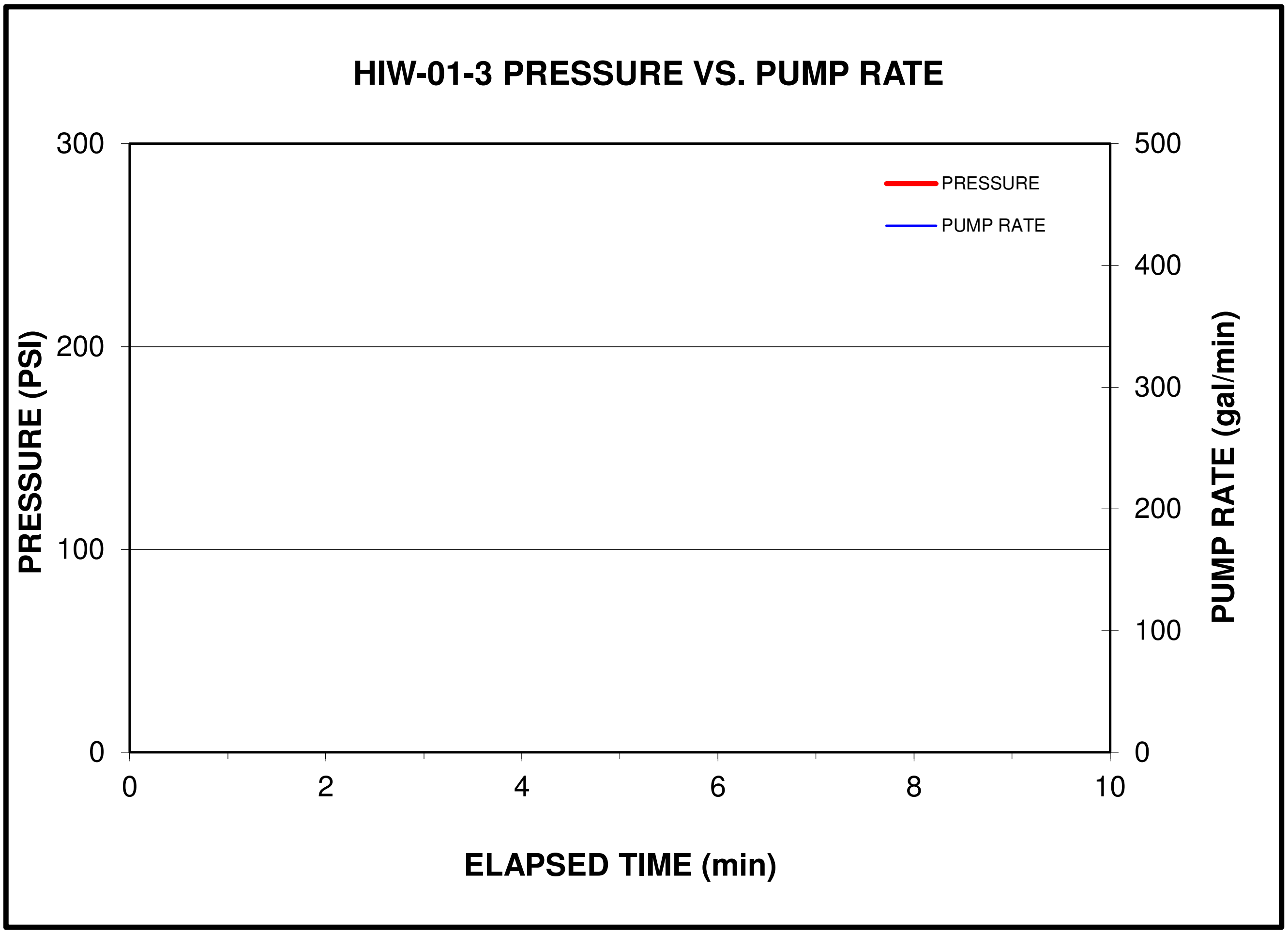


PROJECT NUMBER:	J1607		DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-2b		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	46.0	(ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	581	(gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	SIL 20/45		PROPPANT MASS PUMPED:	4200	(lbs.)
BREAK PRESSURE:	288	(PSI)	AVERAGE PUMP RATE:	107	(gal/min)

REMARKS:

NOTE: Stratigraphy based on information received from CDM Smith Inc.

FRACTURE DATA

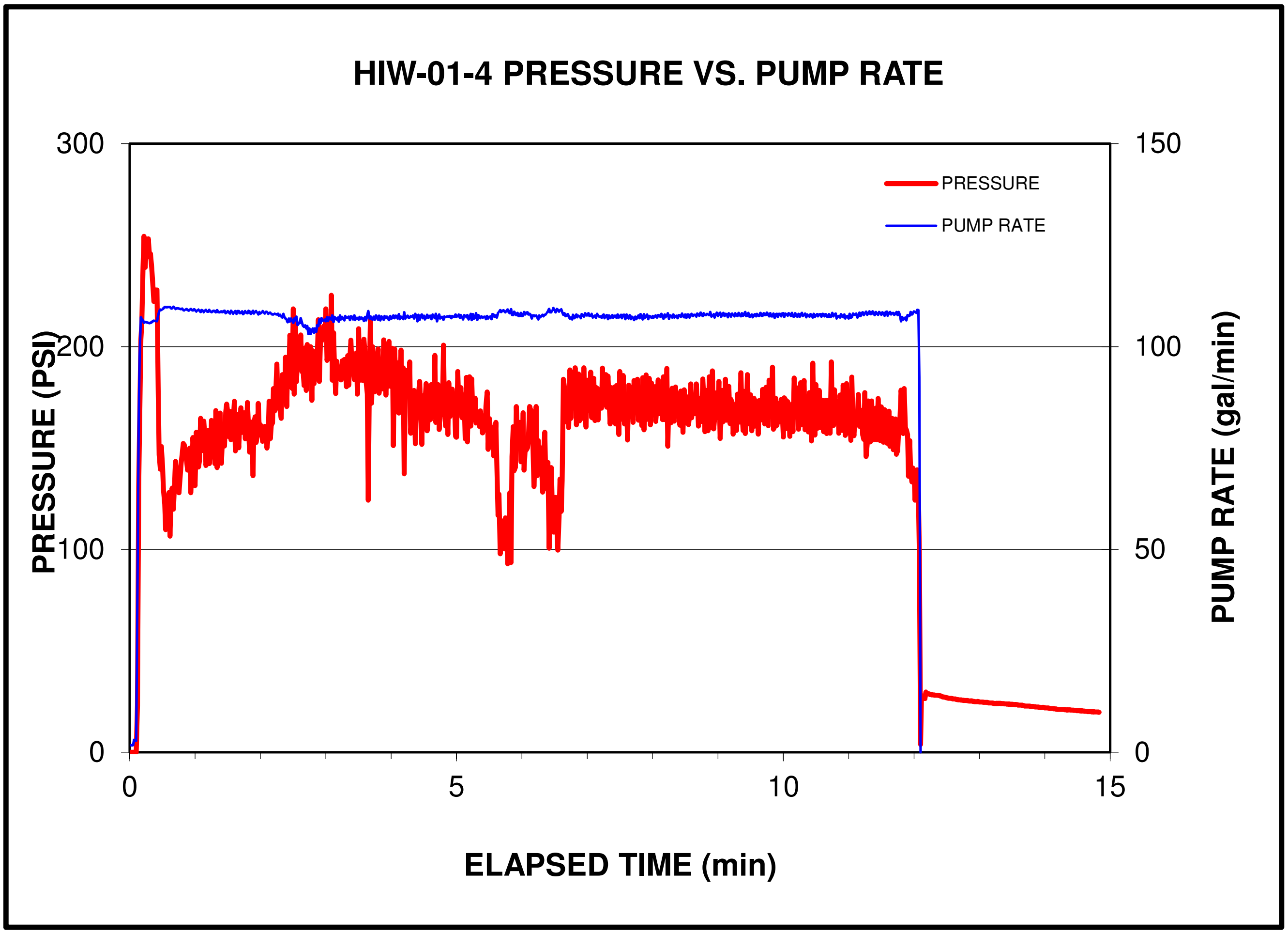


PROJECT NUMBER:	J1607		DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-3		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	42.0	(ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	0	(gal)	PLACEMENT EFFICIENCY:	0	(%)
PROPPANT TYPE:	SIL 20/45		PROPPANT MASS PUMPED:	0	(lbs.)
BREAK PRESSURE:	0.00	(PSI)	AVERAGE PUMP RATE:	0	(gal/min)

REMARKS: Immediate annular surfacing of fluid.

NOTE: Stratigraphy based on information received from CDM Smith Inc.

FRACTURE DATA

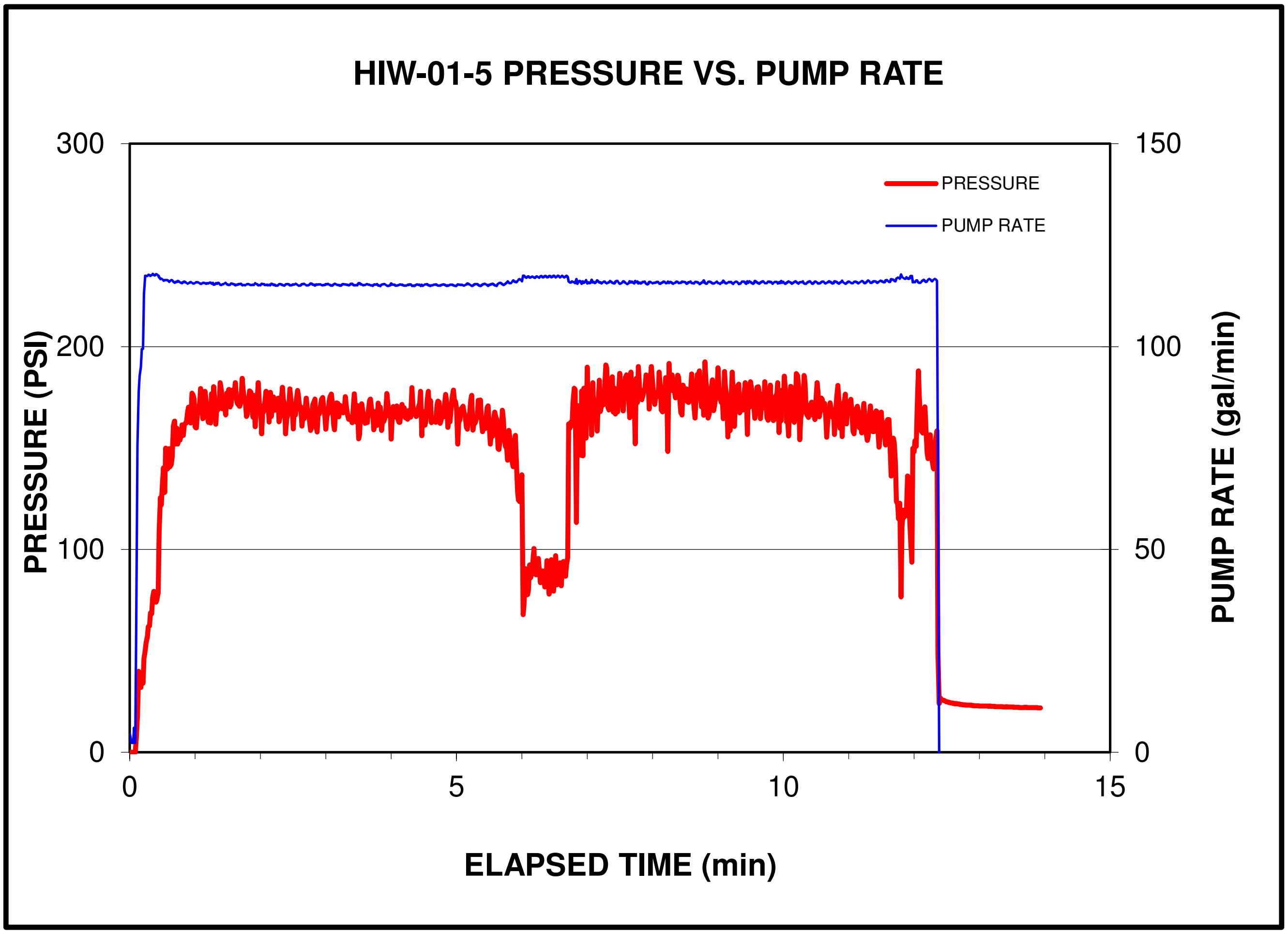


PROJECT NUMBER:	J1607		DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-4		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	40.0	(ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	581	(gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	SIL 20/45		PROPPANT MASS PUMPED:	4200	(lbs.)
BREAK PRESSURE:	254	(PSI)	AVERAGE PUMP RATE:	108	(gal/min)

REMARKS:

NOTE: Stratigraphy based on information received from CDM Smith Inc.

FRACTURE DATA

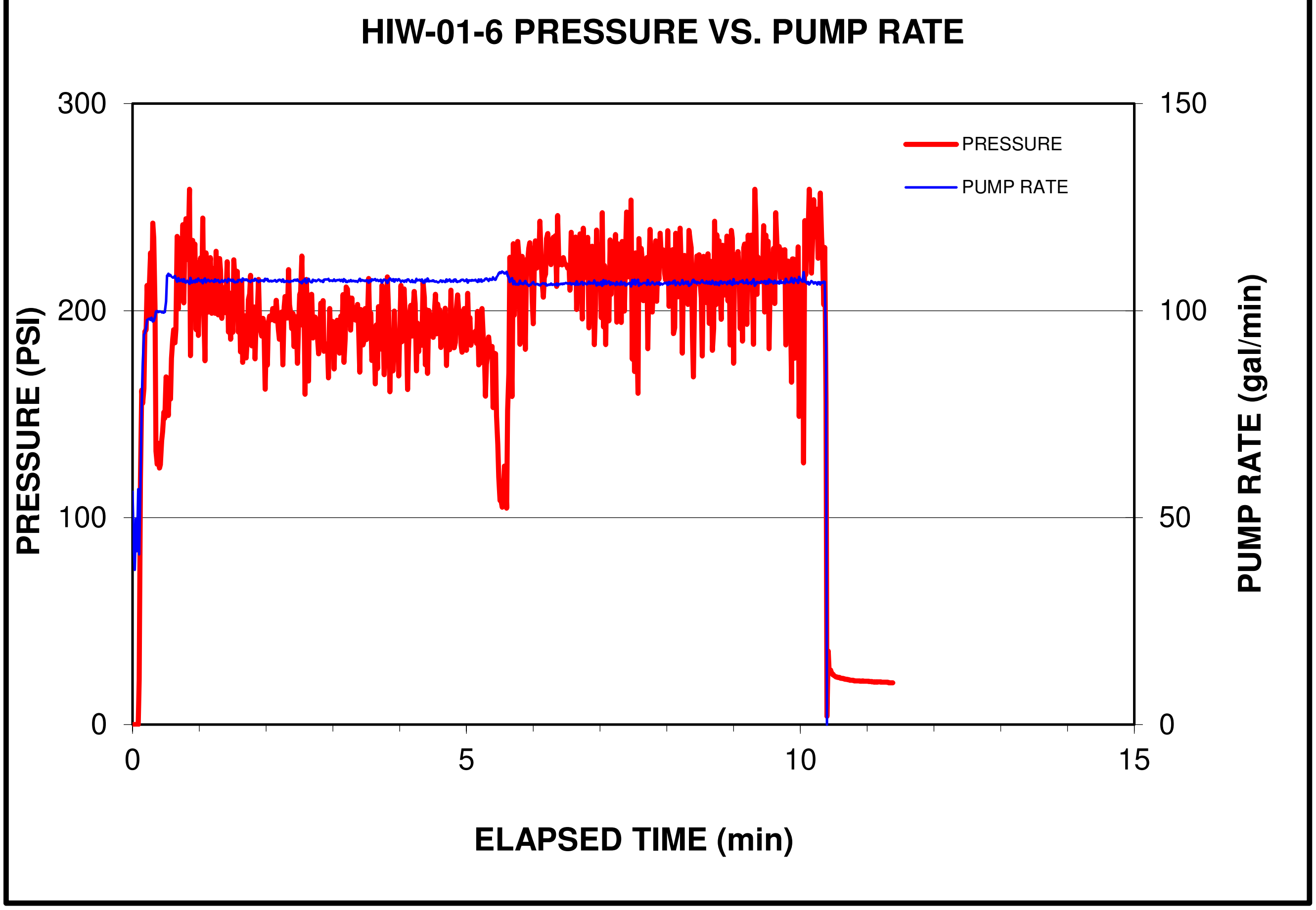


PROJECT NUMBER:	J1607	DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-5	FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	36.0 (ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	601 (gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	SIL 20/45	PROPPANT MASS PUMPED:	4200	(lbs.)
BREAK PRESSURE:	163 (PSI)	AVERAGE PUMP RATE:	115	(gal/min)

REMARKS: No distinct frac break pressure.

NOTE: Stratigraphy based on information received from CDM Smith Inc.

FRACTURE DATA



PROJECT NUMBER:	J1607		DATE:	23 August 2016	
FRACTURE NO.:	HIW-01-6		FRACTURE BOREHOLE:	HIW-01	
FRACTURE DEPTH:	32.0	(ft.)	SOIL TYPE:	Silt	
SLURRY VOL PUMPED:	581	(gal)	PLACEMENT EFFICIENCY:	100	(%)
PROPPANT TYPE:	SIL 20/45		PROPPANT MASS PUMPED:	4200	(lbs.)
BREAK PRESSURE:	242	(PSI)	AVERAGE PUMP RATE:	107	(gal/min)

REMARKS:

NOTE: Stratigraphy based on information received from CDM Smith Inc.

APPENDIX II

TILTMETER GEOPHYSICAL REPORT

Tiltmeter Monitoring of

Hydraulic Fracture Injections

Camp Pendleton Site 1115

Camp Pendleton Marine Corps Base, California

Prepared by:
Geo Tactical Remediation Ltd.
Calgary, Alberta, Canada

September 2017

SUMMARY

On August 23 and 24, 2016 six hydraulic fractures in one borehole were monitored with surface tiltmeters at a field site in Camp Pendleton, California. The purpose of the fracturing was to emplace sand proppant into the subsurface to facilitate the remediation of contaminated soils.

The fractures were initiated from 6 depths ranging between 32 and 50 ft below ground surface. Two fractures were initiated at the same depth interval at the borehole. All fractures were monitored using Geo Tactical's proprietary tiltmeter mapping system. The recorded data quality was generally very good to excellent with high signal to noise ratios. Geophysical analysis was completed for five of the six fractures.

Analysis of the tiltmeter data indicated that planar fractures dipping between 2° to 42° were induced in the subsurface during fracturing.

Data analysis of the hydraulic fractures indicated limited fluid leakoff during the fracturing process with nearly all the fluid remaining in the propped fractures.

Results of the analyses of the tiltmeter data are shown in map view in Appendix A and are summarized in Table 1.

UNITS, DEFINITIONS, AND SIGN CONVENTION FOR FRACTURE DESCRIPTION

Except where explicitly stated otherwise, the following units are used in this report:

Length – feet
Volume – cubic feet
Pressure – psi
Fracture angle – degrees
Tilt angle – microradians
RMS error – nanoradians
Normalized vector error – dimensionless

One microradian is the angle subtended by an arc of length 1 mm at a radius of 1 km.

RMS error is the root mean squared difference between observed and theoretical tilt vectors on completion of a non-robust chi-square optimization.

Normalized vector error is a normalized measure of the difference between the observed and theoretical tilt vectors. This error is normalized for comparison between analyses of different fracture models. A value less than 0.4 is considered a good fit of modeled to observed tilt, a value less than 0.3 is considered very good, and a value less than 0.2 is considered an excellent fit.

Each fracture is described by one or more rectangular dislocations with location and geometry specified as follow:

- The location in space is defined by the (x,y,z) coordinates of the mid-point of the rectangular fracture, where x and y are the magnetic eastings and northings with respect to the injection well, and z is the depth below ground surface.
- Fracture orientation is defined by azimuth and dip using the right hand rule, where azimuth is the direction of strike clockwise from magnetic north, and dip is the angle from horizontal at a right angle from the azimuth. For example, a fracture with an azimuth of 45° and a dip of 45° strikes northeast-southwest and dips to the southeast; a fracture with an azimuth of 225° and a dip of 45° strikes southwest-northeast and dips to the northwest.

Fracture geometry is specified by length along azimuth, width along the direction of dip, and thickness between the fracture faces.

SUMMARY OF THE TILTMETER MAPPING SYSTEM

Many subsurface processes result in small but measurable movements at the Earth's surface. The shape of these surface deformations will depend on the processes which caused them. Geo Tactical's tiltmeter mapping system measures these surface deformations, and a model is created of subsurface processes which caused the deformation.

Various man-made processes can result in measurable deformations at the Earth's surface. Long term processes such as production of oil and gas, or production of water from an aquifer, can result in subsidence of several feet over a period of years. Shorter term processes such as injection or production tests, or hydraulic fracturing produce correspondingly smaller deformations, but with suitably sensitive instrumentations these can be measured and analyzed.

The surface of the Earth is also continuously deforming due to natural processes. These include the tidal effects of the Sun and Moon, and thermal effects as the ground heats up during the day and cools down at night. While these effects are very small, they may be on a similar scale to the effects of the processes being monitored. However, the effects of these natural processes can be predicted and removed from data.

The process of hydraulic fracturing creates a dislocation in the subsurface with a characteristic deformation. A horizontal fracture (dip of 0°) causes an uplift or dome at the surface. A vertical fracture (dip of 90°) causes subsidence at the surface oriented along the azimuth of the fracture with a slight uplift outside the subsidence.

If a point on the Earth's surface is uplifted relative to another point, there will be a change in slope of the surface between the two points. The tiltmeter system continuously records changes in slope, or tilt. The change in tilt at a particular tiltmeter location is measured in two orthogonal directions, and the vector sum of these two measurements yields the magnitude and direction of the change in tilt at that location. The surface deformation due to a subsurface process may then be characterized by measuring the change in tilt an array of tiltmeter locations around an area of interest.

Numerical models and optimization schemes are then used to determine a best fit between observed and theoretical deformations.

DATA ACQUISITION

Tiltmeter data was collected to monitor six hydraulic fractures at one borehole at a field site in Camp Pendleton, California on August 23 and 24, 2016. An array of model 700 tiltmeters was deployed to monitor the fracturing. Tilt data was collected at a 10 second sample interval during the fracturing.

DATA QUALITY

Data quality was generally very good to excellent with high signal to noise ratios for each fracture.

DATA ANALYSIS

Four of the five analyzed fractures were modeled as single planar structures, and one as a conjugate. The results were optimized on the parameters for azimuth, dip, length, width, thickness, depth and offset from the borehole. The fit of the theoretical to observed tilt from the planar fracture models was excellent for three of the analyses, very good for one of the analyses, and good for the remaining one. Figure 1 shows the overall statistical distribution of the fit of theoretical to observed tilt.

Results of the analyses of the tiltmeter data are shown in map view in Appendix A and are summarized in Table 1.

DISCUSSION

Results of the tiltmeter analyses of all the fracturing are summarized in Table 1. Maps of the modeled fractures with real and theoretical tilt vectors for the fractures are shown in Appendix A. Analysis of the fracture parameters was based primarily on the tilt data.

Analyses of the tiltmeter data indicated planar fractures dipping from sub-horizontal to 42° from horizontal. Out of the six planar structures, two of them had dips less than 10°, two had dips between 20° and 30°, one had a dip between 30° and 40°, and one between 40° and 50°. The overall statistical distribution of fracture dip is shown in Figure 2.

Data analysis generally showed a limited range in fluid leakoff during the fracturing with the majority of the analyses showing fracture efficiencies greater than 95%. Fracture efficiency for the individual fracture analyses are shown on the plots in Appendix A.

TABLE 1
Tiltmeter Results Summary

Fracture I.D.	Date	Azimuth (deg)	Dip (deg)	Thickness (ft)	Width (ft)	Length (ft)	Z (ft)	Vector Error	RMS Error (nRad)	Modeled Frac Volume (ft^3)	X (ft)	Y (ft)
HIW-01-1	23-Aug	38	42	0.028	20.0	20.0	50.0	0.218	1.90E+04	11.2	0	0
HIW-01-1 (conjugate)	23-Aug	269	37	0.023	24.0	30.0	50.0	0.218	1.90E+04	16.6	0	0
HIW-01-2b	23-Aug	313	22	0.037	30.0	70.0	40.0	0.301	1.16E+05	77.7	-22.0	14.6
HIW-01-4	23-Aug	50	6	0.030	34.5	75.0	40.0	0.190	8.31E+04	77.6	32.8	17.2
HIW-01-5	24-Aug	282	2	0.0357	30.0	75.0	37.8	0.128	7.48E+04	80.3	16.8	-6.1
HIW-01-6	24-Aug	106	26	0.025	33.6	87.7	28.2	0.108	6.95E+04	73.7	15.3	-6.3

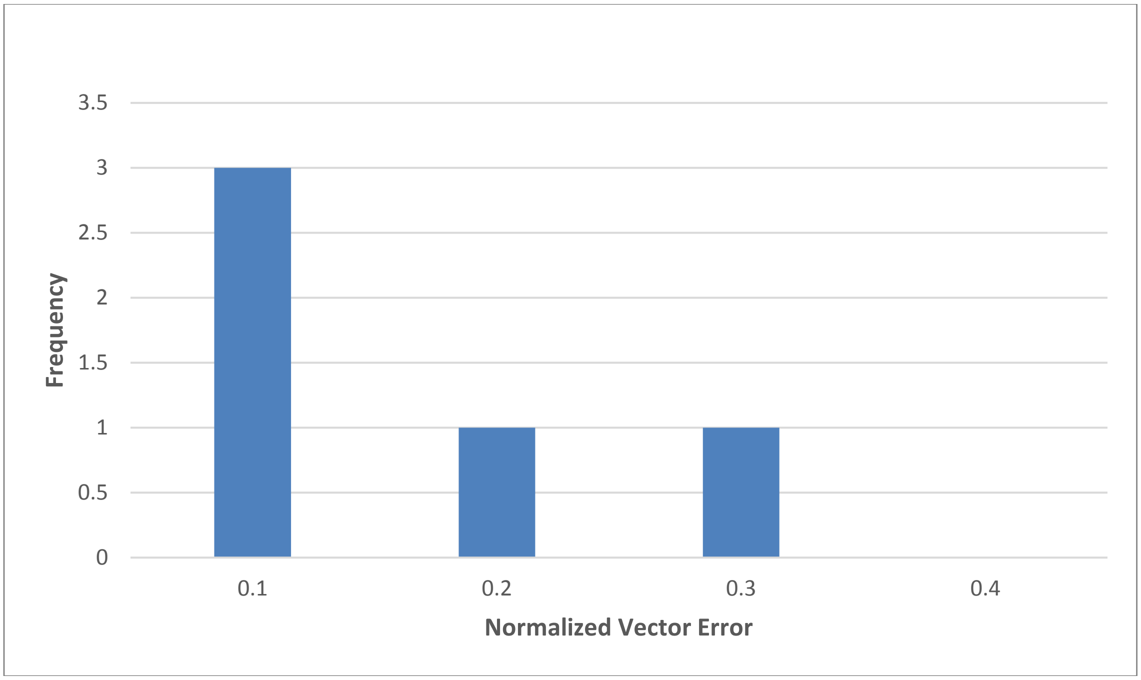


Figure 1 – Statistical Distribution of Normalized Vector Error

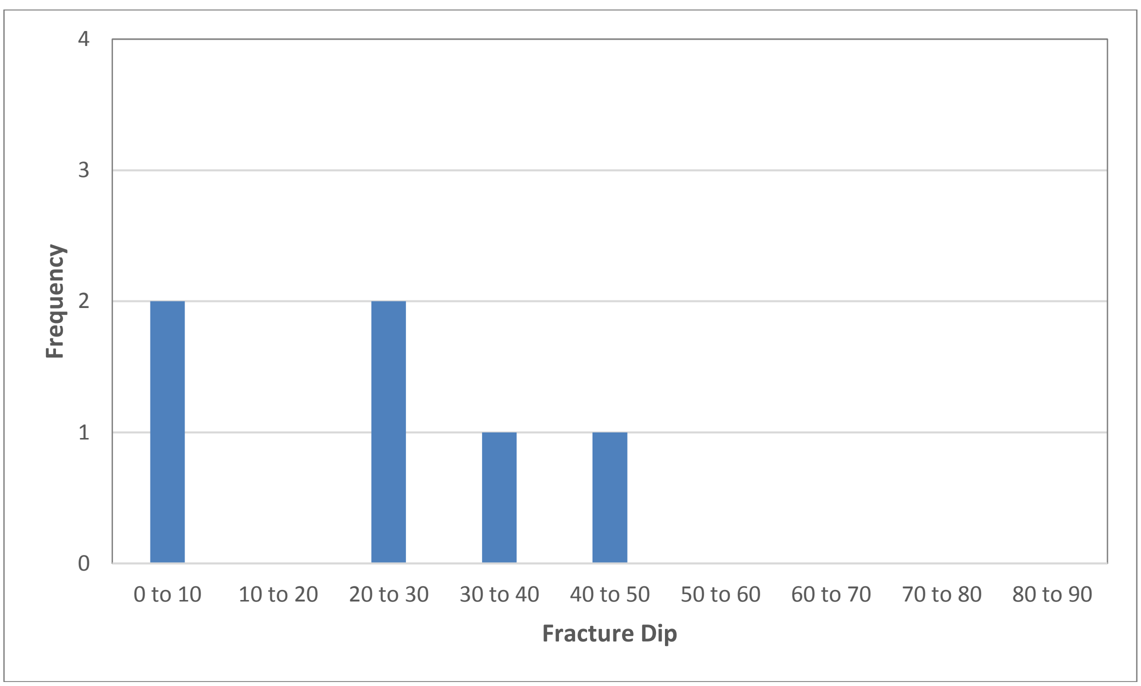
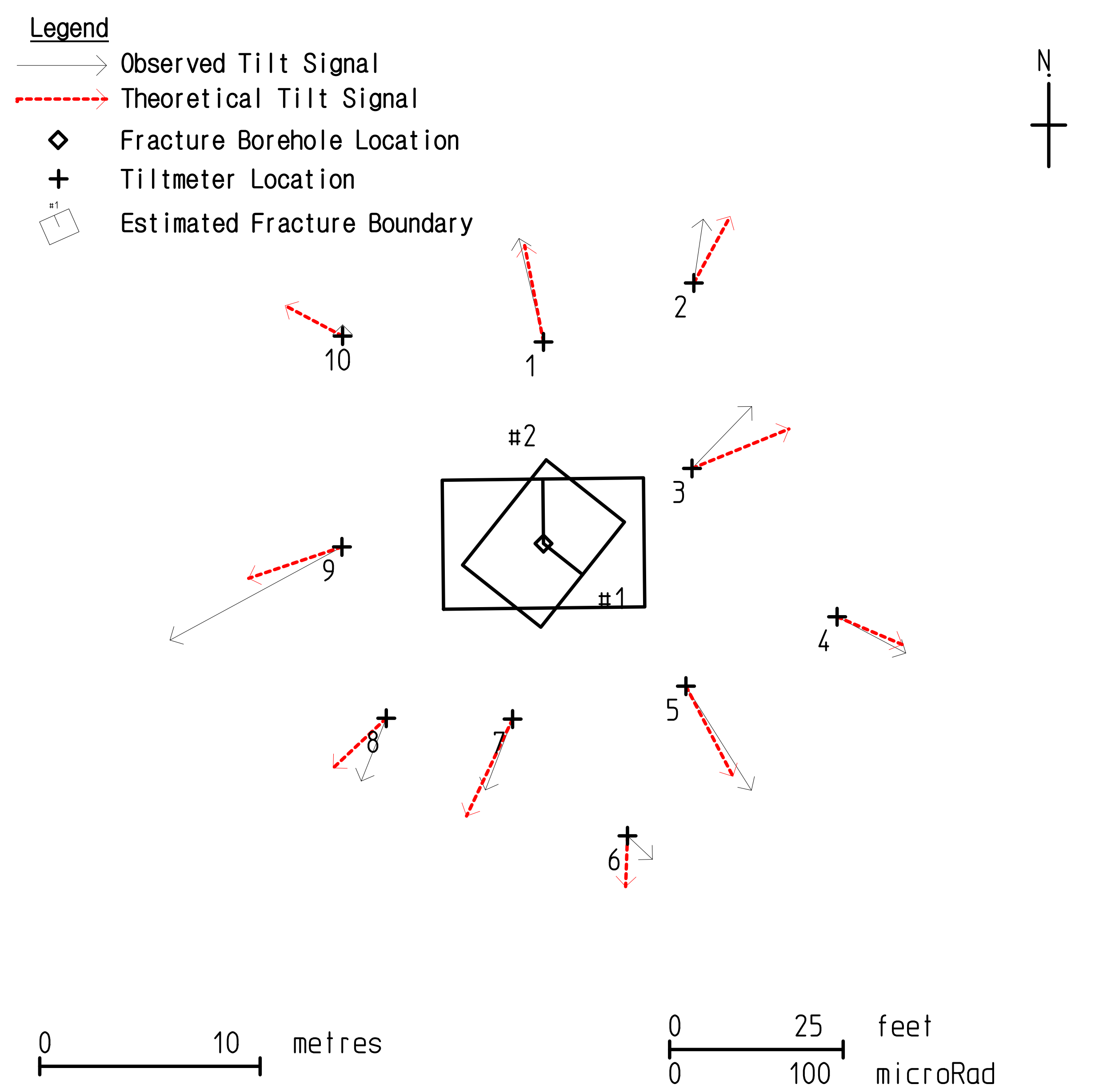


Figure 2 – Statistical Distribution of Fracture Dip

APPENDIX A

TILTMETER RESULTS IN MAP VIEW

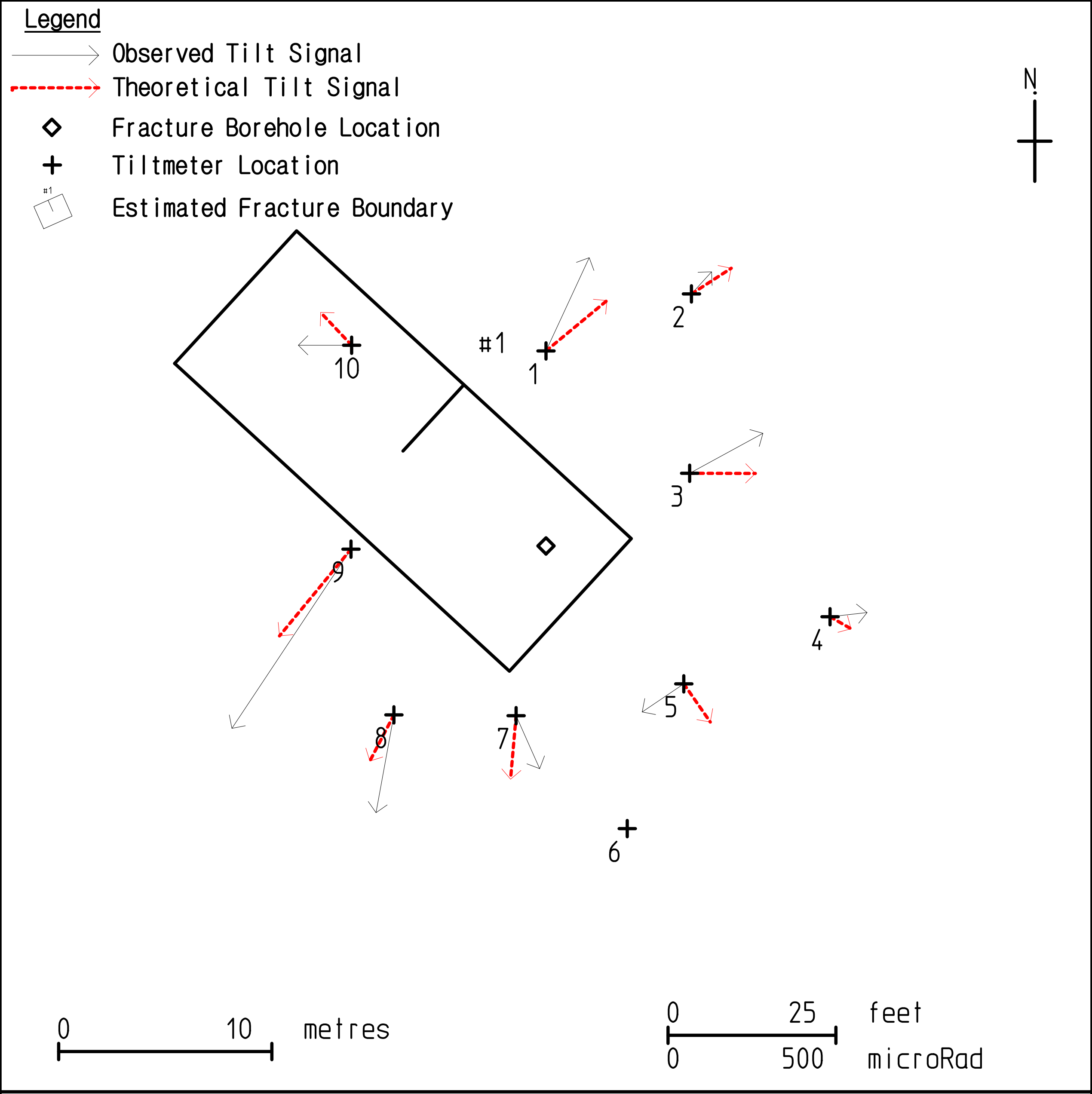


WELL: HIW-01-1
DATE: 8/23/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	38	42	50		2	
2	269	37	50		3	
			TOTAL	5.02	5	98%

Frac 1: Length = 20.0 ft, Width = 20.0 ft, Thickness = 0.028 ft
Frac 2: Length = 30.0 ft, Width = 24.0 ft, Thickness = 0.023 ft
Normalized Vector Error = 0.218, RMS Error = 1.90E04 nRad

Geo Tactical 2017

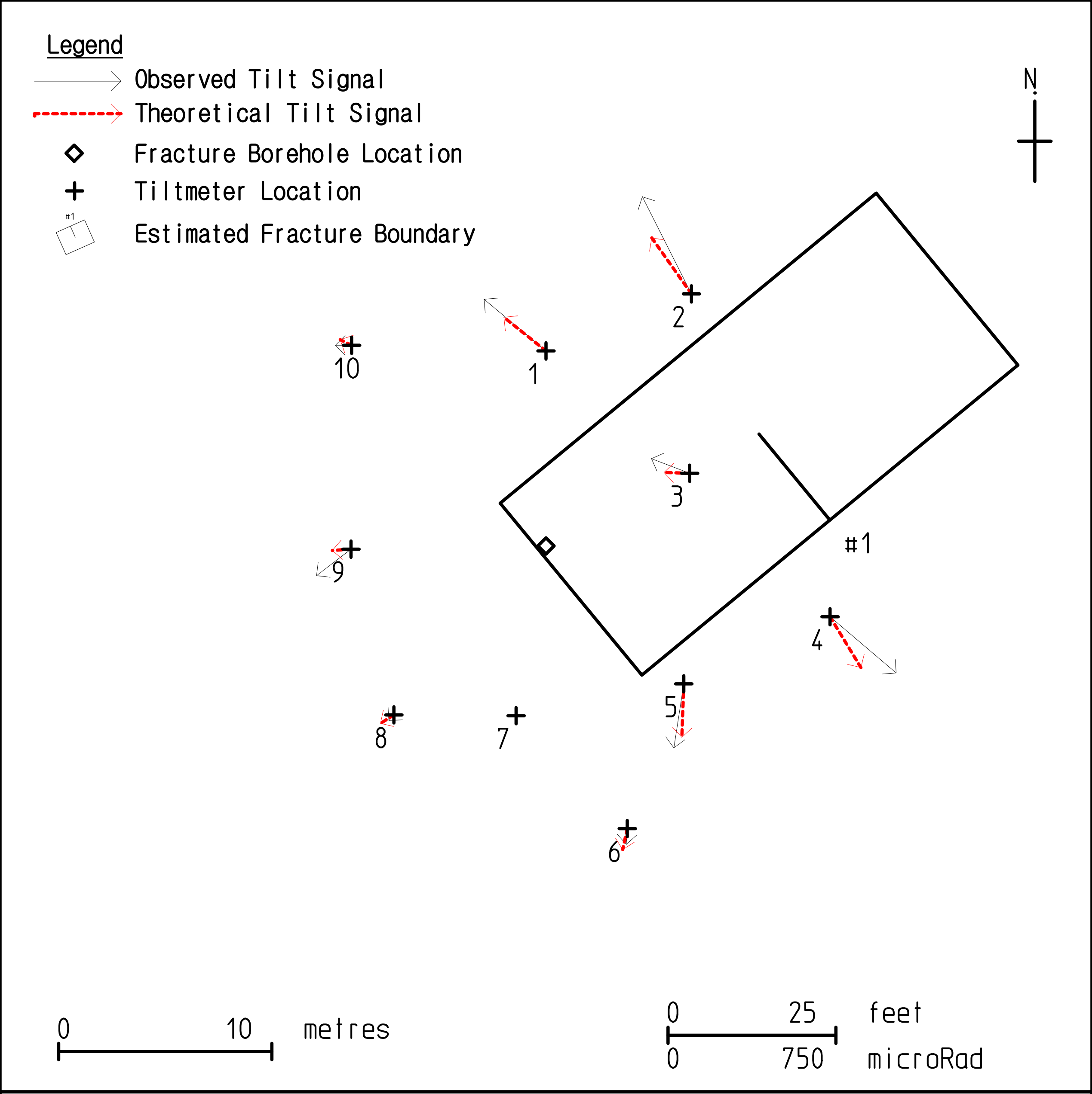


WELL: HIW-01-2b
DATE: 8/23/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	313	22	42	13.83	14	100%

Length = 70.0 ft, Width = 30.0 ft, Thickness = 0.037 ft
Normalized Vector Error = 0.301, RMS Error = 1.16E05 nRad

Geo Tactical 2017

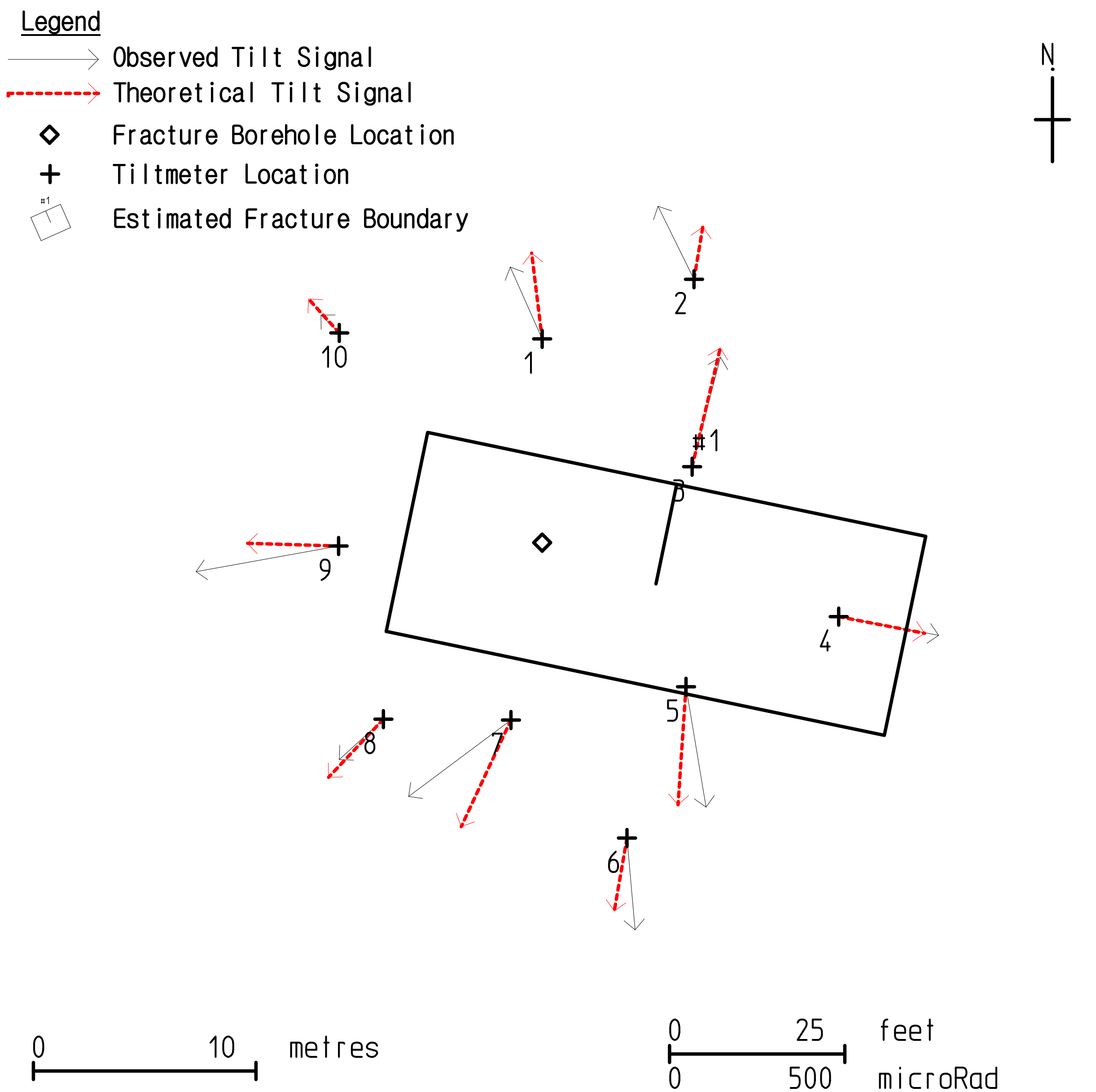


WELL: HIW-01-4
DATE: 8/23/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	50	6	40	13.83	14	100%

Length = 75.0 ft, Width = 34.5 ft, Thickness = 0.030 ft
Normalized Vector Error = 0.190, RMS Error = 8.31E04 nRad

Geo Tactical 2017

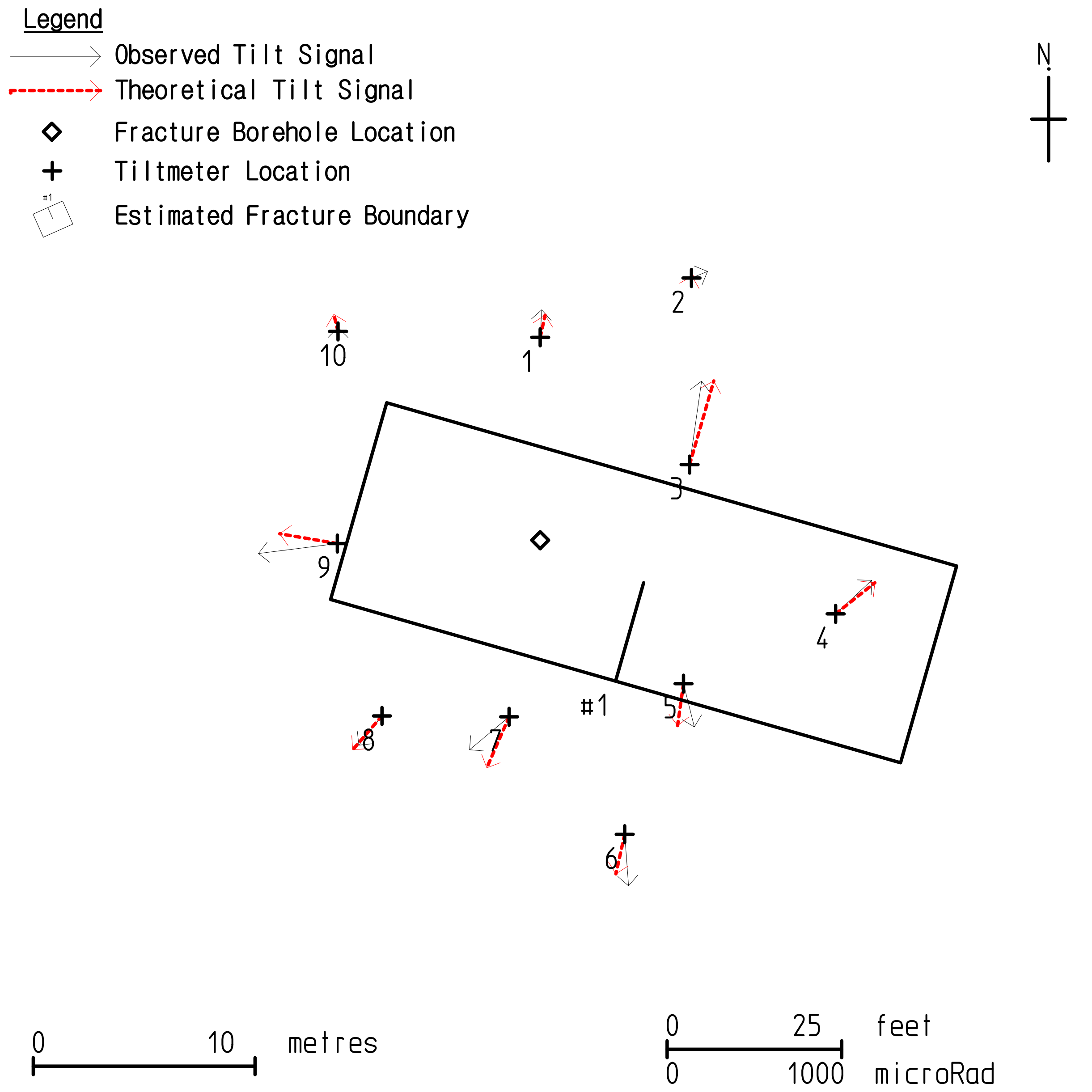


WELL: HIW-01-5
DATE: 8/24/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	282	2	37.8	14.31	14	100%

Length = 75.0 ft, Width = 30.0 ft, Thickness = 0.0357 ft
Normalized Vector Error = 0.128, RMS Error = 7.48E04 nRad

Geo Tactical 2017



WELL: HIW-01-6
DATE: 8/24/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	106	26	28.2	13.83	13	95%

Length = 87.7 ft; Width = 33.6 ft; Thickness = 0.025 ft
Normalized Vector Error = 0.108; RMS Error = 6.95E04 nRad

Geo Tactical 2017

APPENDIX III

SUBSURFACE DISTRIBUTION OF SAND FRACTURES

Fracture Borehole at Camp Pendleton Site

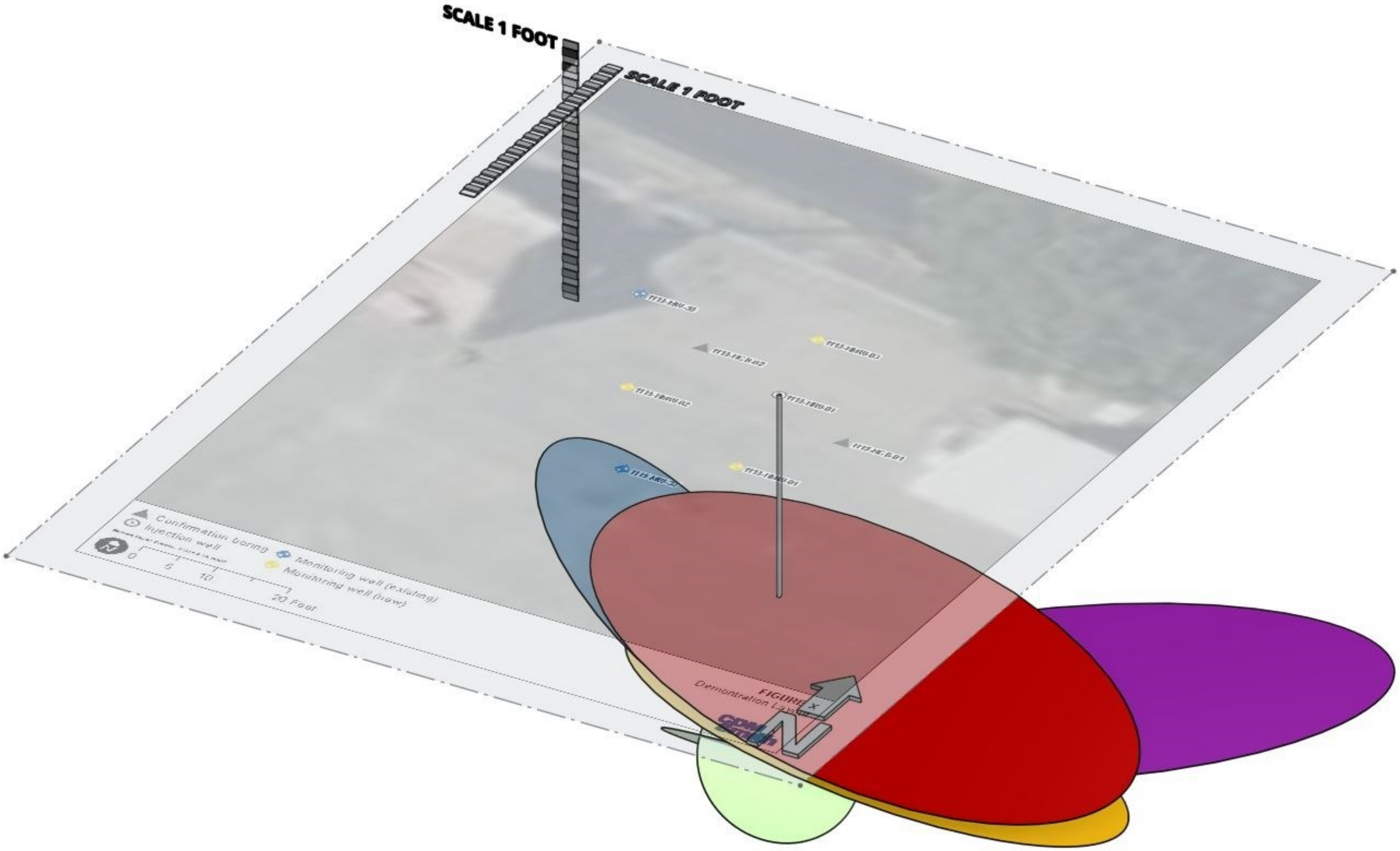


Figure III-1

Three dimensional representation of sand proppant distribution in the subsurface at the site

GeoTactical Remediation

Fracture Borehole HIW-01

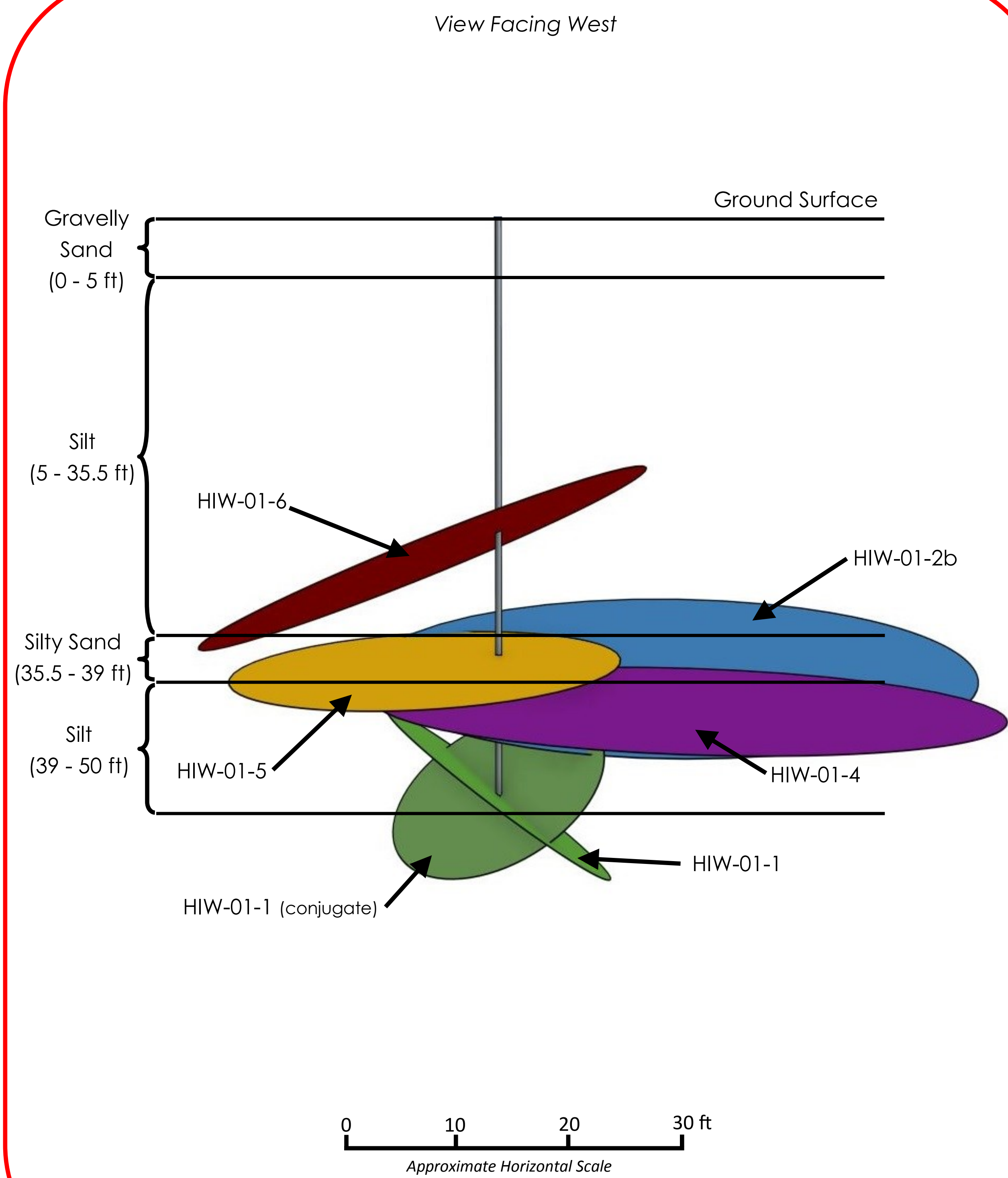


Figure III-2

Three dimensional representation of sand proppant distribution in the subsurface at HIW-01

GeoTactical Remediation

Report on the Emplacement of LactOil® using Environmental Hydraulic Fracturing

Grand Forks Air Force Base
Site TU504
Grand Forks, North Dakota

Prepared for:
CDM Federal Programs Corporation

Prepared by:
Geo Tactical Remediation Ltd.

On Behalf of:
Frac Rite Remediation Inc.

September 2017 **J1610**

Report on the Emplacement of LactOil® using Environmental Hydraulic Fracturing

Grand Forks Air Force Base
Site TU504
Grand Forks, North Dakota

September 2017

Prepared for:
CDM Federal Programs Corporation
3201 Jermantown Road
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Prepared by:
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T2E 7C3

On Behalf of:
Frac Rite Remediation Inc.

Subcontract No. 6446-001-005-SI
J1610

Executive Summary

Geo Tactical Remediation Ltd. was retained by Frac Rite Remediation Inc. on behalf of CDM Federal Programs Corporation (CDM) to emplace a remediation amendment using environmental hydraulic fracturing techniques at the Grand Forks Air Force Base Site TU504. The work was a part of the Environmental Security Technology Certification Program (ESTCP).

ESTCP Project Number ER-201430 involves the demonstration and validation of hydraulic and pneumatic fracturing technologies to enhance the delivery of remediation amendments to low permeability zones and using tiltmeter monitoring technology to quantify the emplaced fracture networks (CDM ESTCP ER-201430 Draft plan May 2015).

The work consisted of fracture emplacing LactOil® into the clay soils underlying the site. The fractures were mapped with tiltmeter monitoring technology. The program was conducted on September 14 and 15, 2016 according to the design and scope of work developed by CDM.

A total of 13 individual LactOil® fractures were successfully initiated and propagated from four fracture borehole locations. Fracture initiation depths ranged from 12 to 20 ft bgs. The total volume of LactOil® solution emplaced was approximately 1,540 gal and contained approximately 107 gal of LactOil®. This was 98% of the total LactOil® design volume.

Analysis of operational pressure-time data and tiltmeter data indicated that that the mode of LactOil® emplacement into subsurface soils was by hydraulic fracturing which created discrete planar features at each depth.

Minor fluid surfacing occurred while pumping at eight of the thirteen fracture depths. All fluid surfacing occurred away from the borehole. Fluid does not typically surface at fracture boreholes in silt or clay soils when implementing a planned fracture emplacement program using fracture specific downhole tooling.

Table of Contents

1.0 Introduction

Geo Tactical Remediation Ltd. (Geo Tactical) was retained by Frac Rite Remediation Ltd. (Frac Rite) on behalf of CDM Federal Programs Corporation (CDM) to emplace a remediation amendment using environmental hydraulic fracturing techniques at the Grand Forks Air Force Base Site TU504. The work was a part of the Environmental Security Technology Certification Program (ESTCP).

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The work consisted of fracture emplacing LactOil® into the clay soils underlying the site. The fractures were mapped with tiltmeter monitoring technology. The program was conducted on September 14 and 15, 2016 according to the design and scope of work developed by CDM.

2.0 Background

The Grand Forks Air Force Base (GFAFB) Site TU504 is located 12 miles west of Grand Forks, North Dakota (Figure 1). It was historically used as an Air Defense Command base that housed KC-135 Stratotankers, B-52 bombers, and B-1B bombers. The area selected for this demonstration is located in the central portion of the base (Figure 2). (CDM Smith 2015)

The base lies on interbedded lacustrine and glacial units, which were deposited during interglacial and glacial periods (EA Engineering, Science, and Technologies Inc.). The shallow soil contains a pale brown coarse sand and silty clay fill, which ranges from 2.5 to 6 ft thick. Below this lies a till unit of brown and gray mottled silty clay with decayed vegetation between 15 and 40 ft thick. Below this is a gray clay unit containing gravel and cobbles, which ranges in thickness from 25 to 58 ft. This is followed by a gray silty clay unit approximately 16 to 32 ft thick. Underlying these soils is the Emerado Sand, a gray sand unit approximately 30 ft thick. The interval targeted for the environmental fracturing technology demonstration lies within the clay zone extending from 3 to 30 ft below ground surface (bgs). (CDM Smith 2015)

In 1996 a petroleum odor was detected in soils removed from an excavated water line. Subsequent analysis of compounds in the site soil and groundwater included detections of JP-4 fuel, hydraulic fluid, engine oil, solvents, TCE, and methyl-ethyl-ketone. A Resource Conservation and Recovery Act Facility Investigation was conducted in 1999 and found VOC and TPH above EPA maximum contaminant levels (MCLs) for soil and groundwater. In 2000 and 2001, a Phase II Resource Conservation and Recovery Act Facility Investigation completed the horizontal and vertical delineation of the TU504 area plume. This Phase II activity also found other VOCs above MCLs, and determined that the soil contamination extended to a depth of 10 feet. (CDM Smith 2015)

3.0 Objective

The overall objective of this project was to:

- Demonstrate the amendment distribution capabilities of environmental hydraulic fracturing in low permeability soils.
- Demonstrate and validate the use of tiltmeter monitoring as a high-resolution, and non-invasive mapping technique to aid in evaluating the performance of environmental fracturing.

4.0 Field Program

4.1 Fracturing Field Implementation

Fracture emplacement of a LactOil® solution commenced on the site on September 14, 2016. Geo Tactical's EFI2000 mixing and pumping unit and downhole fracturing equipment was used to complete the program (Photo 1).

Drilling services were provided by Plains Environmental Services (Plains) based in Salina, KS. Drilling was completed using a 7822DT direct push drill rig (Photo 2).

The LactOil® solution was batch mixed in remote poly tanks by adding approximately 8 gal of LactOil® to 122 gal of potable water (Photo 3). CDM then added fluorescein and potassium chloride to the solution as part of the distribution verification.

The fracturing process began with Plains Environmental Services (Plains) driving Geo Tactical's direct push fracture tooling to the first fracture initiation depth. The LactOil® solution was then pumped from the EFI2000, downhole through the rods and propagated away from the borehole until the pre-determined volume was emplaced, or fluid surfacing occurred. When the pumping ceased, the rods were advanced to the next desired depth and the process repeated until fracture initiation and propagation at the bottom depth were completed. This method is the top down approach and ensures that discrete fractures are emplaced at each depth. This is completed by isolating each subsequent depth from the one above by maintaining a seal around the rods and downhole tooling. The downhole tooling used is specifically designed for fracturing and is designed to maintain the borehole seal at fracture initiation pressures.

Upon completion of a borehole, the rods and tooling were moved to the next borehole, where the entire process was repeated.

During all pumping events at the site, pumping pressure and flow rate data were monitored and recorded to help verify the mode of LactOil® solution emplacement in the subsurface.

4.2 Mapping of Subsurface Fractures

Tiltmeter geophysics was used to map the distribution of LactOil® emplaced by fracturing at the site. The tiltmeter mapping helps verify the final LactOil® distribution in the subsurface.

Prior to pumping the fractures, ten biaxial ES model 700 tiltmeter sensors were placed in two concentric circular arrays (inner and outer) around the fracture borehole location (Photo 4) to monitor the micro-movements in the ground surface in response to each fracturing event. The radial distance of the tiltmeters in the inner array was approximately 10 ft and the outer array 15ft.

Tiltmeters were set on prepared locations and leveled to read a tilt angle of approximately zero degrees. During each hydraulic fracturing event, signal data was collected and stored in the memory modules of dataloggers at a collection frequency of 1 tilt data signal every 10 seconds. Upon the completion of fracturing at each depth interval, the tiltmeter sensors were leveled again in preparation for the next fracturing event. This process was repeated until all fractures at the borehole were completed.

Geophysical data were analyzed using inverse parameter modeling to determine fracture geometry (modeled as planar disc features) defined by length, width, thickness, asymmetry, orientation, and angle of ascent from horizontal (measured in degrees). The fracture plots were correlated with operational fracturing data (pressure and flow vs. time plots) and transformed into three dimensional, dynamic computer graphics.

5.0 Results

5.1 LactOil® Fracturing

The LactOil® fracturing program was conducted on September 14 and 15, 2016. A total of 13 individual LactOil® fractures were successfully initiated and propagated from four fracture borehole locations at the site (Figure 3). Fracture initiation depths ranged from 12 to 20 ft bgs. The total volume of LactOil® solution emplaced was approximately 1,540 gal and contained approximately 107 gal of LactOil®. All the fracture boreholes were completed using top down direct push drilling.

Table 5-1 shows the summary results of the LactOil® emplacement at each of the boreholes, details for each fracture are presented in Table 1 attached.

TABLE 5-1
Summary of Fracture Emplacement Results

Borehole I.D.	Fracture Depth Range (ft)	Number of Fracture Depths	Solution Volume Emplaced (gal)	Volume LactOil® Emplaced (gal)
HIP-01	12 – 18	3	367	23
HIP-02	12 – 20	4	380	23
HIP-03	12 – 18	3	390	24
HIP-04	12 – 18	3	405	37
SITE TOTAL		**13**	**1,542**	**107**

Notes:
1. CDM also added fluorescein and potassium chloride to the solution as part of distribution verification.
2. Concentration of LactOil® was approximately 6.15% [volume of LactOil® to volume of solution].
3. At HIP-01 five pumping events occurred at the three fracture depths.

A limited amount of fluid surfacing occurred at the site. A total of approximately 38 gal of LactOil® solution was lost to surface while pumping at HIP-01, HIP-02, and HIP-04. At HIP-01 fluid surfacing occurred at several spots 3 to 10 ft north and northeast of the borehole. Fluid surfacing also occurred from MW15 and MW17 during the last fracture (Photo 5). At HIP-02 fluid surfacing occurred at several spots 3 to 10 ft west and northwest of the borehole. At HIP-04 fluid surfacing occurred only during the last fracture approximately 10 ft west of the borehole. All fluid surfacing was remote and did not occur at the fracture borehole locations. The volume of fluid that surfaced was approximately 2% of the total volume pumped into the subsurface.

Analysis of operational pressure-time curve and flow rate data (Appendix I) indicated that average pressures for initiating LactOil® fractures (i.e. "Break Pressures"), including pressure required to overcome friction losses, ranged from 65 to 217 psi. The average propagation pressure during extension of the fracture away from borehole ranged from 53 to 114 psi with an average pump rate from 13 to 15 gal/min. Pressure time curves with fracture summary sheets are depicted in Appendix I.

5.2 Tiltmeter Mapping Results

Twelve fractures (each individual pumping event was mapped as a separate fracture) from three borehole locations were mapped using tiltmeter geophysics. The size and orientation of the fractures are summarized in Table 5-2 below. A more detailed report of the tiltmeter analysis is included in Appendix II and graphical depictions of the fractures in Appendix III.

Table 5-2
Summary of Tiltmeter Geophysical Results

Fracture I.D.	Depth of Fracture Initiation[1] (ft)	Fracture Thickness (inches)	Fracture Width[2] (ft)	Fracture Length[3] (ft)	Fracture Azimuth[4] (°)	Fracture Dip Angle[5] (°)
HIP-01-1	12	0.12	10.9	13.9	246	6
HIP-01-2a	15	0.19	10.0	16.5	255	17
HIP-01-2b	15	0.20	15.0	20.5	265	23
HIP-01-3a	18	0.48	7.7	12.3	228	2
HIP-01-3b	18	0.48	15.0	25.0	35	5
HIP-02-1	12	0.20	18.5	12.9	156	46
HIP-02-2	15	0.40	20.3	8.0	179	33
HIP-02-3	18	0.60	12.0	26.8	103	17
HIP-02-4	20	0.12	47.8	18.1	170	43
HIP-04-1	12	0.36	26.7	16.9	65	52
HIP-04-2	15	0.48	17.0	25.0	119	35
HIP-04-3	18	0.73	15.6	20.3	52	34

Notes: 1. Depth measured from ground surface to ports on fracture tool.
2. Width – fracture dimension measured along dip.
3. Length – fracture dimension measured along azimuth.
4. Fracture Azimuth – describes the compass bearing when looking along a line perpendicular to dip direction (strike), with the fracture dipping down to right.
5. Dip Angle – Angle of fracture inclination from horizontal.

The twelve pumping events were modeled as single planar structures. Fractures may be more complex than interpreted due to effects that include: leak off into more permeable or naturally occurring fractures in bedrock or soils encountered, fluid losses through existing subsurface disturbances (e.g. existing boreholes, excavations, etc.), and possible excessive curvatures of fractures emplaced.

In general, the modeled fracture thickness of the hydraulic fractures during propagation ranged from 0.12 inches at HIP-01-1 and HIP-02-4 to 0.73 inches at HIP-04-3, with an average thickness during pumping of 0.36 inches.

The width of fractures was compared to their length to determine the average fracture aspect ratio. At HIP-01 the average width of fractures was 12 ft and the average length was 18 ft. Thus, the average aspect ratio was under 1.0, meaning that the dimension along dip is shorter than the dimension along azimuth. At HIP-02 the average width of fractures was 25 ft and the average length was 16 ft. Thus, the average aspect ratio was above 1.0, meaning that the dimension along dip is larger than the dimension along azimuth. At HIP-04 the average width of fractures was 20 ft and the average length was 21 ft. Thus, the average aspect ratio was just under 1.0, meaning that the dimension along dip is slightly shorter than the dimension along azimuth. Fractures generally have some component of asymmetry, and fracture aspect ratios greater or less than 1.0 are common.

The five fractures at HIP-01 dipped at 23° or less, the four fractures at HIP-02 dipped between 17° and 46°, and the three fractures at HIP-04 dipped between 34° and 52°.
The bottom two fracture depths at HIP-01 (HIP-01-2 and HIP-01-3) had two pumping events at each depth. Each pumping event was modeled as a separate fracture. The two fractures modeled for HIP-01-2 have similar results for thickness, dip angle, and azimuth. The results for thickness and dip for the two fractures at HIP-01-3 were similar, the orientation was also similar although the azimuths differed by approximately 180°. The width was also smaller than the length for all four fractures.

6.0 Discussion

Analysis of operational pressure-time data indicate that the mode of LactOil® emplacement into subsurface soils was by hydraulic fracturing, with 13 fractures initiated and propagated from four boreholes.

Hydraulic fracturing emplacement as the mode of emplacement is further supported by analysis of the tiltmeter data collected during twelve of the pumping events. These twelve pumping events were modelled as planar features as is consistent with hydraulic fractures. Tiltmeter field data was regarded as very good to excellent providing modeling results that were generally of excellent quality.

Minor fluid surfacing occurred while pumping at eight of the thirteen fracture depths. All fluid surfacing occurred away from the borehole. This is likely because discrete fractures were initiated at each depth interval. Then and as the fractures propagated away from the boreholes they may have intersected a natural pathway or previous site disturbance such as an abandoned borehole. Some of the fracture fluid would then have travelled through these pathways to the surface. The tiltmeter analysis shows only one fracture intersecting ground level providing further indication that fluid surfacing generally resulted from secondary pathways existing in the subsurface prior to fracturing.

No fluid surfacing occurred directly from the fracture boreholes. Fluid does not typically surface at fracture boreholes in silt or clay soils when implementing a planned fracture emplacement program using fracture specific downhole tooling.

3D modeling from tiltmeter analysis shows good fracture coverage of the target zone. Only one instance of a fracture connecting with a fracture from another borehole is seen in the 3D model, therefore direct contact between fracture boreholes is limited. There is overlap of fractures in plan view and it is expected that this overlap and diffusion of LactOil® from the fractures will result in good distribution across the treatment zone.

Two pumping events were done at the middle depth (HIP-01-1a, HIP-01-1b) and the lowest depth (HIP-01-3a, HIP-01-3b) of fracture borehole HIP-01. Tiltmeter data analysis and pressure-time data indicate that in both instances the second pumping event propagated the fracture created by the first pumping event.

7.0 Conclusions

The following conclusions were made based on: observations made in the field, analysis of tiltmeter data, and analysis of pressure/pump rate data.

- 107 gal of LactOil® (98% of the total design volume of 110 gal of LactOil®) was distributed into the soils from four borehole locations.
- The mode of emplacement was hydraulic fracturing.
- Good vertical and lateral extent of the LactOil® fracture network was achieved across the target interval. The fracture network is expected to provide significant contact with the chlorinated hydrocarbons present in the soil and groundwater.
- Implementing a program of planned hydraulic fracture emplacement using downhole tooling specifically for hydraulic fracturing resulted in effective distribution of LactOil® without occurrences of fluid surfacing at the emplacement boreholes.

8.0 Closure

This report has been prepared by Geo Tactical Remediation Ltd. in a manner consistent with that level of skill and care ordinarily exercised by members of the engineering profession currently practicing under similar conditions. No other warranty, expressed or implied is made.

Geo Tactical guarantees that the quality of its work is of the highest standard using best available technology, but does not warrant or guarantee the long-term success of enhanced *in situ* remediation using LactOil®, or any other treatment amendment provided by third party vendors. Geo Tactical has created a network of subsurface fractures radiating from the borehole into surrounding sediments; however, CDM Federal Programs Corporation. understands that these fractures cannot be "steered" or manipulated to assume any particular geometry or orientation. The fractures propagate in a manner determined by the *in situ* stress conditions and fabric of subsurface soils and bedrock.

We trust that this report meets your satisfaction. Should you have any questions or concerns, then please feel welcome to contact us. Thank you for the opportunity to work with CDM Federal Programs Corporation on this innovative remedial project.

Yours truly,
Geo Tactical Remediation Ltd.

Heather A. Sturm, P.Eng.
Environmental Engineer

Gordon T. Guest, P.Geol.
Principal

9.0 References

CDM Smith Inc. May 2015. Draft Technology Demonstration Plan, A Rigorous Demonstration of Environmental Fracturing in Low Permeability Media, ESTCP Project Number ER-201430

EA Engineering, Science, and Technologies Inc. March 2010. 2009 Annual Long-Term Monitoring Program Report, Area of Concern 539, Grand Forks Air Force Base.

FIGURES

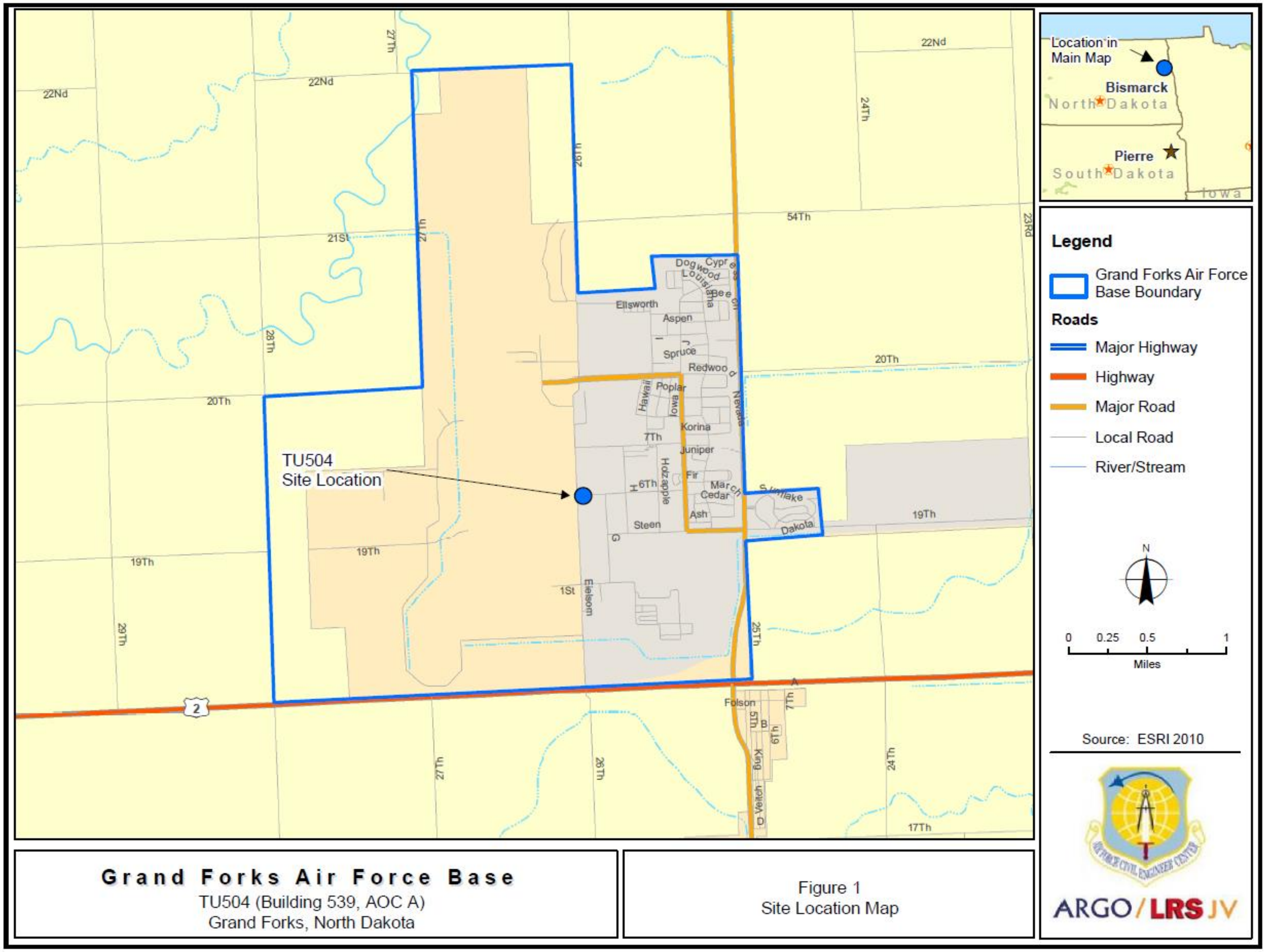


Figure 1 – Site Location Map

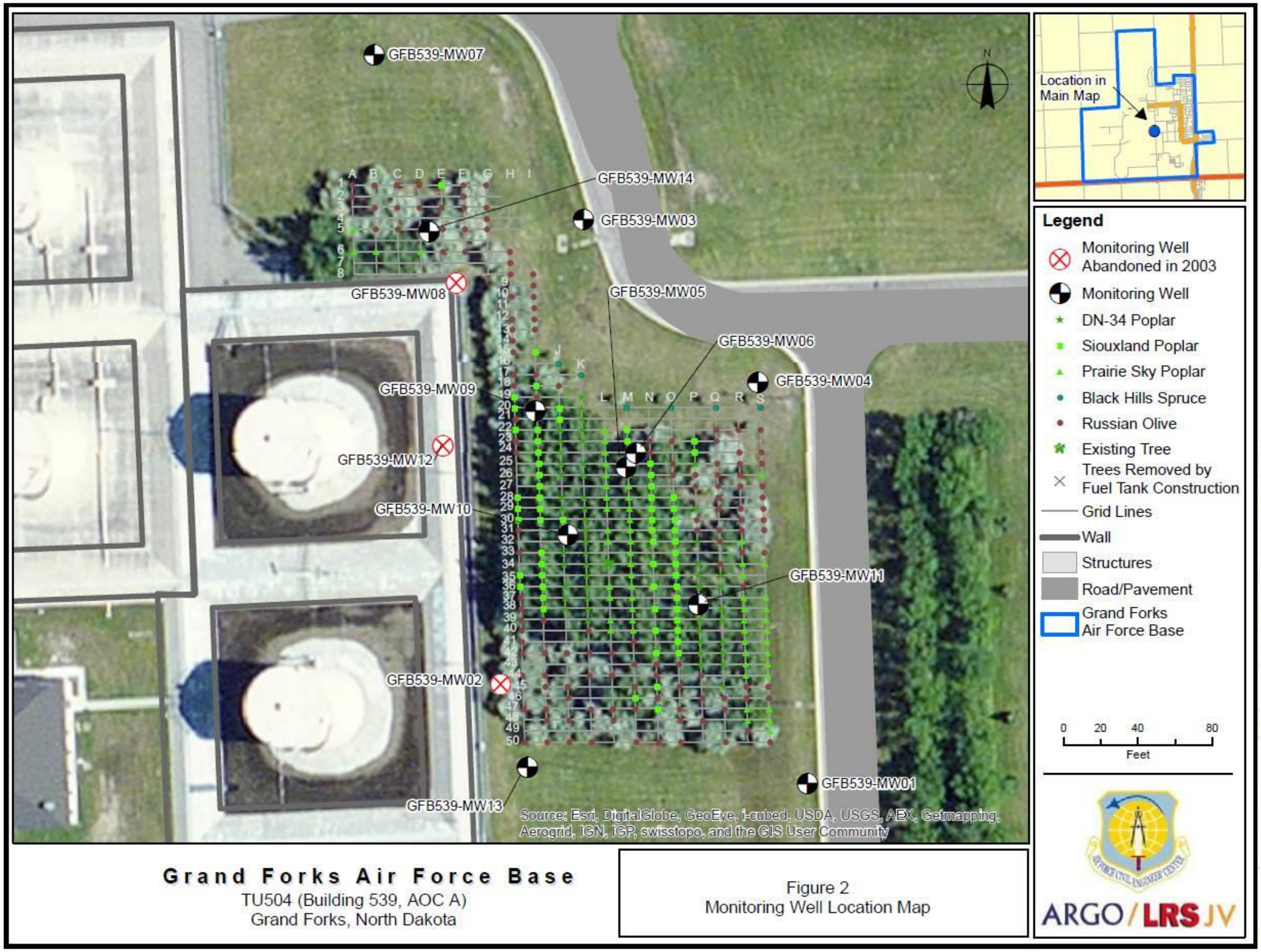


Figure 2 – Site Plan

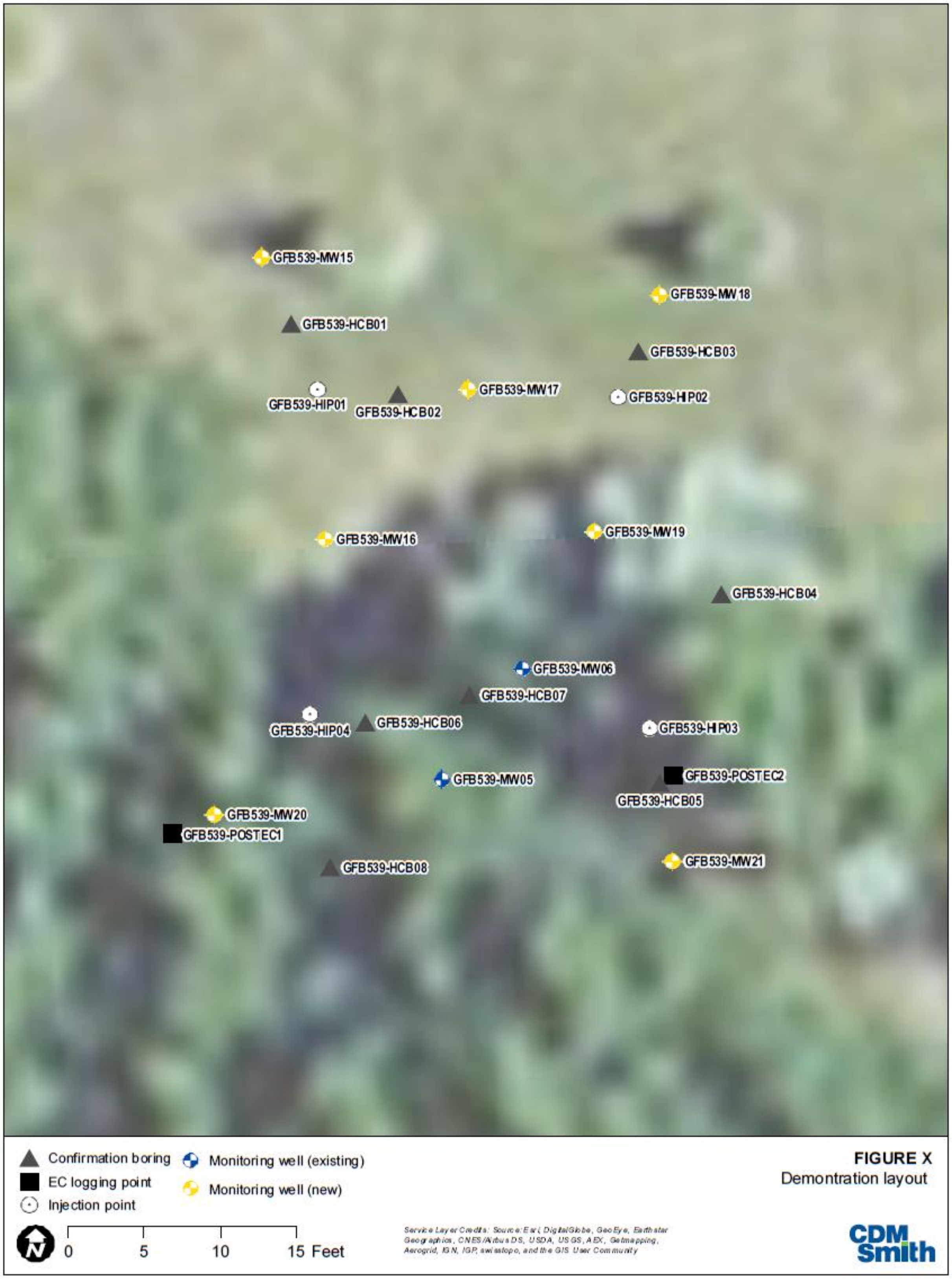


Figure 3 – Borehole Location Map

TABLES

TABLE 1
Summary of Fracture Emplacement Results

Fracture Borehole	*Fracture I.D.*	*Depth (ft bgs)*	*Solution Volume Pumped (gal)*	*LactOil ®* Volume Pumped *(gal)*	*Fluid Surfacing Volume (gal)*	*Solution Volume Emplaced (gal)*	*LactOil ®* Volume Emplaced *(gal)*	Emplacement Efficiency (%)
HIP-01	HIP-01-1	12	85	5.25	3	82	5.0	96
	HIP-01-2	15	140	8.50	13	127	7.75	91
	HIP-01-3	18	165	10.25	7	158	9.75	96
HIP-02	HIP-02-1	12	80	5	4	76	4.75	95
	HIP-02-2	15	50	3	1	49	3.0	98
	HIP-02-3	18	130	8	4	126	7.75	97
	HIP-02-4	20	130	8	1	129	8.0	99
HIP-03	HIP-03-1	12	130	8	0	130	8.0	100
	HIP-03-2	15	130	8	0	130	8.0	100
	HIP-03-3	18	130	8	0	130	8.0	100
HIP-04	HIP-04-1	12	130	8	0	130	8.0	100
	HIP-04-2	15	130	8	0	130	8.0	100
	HIP-04-3	18	150	22	5	145	21.25	97
		TOTAL	***1,580***	***110***	***38***	***1,542***	***107.25***	***98***

Notes:

bgs below ground surface

CDM also added fluorescein and potassium chloride to the solution as part of distribution verification.

Concentration of LactOil® was approximately 6.15% [volume of LactOil® to volume of solution].

SITE PHOTOGRAPHS

Photo 1 – EFI2000 Mixing and Pumping Unit with Ancillaries

Photo 2 – Plain's Track Mounted Direct Push Drilling Rig

Photo 3 – Adding Potable Water to the Mixing Tank Prior to Adding LactOil®

Photo 4 – Tiltmeters Placed Around HIP-01

Photo 5 – Fluid Surfacing from MW17

APPENDIX I

PRESSURE TIME CURVES AND FRACTURE SUMMARY SHEETS

FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1610 DATE: September 14, 2016

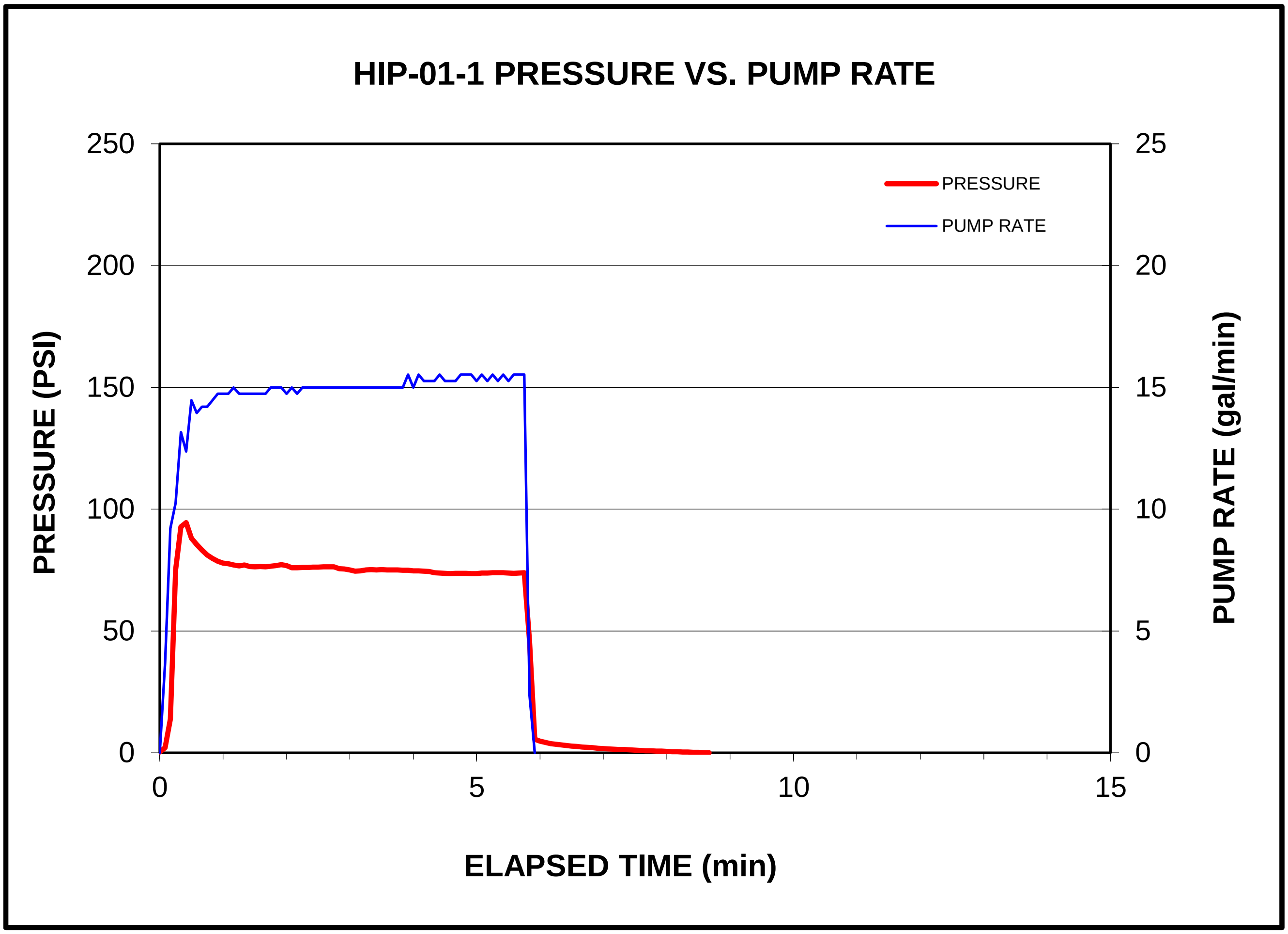
FRACTURE BOREHOLE ID: HIP-01

FRACTURE ID:	HIP-01-1	HIP-01-2	HIP-01-3
DEPTH (ft.)	12.0	15.0	18.0
SOIL TYPE	Silty Clay	Clay	Clay
AMENDMENT TYPE	LactOil®	LactOil®	LactOil®
SOLUTION VOLUME PUMPED (gal)	85	140	165
AMENDMENT VOLUME PUMPED (gal)	5	9	10
SOLUTION CONCENTRATION (%)	6.0	6.0	6.0
VENT/LOSS (gal)	3	13	7
VENT/LOSS TYPE	Remote	Remote	Remote
PLACEMENT EFFICY. (%)	96.5	90.7	95.8
AMENDMENT VOLUME EMPLACED (gal)	5	8	10
PEAK PRESSURE (PSI)	95	69	215
AVG. PRESSURE (PSI)	76	66	79
BREAK PRESSURE (PSI)	95	65	215
PEAK RATE (gal/min)	16	15	15
AVG. RATE (gal/min)	15	14	14
RATE AT BREAK (gal/min)	12	15	9
REMARKS	Stopped pumping at 6 min because fluid surfacing 7 ft NE of borehole.	At 3 min stopped to mix a new tank. Resumed pumping at 9.5 min. Stopped pumping at 16 min because fluid surfacing at several locations 3 to 10 ft N and NE of borehole.	At 3 min stopped to mix a new tank. Resumed pumping at 9.5 min. Fluid surfacing 3 ft NE of borehole and at MW15 and MW17.

Note:	Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

ND - Not Determined NA - Not Applicable

FRACTURE DATA

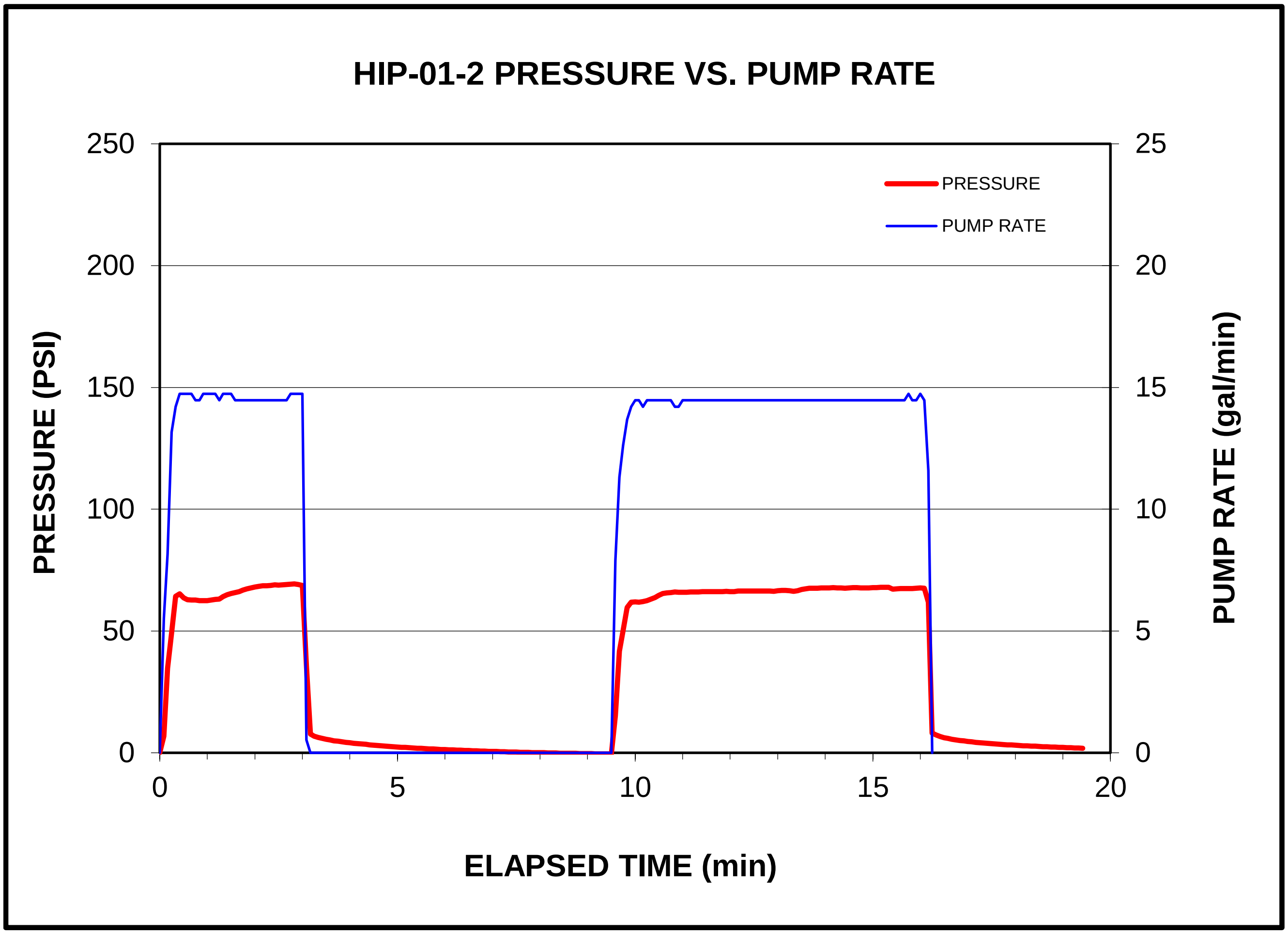


PROJECT NUMBER:	J1610		DATE:	14 September 2016	
FRACTURE NO.:	HIP-01-1		FRACTURE BOREHOLE:	HIP-01	
FRACTURE DEPTH:	12.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	85	(gal)	PLACEMENT EFFICIENCY:	97	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	5	(lbs.)
BREAK PRESSURE:	95	(PSI)	AVERAGE PUMP RATE:	15	(gal/min)

REMARKS: Stopped pumping at 6 min because fluid surfacing 7 ft NE of borehole.

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA

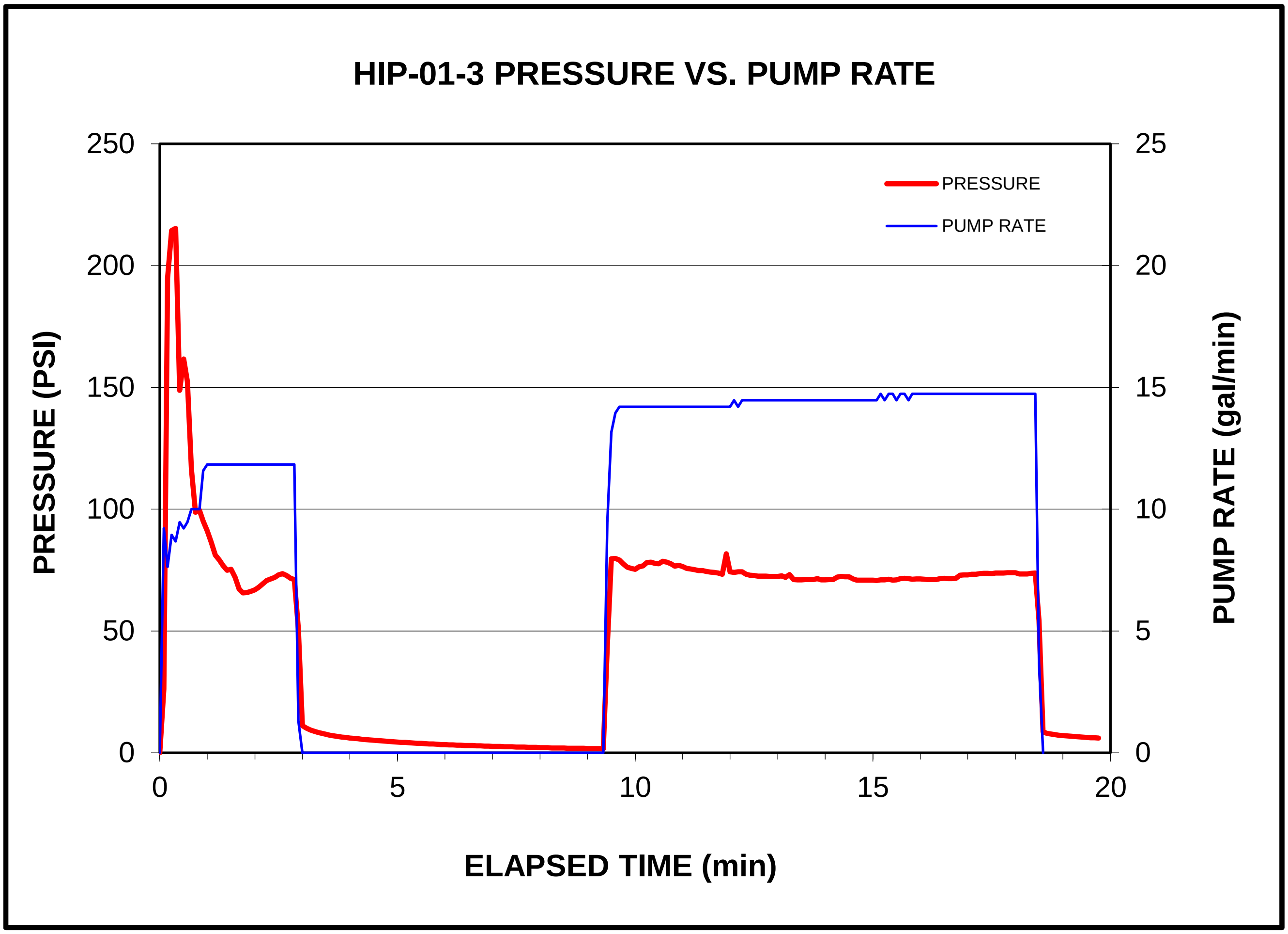


PROJECT NUMBER:	J1610		DATE:	14 September 2016	
FRACTURE NO.:	HIP-01-2		FRACTURE BOREHOLE:	HIP-01	
FRACTURE DEPTH:	15.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	140	(gal)	PLACEMENT EFFICIENCY:	91	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	9	(lbs.)
BREAK PRESSURE:	65	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS: At 3 min stopped to mix a new tank. Resumed pumping at 9.5 min. Stopped pumping at 16 min because fluid surfacing at several locations 3 to 10 ft N and NE of

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA



PROJECT NUMBER:	J1610		DATE:	14 September 2016	
FRACTURE NO.:	HIP-01-3		FRACTURE BOREHOLE:	HIP-01	
FRACTURE DEPTH:	18.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	165	(gal)	PLACEMENT EFFICIENCY:	96	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	10	(lbs.)
BREAK PRESSURE:	215	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS: At 3 min stopped to mix a new tank. Resumed pumping at 9.5 min. Fluid surfacing 3 ft NE of borehole and at MW15 and MW17.

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1610 DATE: September 15, 2016

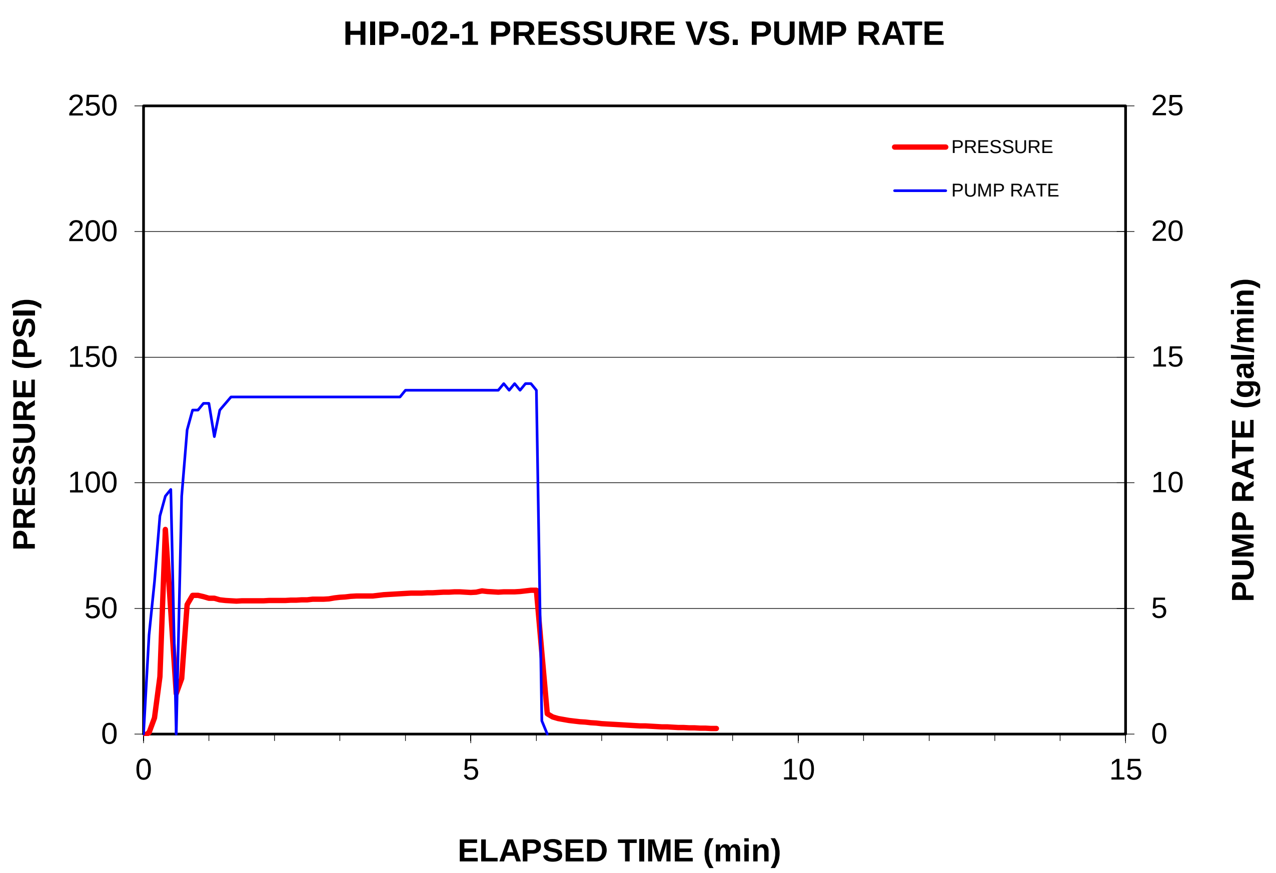
FRACTURE BOREHOLE ID: HIP-02

FRACTURE ID:	HIP-02-1	HIP-02-2	HIP-02-3	HIP-02-4
DEPTH (ft.)	12.0	15.0	18.0	20.0
SOIL TYPE	Silty Clay	Clay	Clay	Clay
AMENDMENT TYPE	LactOil®	LactOil®	LactOil®	LactOil®
SOLUTION VOLUME PUMPED (gal)	80	50	130	130
AMENDMENT VOLUME PUMPED (gal)	5	3	8	8
SOLUTION CONCENTRATION (%)	6.0	6.0	6.0	6.0
VENT/LOSS (gal)	4	1	4	1
VENT/LOSS TYPE	Remote	Remote	Remote	Remote
PLACEMENT EFFICY. (%)	95.0	98.0	96.9	99.2
AMENDMENT VOLUME EMPLACED (gal)	5	3	8	8
PEAK PRESSURE (PSI)	81	153	217	144
AVG. PRESSURE (PSI)	53	74	87	114
BREAK PRESSURE (PSI)	81	153	217	144
PEAK RATE (gal/min)	14	14	14	15
AVG. RATE (gal/min)	13	13	14	14
RATE AT BREAK (gal/min)	9	6	9	9
REMARKS	Stopped pumping at 6 min because fluid surfacing at several locations 3 to 10 ft N and NW of borehole.	Stopped pumping at 4 min because fluid surfacing 3 ft W of borehole.	Fluid surfacing at several locations 3 to 10 ft N and NW of borehole.	Fluid surfacing 3 ft W of borehole.

Note:	Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

ND - Not Determined NA - Not Applicable

FRACTURE DATA

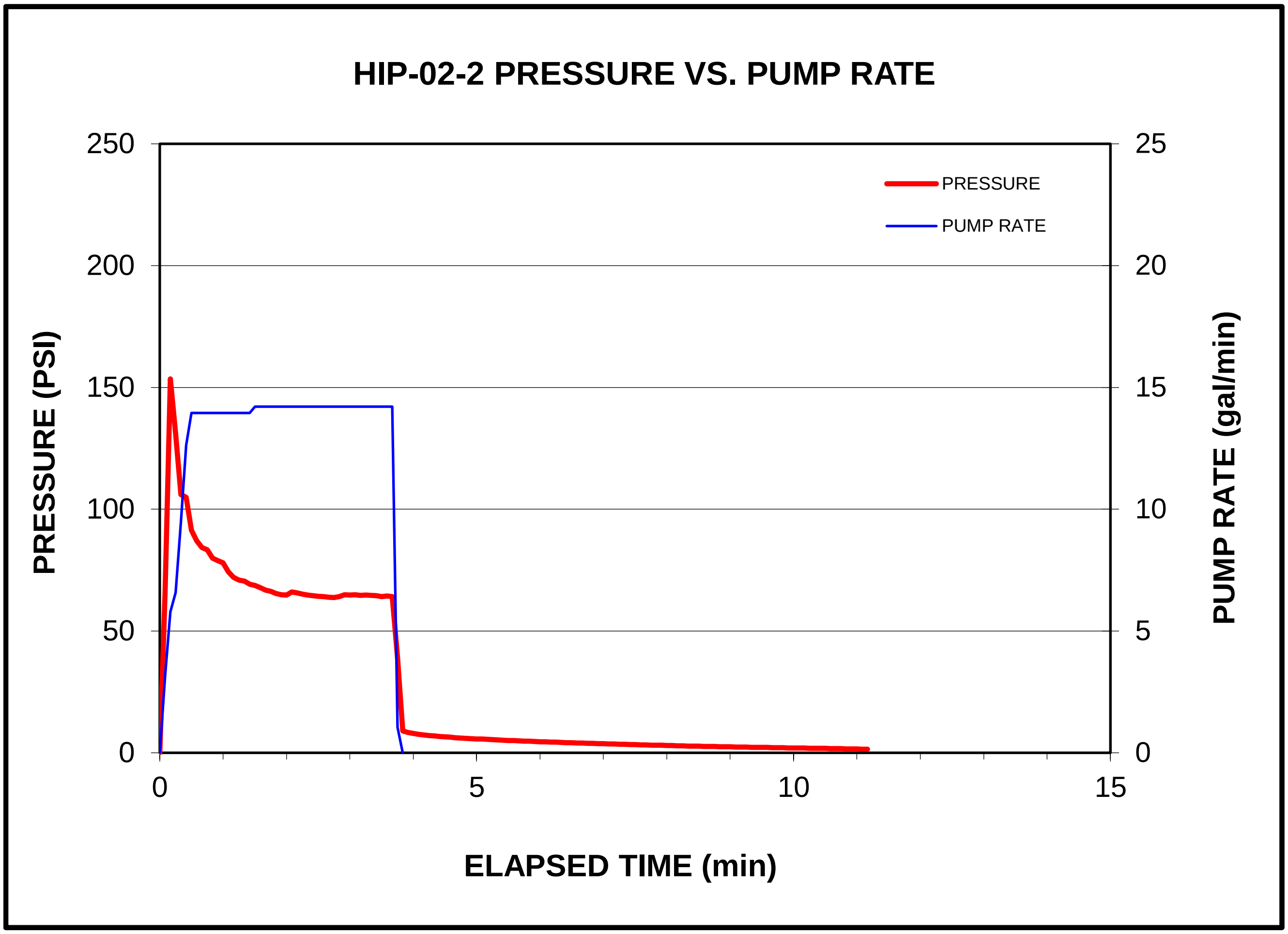


PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-02-1		FRACTURE BOREHOLE:	HIP-02	
FRACTURE DEPTH:	12.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	80	(gal)	PLACEMENT EFFICIENCY:	95	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	5	(lbs.)
BREAK PRESSURE:	81	(PSI)	AVERAGE PUMP RATE:	13	(gal/min)

REMARKS: Stopped pumping at 6 min because fluid surfacing at several locations 3 to 10 ft N and NW of borehole.

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA

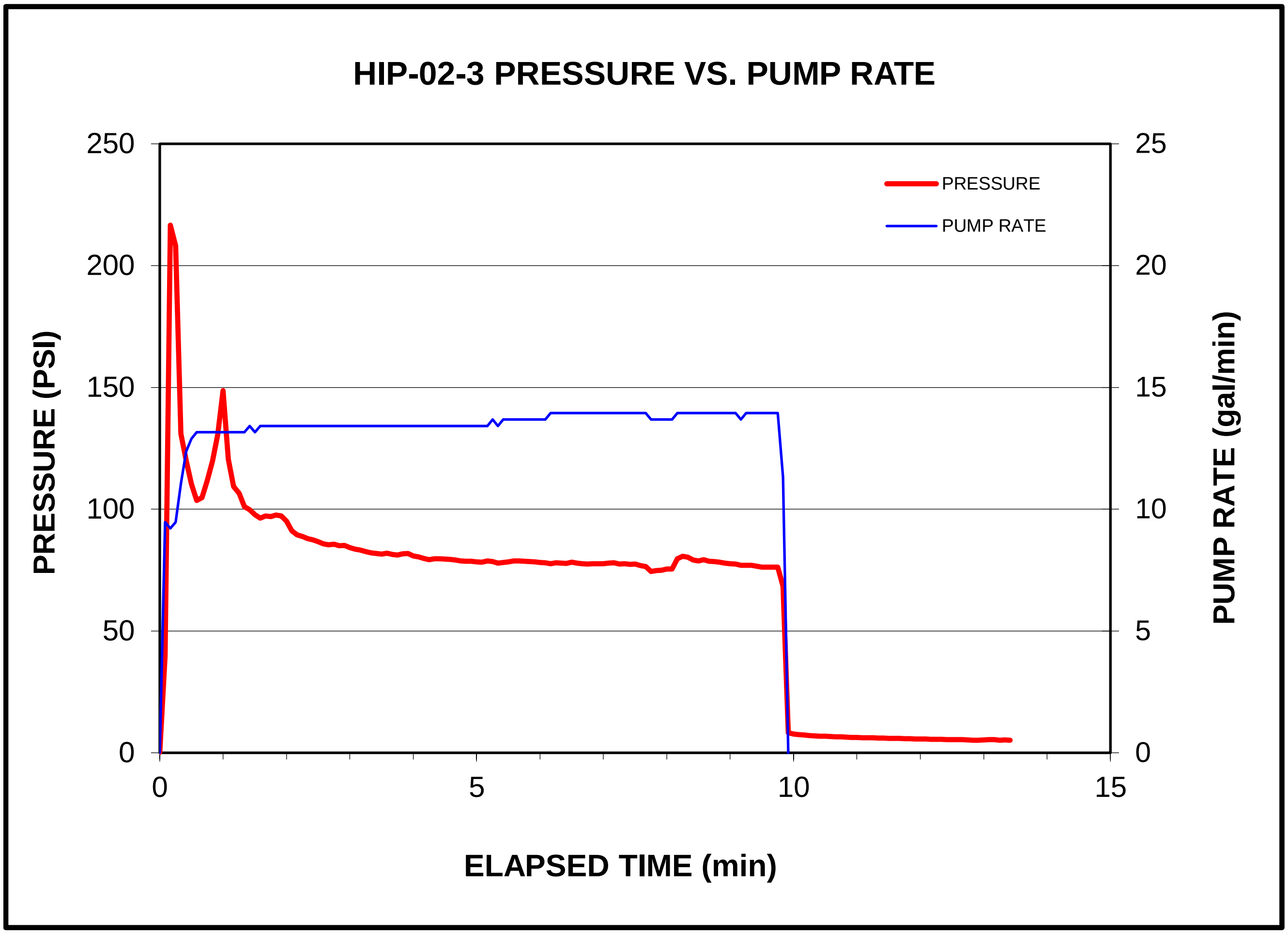


PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-02-2		FRACTURE BOREHOLE:	HIP-02	
FRACTURE DEPTH:	15.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	50	(gal)	PLACEMENT EFFICIENCY:	98	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	3	(lbs.)
BREAK PRESSURE:	153	(PSI)	AVERAGE PUMP RATE:	13	(gal/min)

REMARKS: Stopped pumping at 4 min because fluid surfacing 3 ft W of borehole.

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA

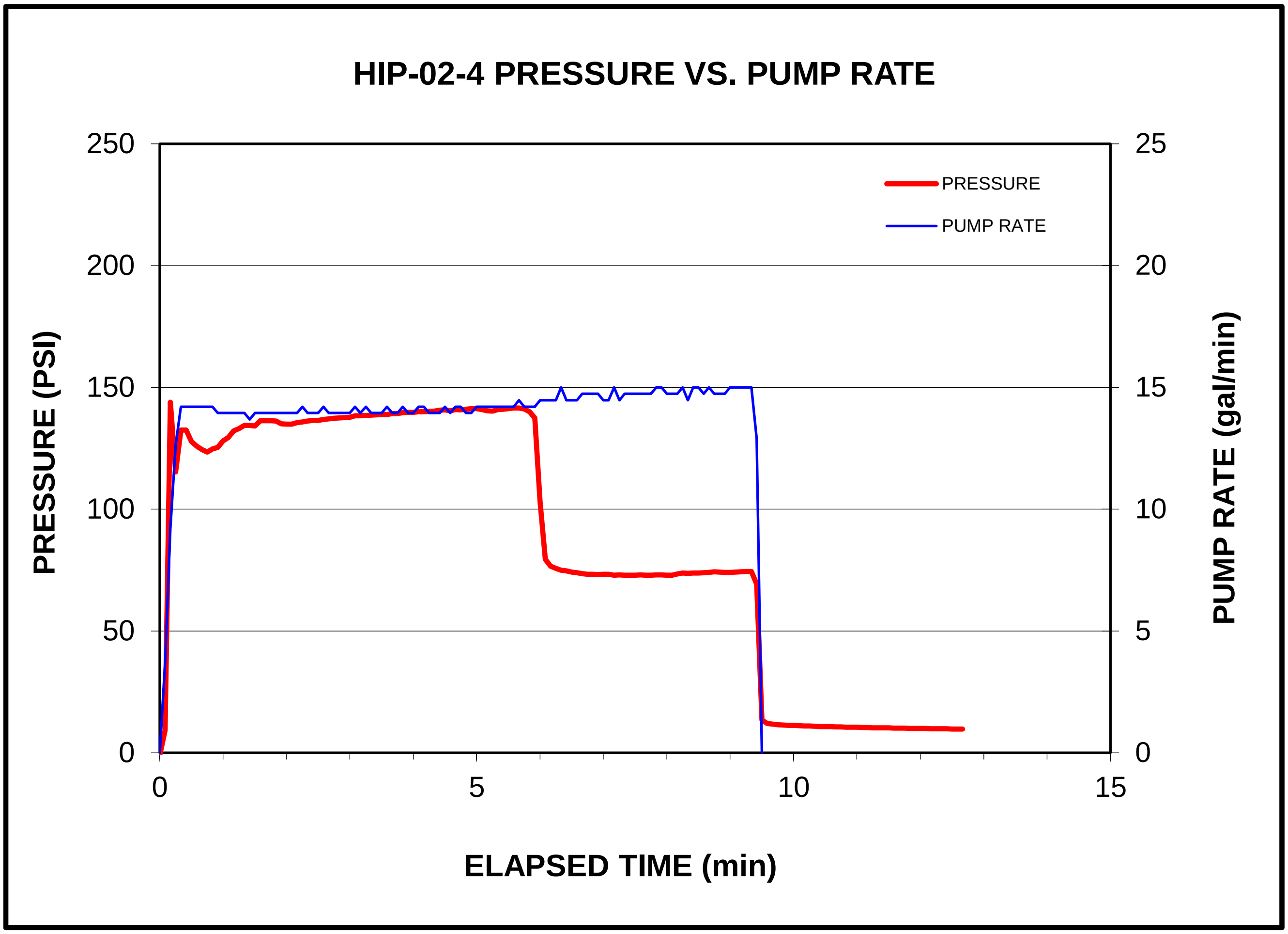


PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-02-3		FRACTURE BOREHOLE:	HIP-02	
FRACTURE DEPTH:	18.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	97	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	217	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS: Fluid surfacing at several locations 3 to 10 ft N and NW of borehole.

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA



PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-02-4		FRACTURE BOREHOLE:	HIP-02	
FRACTURE DEPTH:	20.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	99	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	144	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS: Fluid surfacing 3 ft W of borehole.

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1610 DATE: September 14, 2016

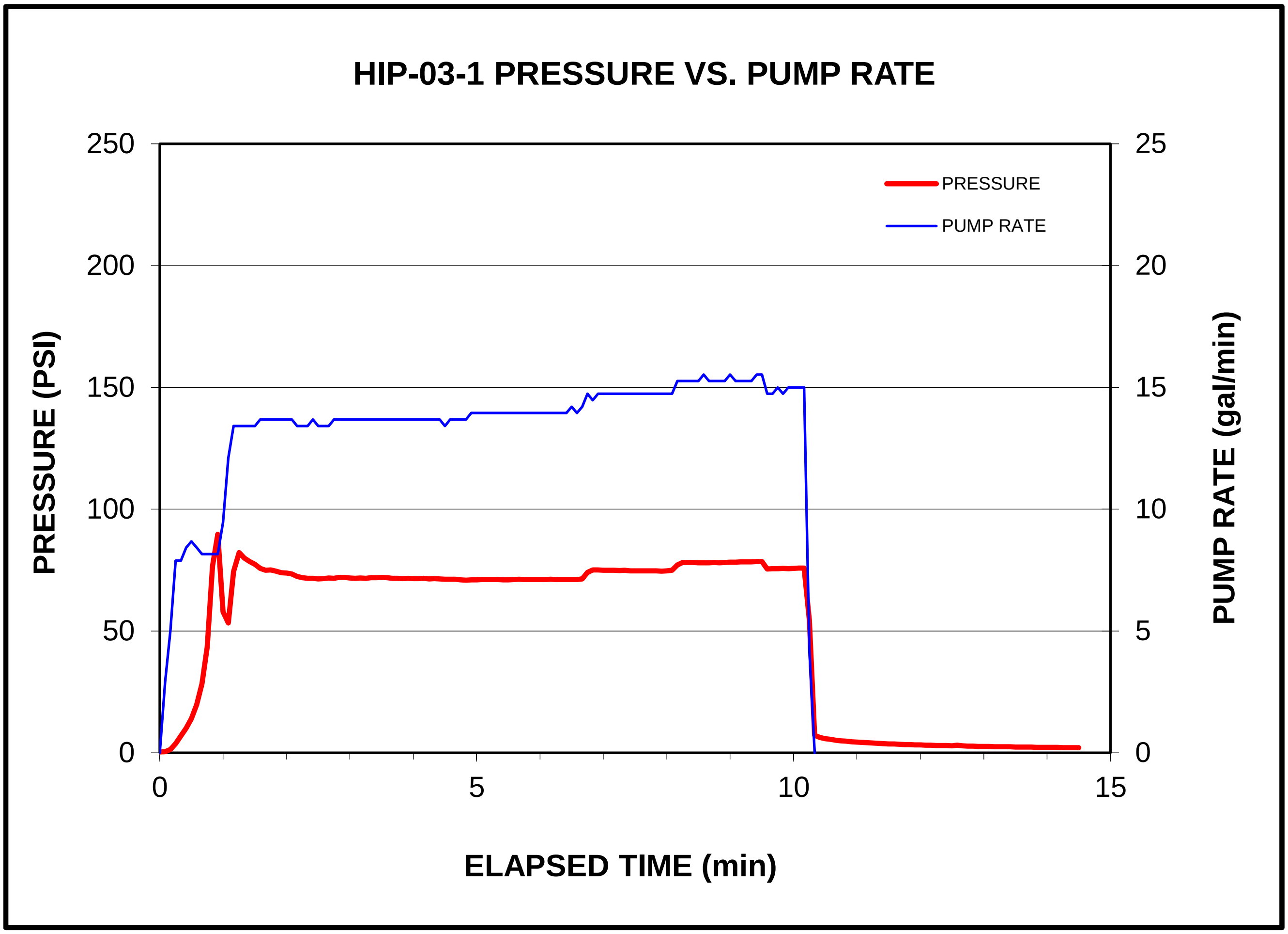
FRACTURE BOREHOLE ID: HIP-03

FRACTURE ID:	HIP-03-1	HIP-03-2	HIP-03-3
DEPTH (ft.)	12.0	15.0	18.0
SOIL TYPE	Silty Clay	Clay	Clay
AMENDMENT TYPE	LactOil®	LactOil®	LactOil®
SOLUTION VOLUME PUMPED (gal)	130	130	130
AMENDMENT VOLUME PUMPED (gal)	8	8	8
SOLUTION CONCENTRATION (%)	6.0	6.0	6.0
VENT/LOSS (gal)	0	0	0
VENT/LOSS TYPE	NA	NA	NA
PLACEMENT EFFICY. (%)	100	100	100
AMENDMENT VOLUME EMPLACED (gal)	8	8	8
PEAK PRESSURE (PSI)	90	92	108
AVG. PRESSURE (PSI)	70	79	78
BREAK PRESSURE (PSI)	90	92	108
PEAK RATE (gal/min)	16	16	14
AVG. RATE (gal/min)	14	15	14
RATE AT BREAK (gal/min)	8	14	9
REMARKS			

Note:	Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

ND - Not Determined NA - Not Applicable

FRACTURE DATA

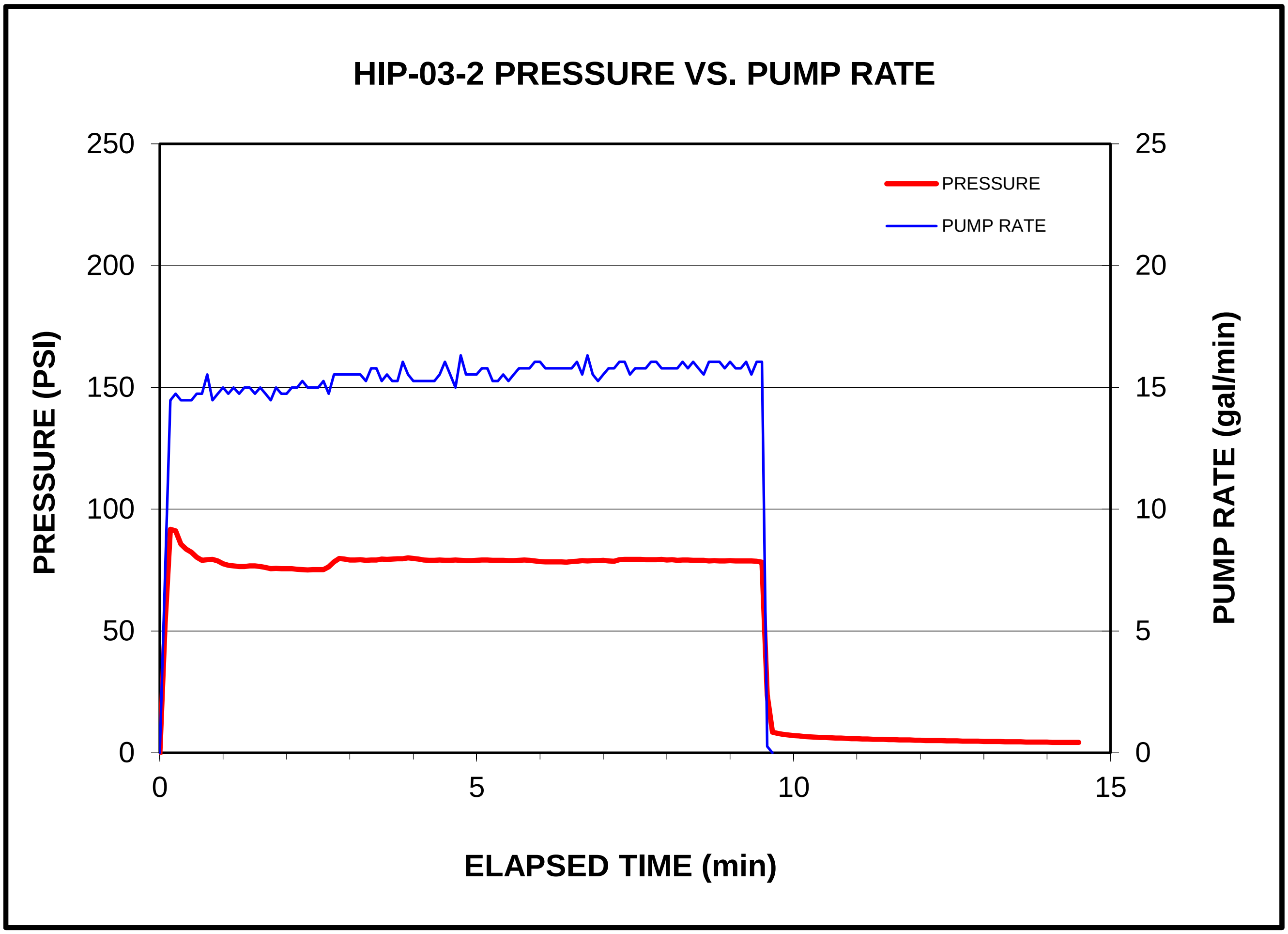


PROJECT NUMBER:	J1610		DATE:	14 September 2016	
FRACTURE NO.:	HIP-03-1		FRACTURE BOREHOLE:	HIP-03	
FRACTURE DEPTH:	12.0	(ft.)	SOIL TYPE:	Silty Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	100	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	90	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS:

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA

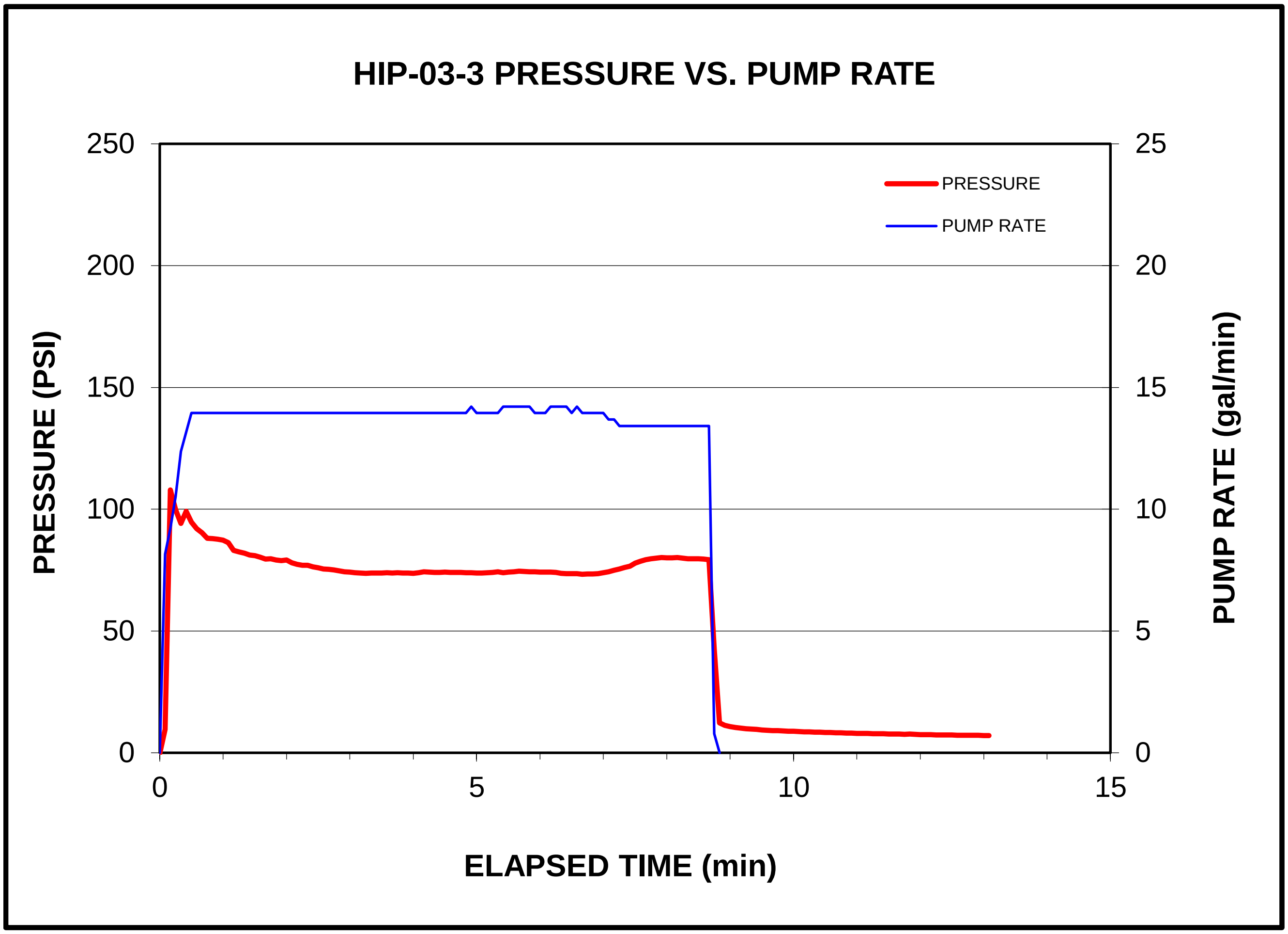


PROJECT NUMBER:	J1610		DATE:	14 September 2016	
FRACTURE NO.:	HIP-03-2		FRACTURE BOREHOLE:	HIP-03	
FRACTURE DEPTH:	15.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	100	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	92	(PSI)	AVERAGE PUMP RATE:	15	(gal/min)

REMARKS:

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURE DATA



PROJECT NUMBER:	J1610		DATE:	14 September 2016	
FRACTURE NO.:	HIP-03-3		FRACTURE BOREHOLE:	HIP-03	
FRACTURE DEPTH:	18.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	100	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	108	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS:

NOTE: Stratigraphy inferred from MW06 borehole log provided by CDM Smith.

FRACTURED BOREHOLE SUMMARY SHEET

PROJECT NUMBER: J1610

DATE: September 15, 2016

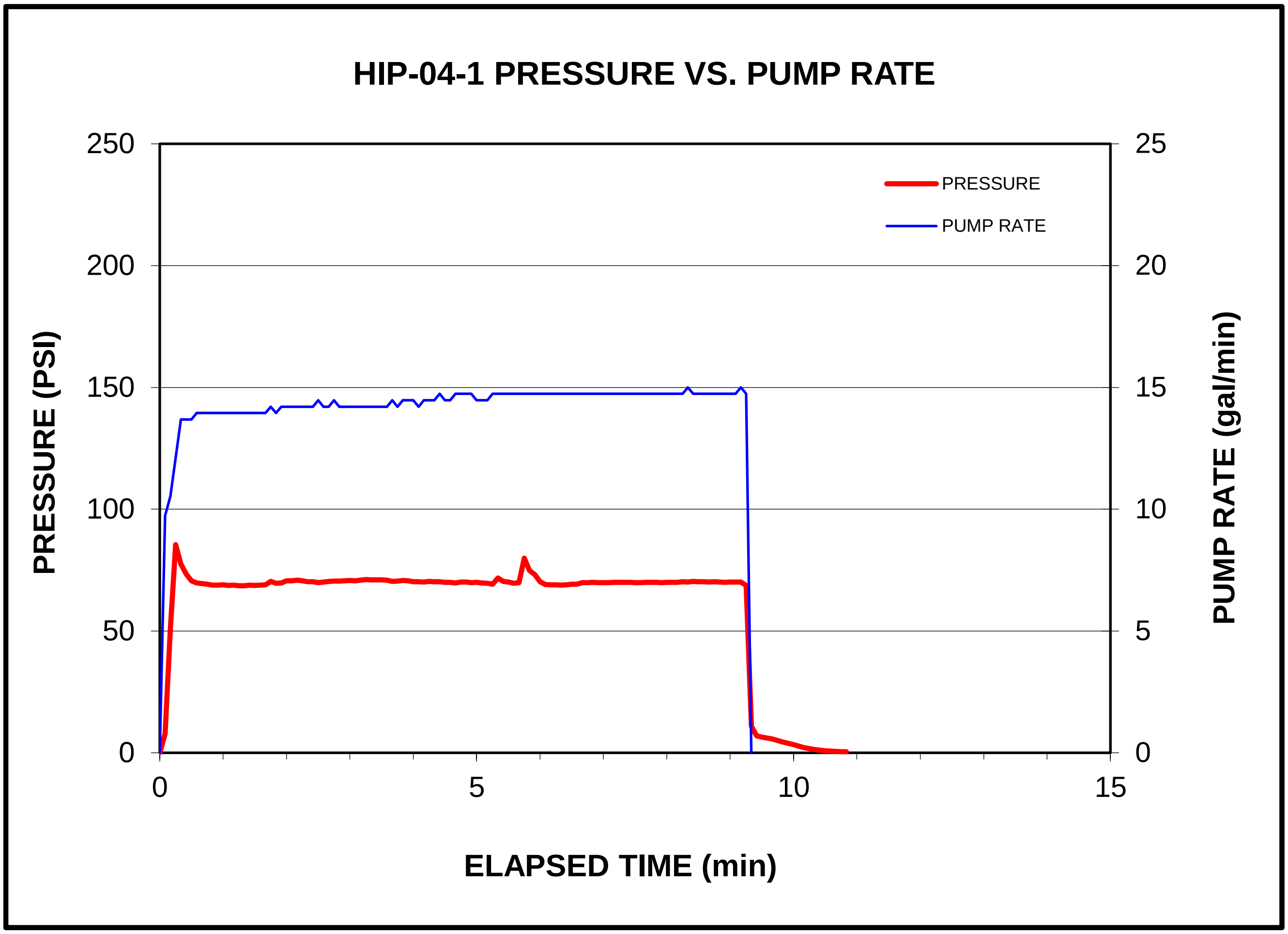
FRACTURE BOREHOLE ID: HIP-04

FRACTURE ID:	HIP-04-1	HIP-04-2	HIP-04-3
DEPTH (ft.)	12.0	15.0	18.0
SOIL TYPE	Clay	Clay	Unknown
AMENDMENT TYPE	LactOil®	LactOil®	LactOil®
SOLUTION VOLUME PUMPED (gal)	130	130	150
AMENDMENT VOLUME PUMPED (gal)	8	8	22
SOLUTION CONCENTRATION (%)	6.0	6.0	15.0
VENT/LOSS (gal)	0	0	5
VENT/LOSS TYPE	NA	NA	Remote
PLACEMENT EFFICY. (%)	100.0	100.0	96.7
AMENDMENT VOLUME EMPLACED (gal)	8	8	21
PEAK PRESSURE (PSI)	85	76	140
AVG. PRESSURE (PSI)	70	66	91
BREAK PRESSURE (PSI)	85	76	140
PEAK RATE (gal/min)	15	15	17
AVG. RATE (gal/min)	14	15	14
RATE AT BREAK (gal/min)	12	13	15
REMARKS			Flushed 15 gal of water at end of frac. Fluid surfacing 10 ft W of borehole at the end of the frac.

Note:	Stratigraphy inferred from MW05 borehole log provided by CDM Smith.

ND - Not Determined NA - Not Applicable

FRACTURE DATA

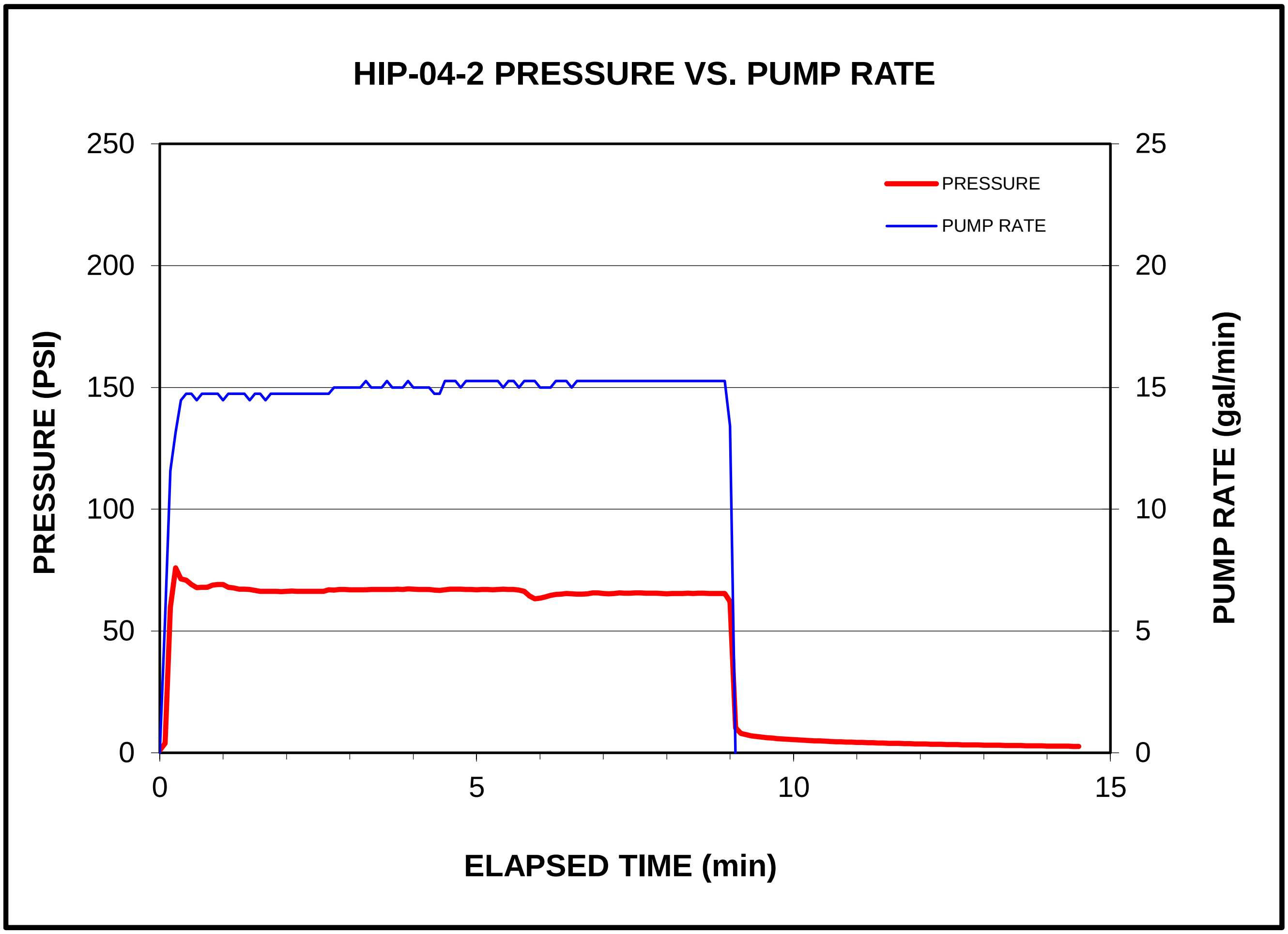


PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-04-1		FRACTURE BOREHOLE:	HIP-04	
FRACTURE DEPTH:	12.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	100	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	85	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS:

NOTE: Stratigraphy inferred from MW05 borehole log provided by CDM Smith.

FRACTURE DATA

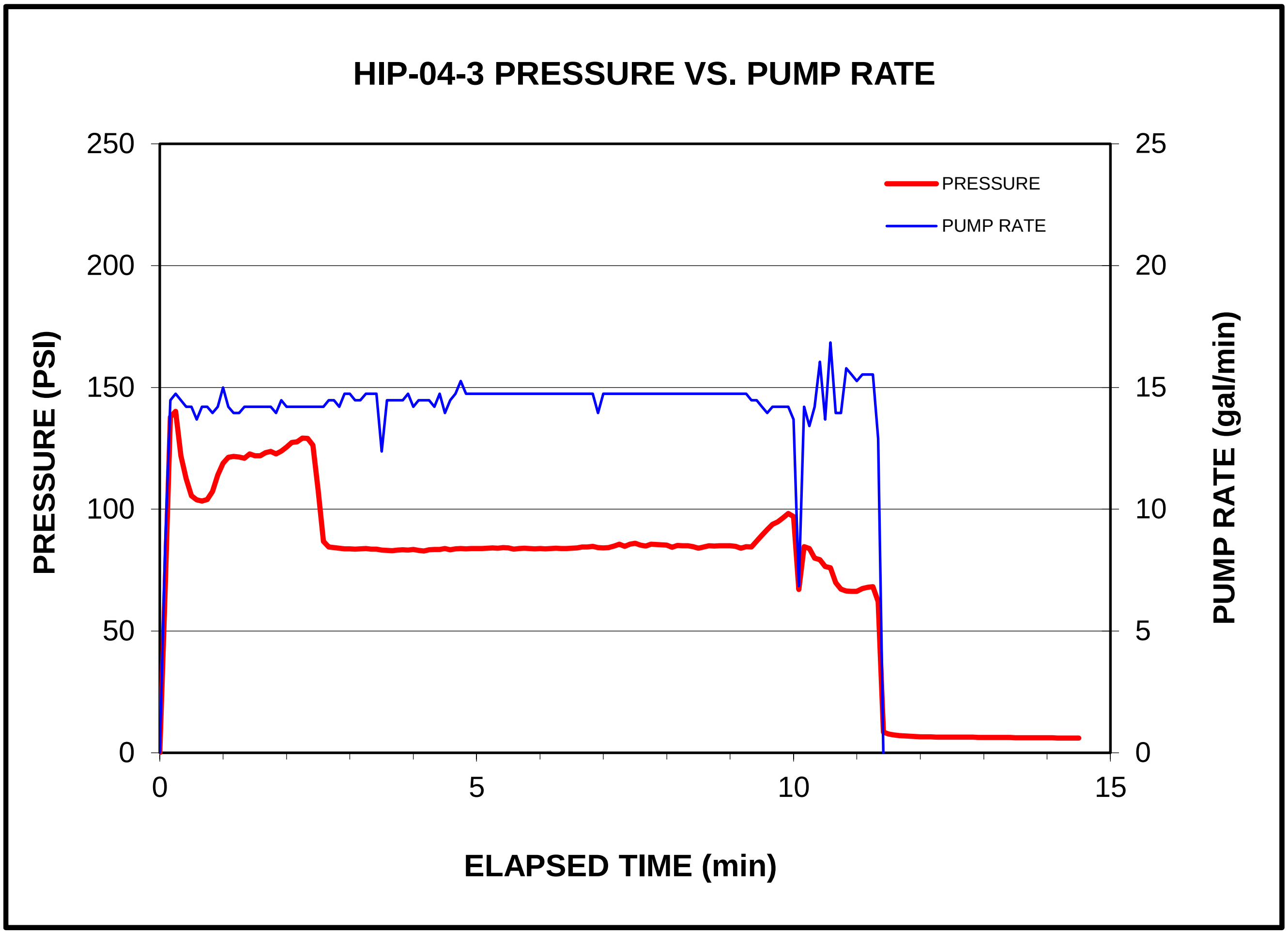


PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-04-2		FRACTURE BOREHOLE:	HIP-04	
FRACTURE DEPTH:	15.0	(ft.)	SOIL TYPE:	Clay	
SLURRY VOL PUMPED:	130	(gal)	PLACEMENT EFFICIENCY:	100	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	8	(lbs.)
BREAK PRESSURE:	76	(PSI)	AVERAGE PUMP RATE:	15	(gal/min)

REMARKS:

NOTE: Stratigraphy inferred from MW05 borehole log provided by CDM Smith.

FRACTURE DATA



PROJECT NUMBER:	J1610		DATE:	15 September 2016	
FRACTURE NO.:	HIP-04-3		FRACTURE BOREHOLE:	HIP-04	
FRACTURE DEPTH:	18.0	(ft.)	SOIL TYPE:	Unknown	
SLURRY VOL PUMPED:	150	(gal)	PLACEMENT EFFICIENCY:	97	(%)
AMENDMENT TYPE:	LactOil®		AMENDMENT MASS PUMPED:	22	(lbs.)
BREAK PRESSURE:	140	(PSI)	AVERAGE PUMP RATE:	14	(gal/min)

REMARKS: Flushed 15 gal of water at end of frac. Fluid surfacing 10 ft W of borehole at the end of the frac.

NOTE: Stratigraphy inferred from MW05 borehole log provided by CDM Smith.

APPENDIX II

TILTMETER GEOPHYSICAL REPORT

Tiltmeter Monitoring of

Hydraulic Fracture Injections

Grand Forks Air Force Base Site TU504

Grand Forks, North Dakota

Prepared by:
Geo Tactical Remediation Ltd.
Calgary, Alberta, Canada

August 2017

SUMMARY

On September 14 and 15, 2016 twelve hydraulic fractures in four boreholes were monitored with surface tiltmeters at a field site in Grand Forks, North Dakota. The purpose of the fracturing was for emplacing a LactOil® solution into the subsurface to facilitate remediation of soils contaminated with chlorinated hydrocarbons.

The fractures were initiated at ranging between 12 and 20 ft below ground surface. Multiple fractures were initiated at the same depth interval at one borehole. All fractures were monitored using Geo Tactical's proprietary tiltmeter mapping system. The recorded data quality was generally very good to excellent with high signal to noise ratios.

Analysis of the tiltmeter data indicated that planar fractures dipping between 2° to 52° were induced in the subsurface during fracturing. One fracture appears to have propagated uphole from the fracture depth.

Data analysis showed a large range in fluid leakoff during the fracturing with the majority of the analyses showing fracture efficiencies greater than 50%.

Results of the analyses of the tiltmeter data are shown in map view in Appendix A and are summarized in Table 1.

UNITS, DEFINITIONS, AND SIGN CONVENTION FOR FRACTURE DESCRIPTION

Except where explicitly stated otherwise, the following units are used in this report:

Length – feet
Volume – cubic feet
Pressure – psi
Fracture angle – degrees
Tilt angle – microradians
RMS error – nanoradians
Normalized vector error – dimensionless

One microradian is the angle subtended by an arc of length 1 mm at a radius of 1 km.

RMS error is the root mean squared difference between observed and theoretical tilt vectors on completion of a non-robust chi-square optimization.

Normalized vector error is a normalized measure of the difference between the observed and theoretical tilt vectors. This error is normalized for comparison between analyses of different fracture models. A value less than 0.4 is considered a good fit of modeled to observed tilt, a value less than 0.3 is considered very good, and a value less than 0.2 is considered an excellent fit.

Each fracture is described by one or more rectangular dislocations with location and geometry specified as follow:

- The location in space is defined by the (x,y,z) coordinates of the mid-point of the rectangular fracture, where x and y are the magnetic eastings and northings with respect to the injection well, and z is the depth below ground surface.
- Fracture orientation is defined by azimuth and dip using the right hand rule, where azimuth is the direction of strike clockwise from magnetic north, and dip is the angle from horizontal at a right angle from the azimuth. For example, a fracture with an azimuth of 45° and a dip of 45° strikes northeast-southwest and dips to the southeast; a fracture with an azimuth of 225° and a dip of 45° strikes southwest-northeast and dips to the northwest.

Fracture geometry is specified by length along azimuth, width along the direction of dip, and thickness between the fracture faces.

SUMMARY OF THE TILTMETER MAPPING SYSTEM

Many subsurface processes result in small but measurable movements at the Earth's surface. The shape of these surface deformations will depend on the processes which caused them. Geo Tactical's tiltmeter mapping system measures these surface deformations, and a model is created of subsurface processes which caused the deformation.

Various man-made processes can result in measurable deformations at the Earth's surface. Long term processes such as production of oil and gas, or production of water from an aquifer, can result in subsidence of several feet over a period of years. Shorter term processes such as injection or production tests, or hydraulic fracturing produce correspondingly smaller deformations, but with suitably sensitive instrumentations these can be measured and analyzed.

The surface of the Earth is also continuously deforming due to natural processes. These include the tidal effects of the Sun and Moon, and thermal effects as the ground heats up during the day and cools down at night. While these effects are very small, they may be on a similar scale to the effects of the processes being monitored. However, the effects of these natural processes can be predicted and removed from data.

The process of hydraulic fracturing creates a dislocation in the subsurface with a characteristic deformation. A horizontal fracture (dip of 0°) causes an uplift or dome at the surface. A vertical fracture (dip of 90°) causes subsidence at the surface oriented along the azimuth of the fracture with a slight uplift outside the subsidence.

If a point on the Earth's surface is uplifted relative to another point, there will be a change in slope of the surface between the two points. The tiltmeter system continuously records changes in slope, or tilt. The change in tilt at a particular tiltmeter location is measured in two orthogonal directions, and the vector sum of these two measurements yields the magnitude and direction of the change in tilt at that location. The surface deformation due to a subsurface process may then be characterized by measuring the change in tilt an array of tiltmeter locations around an area of interest.

Numerical models and optimization schemes are then used to determine a best fit between observed and theoretical deformations.

DATA ACQUISITION

Tiltmeter data was collected to monitor 12 hydraulic fractures at three boreholes at a field site in Grand Forks, North Dakota on September 14 and 15, 2016. An array of model 700 tiltmeters was deployed to monitor the fracturing. Tilt data was collected at a 10 second sample interval during the fracturing.

DATA QUALITY

Data quality was generally very good to excellent with high signal to noise ratios for each fracture.

DATA ANALYSIS

All twelve fractures were modeled as single planar structures. The results were optimized on the parameters for azimuth, dip, length, width, thickness, depth and offset from the borehole. The fit of the theoretical to observed tilt from the planar fracture models was excellent for eleven of the analyses and very good for one of the analyses. Figure 1 shows the overall statistical distribution of the fit of theoretical to observed tilt.

Results of the analyses of the tiltmeter data are shown in map view in Appendix A and are summarized in Table 1.

DISCUSSION

Results of the tiltmeter analyses of all the fracturing are summarized in Table 1. Maps of the modeled fractures with real and theoretical tilt vectors for the fractures are shown in Appendix A. Analysis of the fracture parameters was based primarily on the tilt data.

Analyses of the tiltmeter data indicated planar fractures dipping from sub-horizontal 52° from horizontal. Out of the twelve planar structures modeled, five of them had dips less than 20°, three had dips between 43° and 52°, and the remaining were between 20° and 40°. The overall statistical distribution of fracture dip is shown in Figure 2.

The analyses indicated that one of the fractures (HIP-04-3) appears to have migrated uphole from the initiation depth.

Data analysis generally showed a large range in fluid leakoff during the fracturing with the majority of the analyses showing fracture efficiencies greater than 50%. Fracture efficiency for the individual fracture analyses are shown on the plots in Appendix A.

TABLE 1
Tiltmeter Results Summary

Fracture I.D.	Date	Azimuth (deg)	Dip (deg)	Width (ft)	Length (ft)	Height (ft)	Z (ft)	Vector Error	RMS Error (nRad)	Modeled Frac Volume (ft^3)	X (ft)	Y (ft)
HIP-01-1	14-Sep	246	6	0.010	13.9	10.9	12.0	0.070	3.04E+04	1.5	-4.2	0.4
HIP-01-2a	14-Sep	255	17	0.016	16.5	10.0	15.0	0.088	4.39E+04	2.6	-0.3	0.8
HIP-01-2b	14-Sep	265	23	0.017	20.5	15.0	15.0	0.133	8.75E+04	5.2	0.1	1.0
HIP-01-3a	14-Sep	228	2	0.040	12.3	7.7	18.0	0.124	6.23E+05	3.8	-3.3	0.2
HIP-01-3b	14-Sep	35	5	0.040	25.0	15.0	18.2	0.118	1.74E+05	15.0	-2.1	1.3
HIP-02-1	15-Sep	156	46	0.017	12.9	18.5	11.9	0.052	6.28E+04	4.1	2.1	-1.3
HIP-02-2	15-Sep	179	33	0.033	8.0	20.3	15.0	0.046	6.02E+04	5.4	0.6	-2.6
HIP-02-3	15-Sep	103	17	0.050	26.8	12.0	18.0	0.185	2.60E+05	16.1	-1.1	-2.3
HIP-02-4	15-Sep	170	43	0.010	18.1	47.8	25.0	0.110	4.94E+04	8.7	-7.4	1.1
HIP-04-1	15-Sep	65	52	0.030	16.9	26.7	10.2	0.095	2.47E+05	13.5	-0.1	4.7
HIP-04-2	15-Sep	119	35	0.040	25.0	17.0	12.9	0.202	4.16E+05	17.0	1.4	5.9
HIP-04-3	15-Sep	52	34	0.061	20.3	15.6	10.1	0.115	4.60E+05	19.3	2.4	3.8

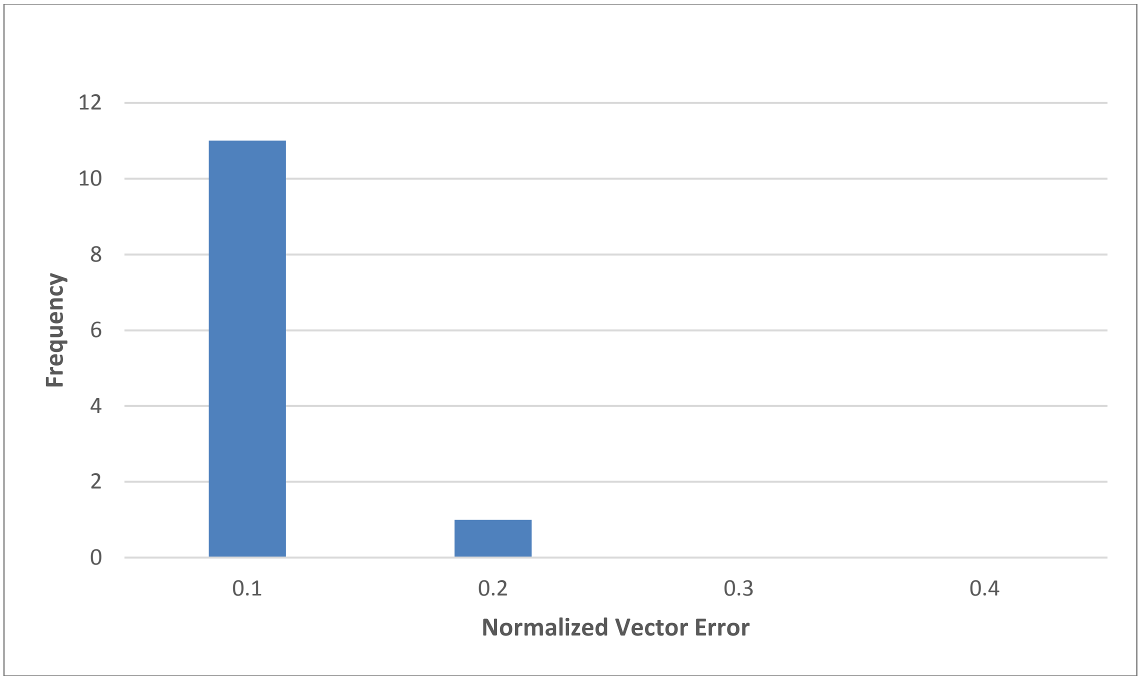


Figure 1 – Statistical Distribution of Normalized Vector Error

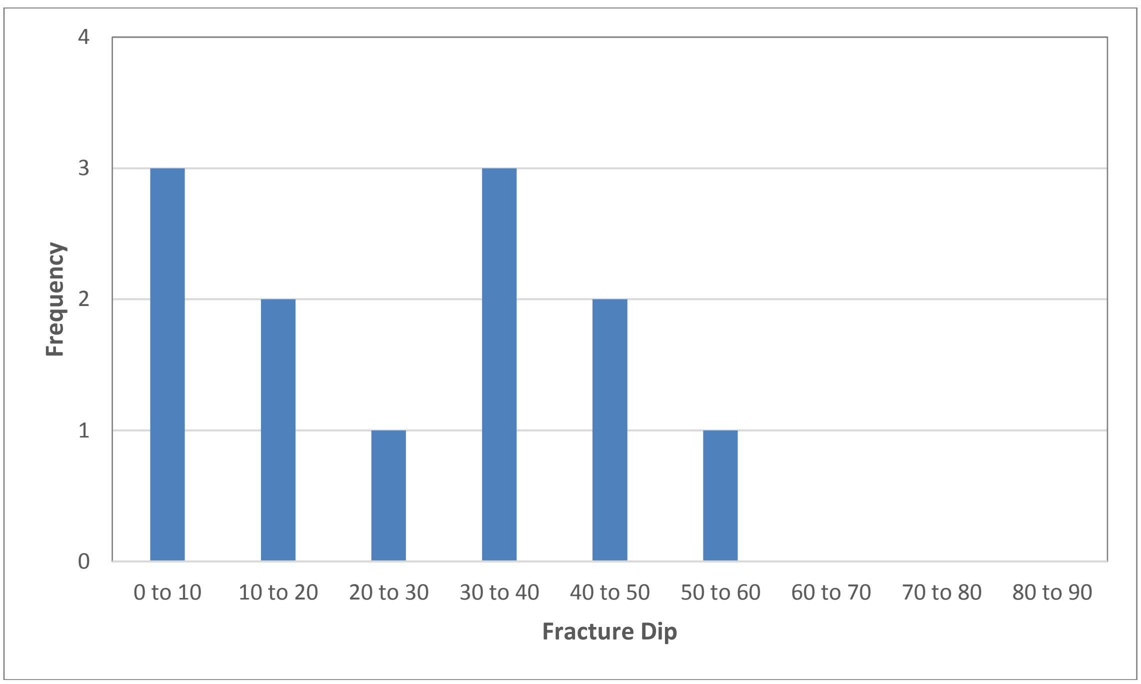
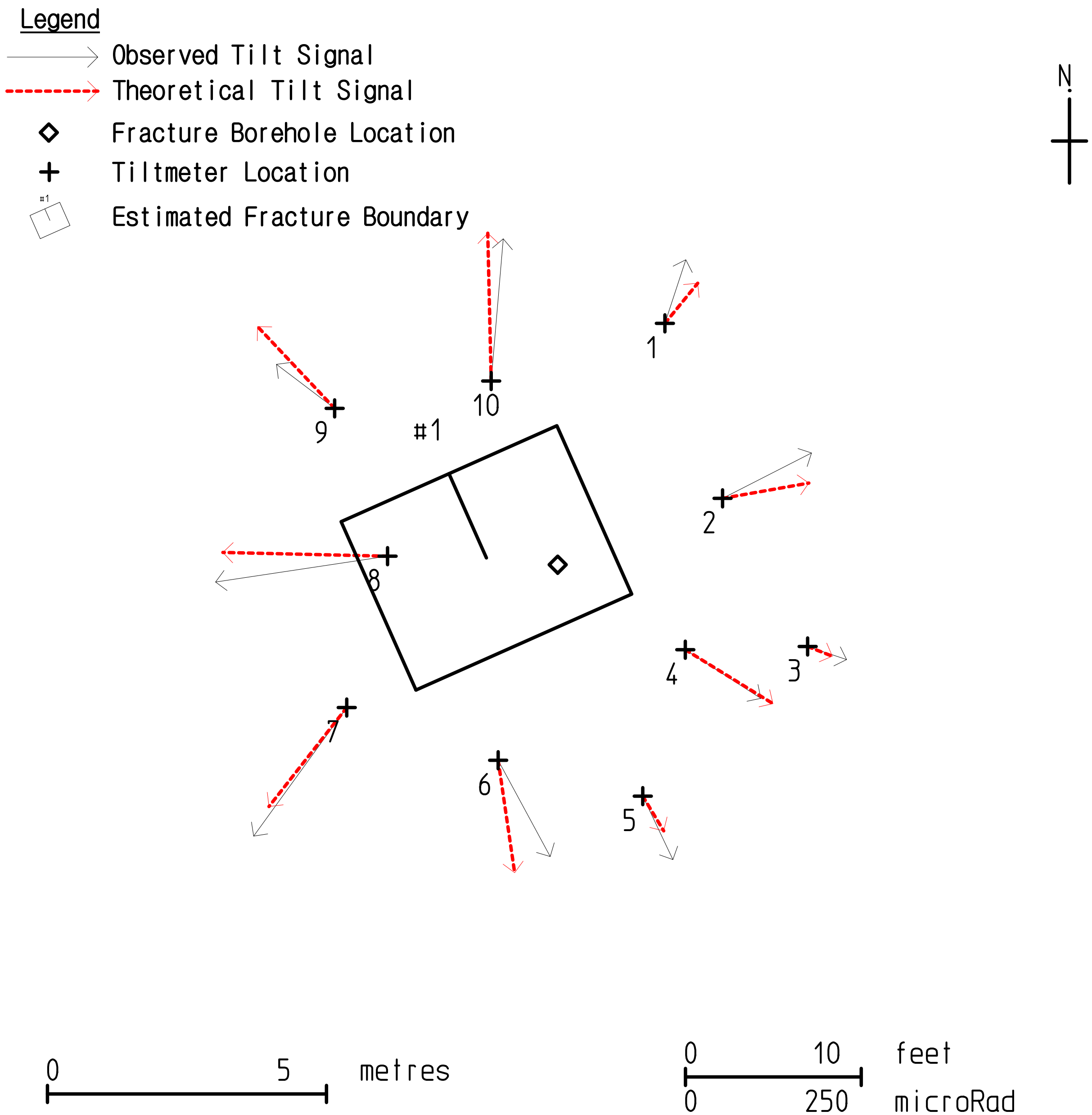


Figure 2 – Statistical Distribution of Fracture Dip

APPENDIX A

TILTMETER RESULTS IN MAP VIEW

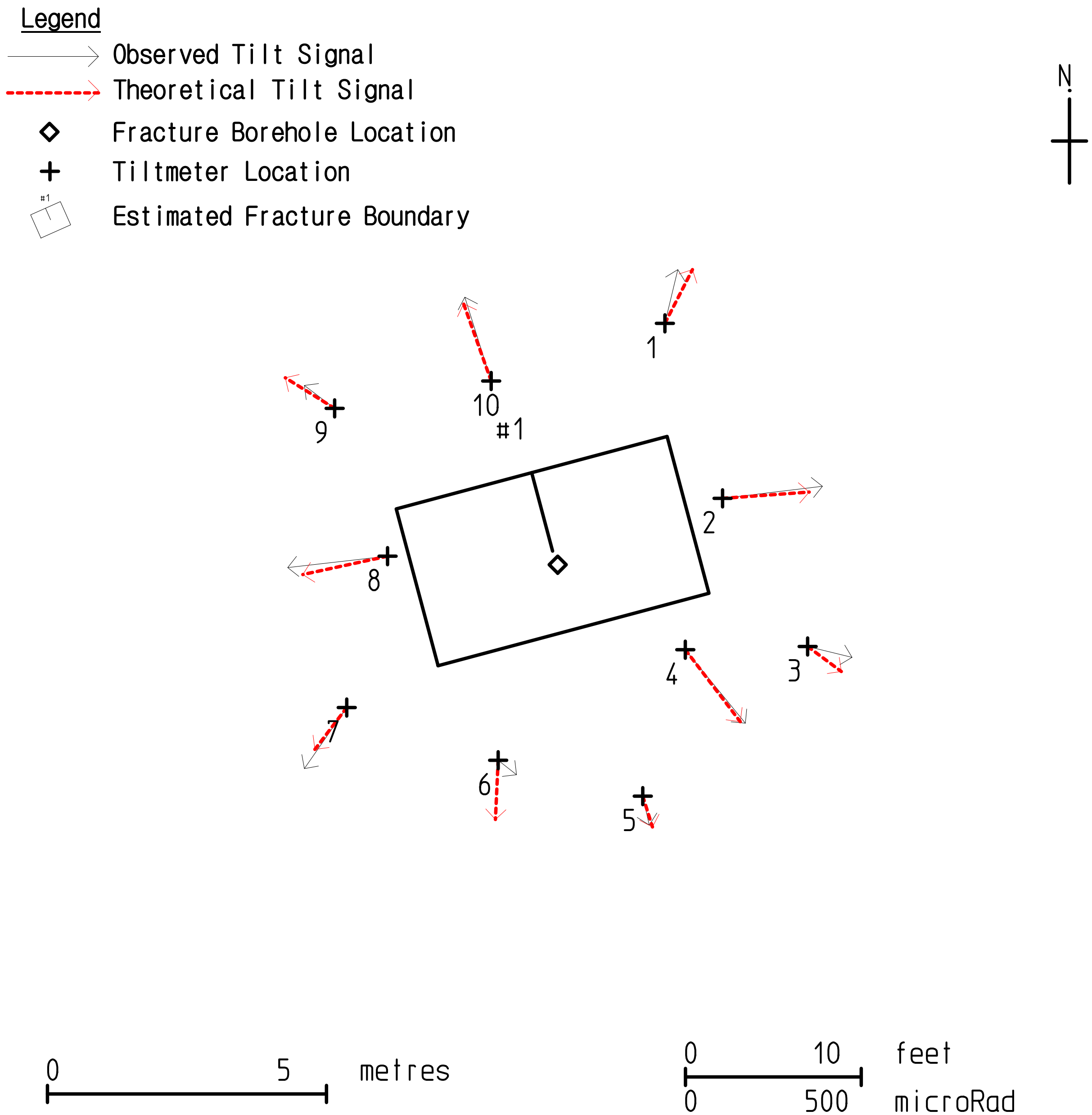


WELL: HIP-01-1
DATE: 9/14/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	246	6	12	1.95	0	14%

Length = 13.9 ft, Width = 10.9 ft, Thickness = 0.010 ft
Normalized Vector Error = 0.070, RMS Error = 3.04E04 nRad

Geo Tactical 2017

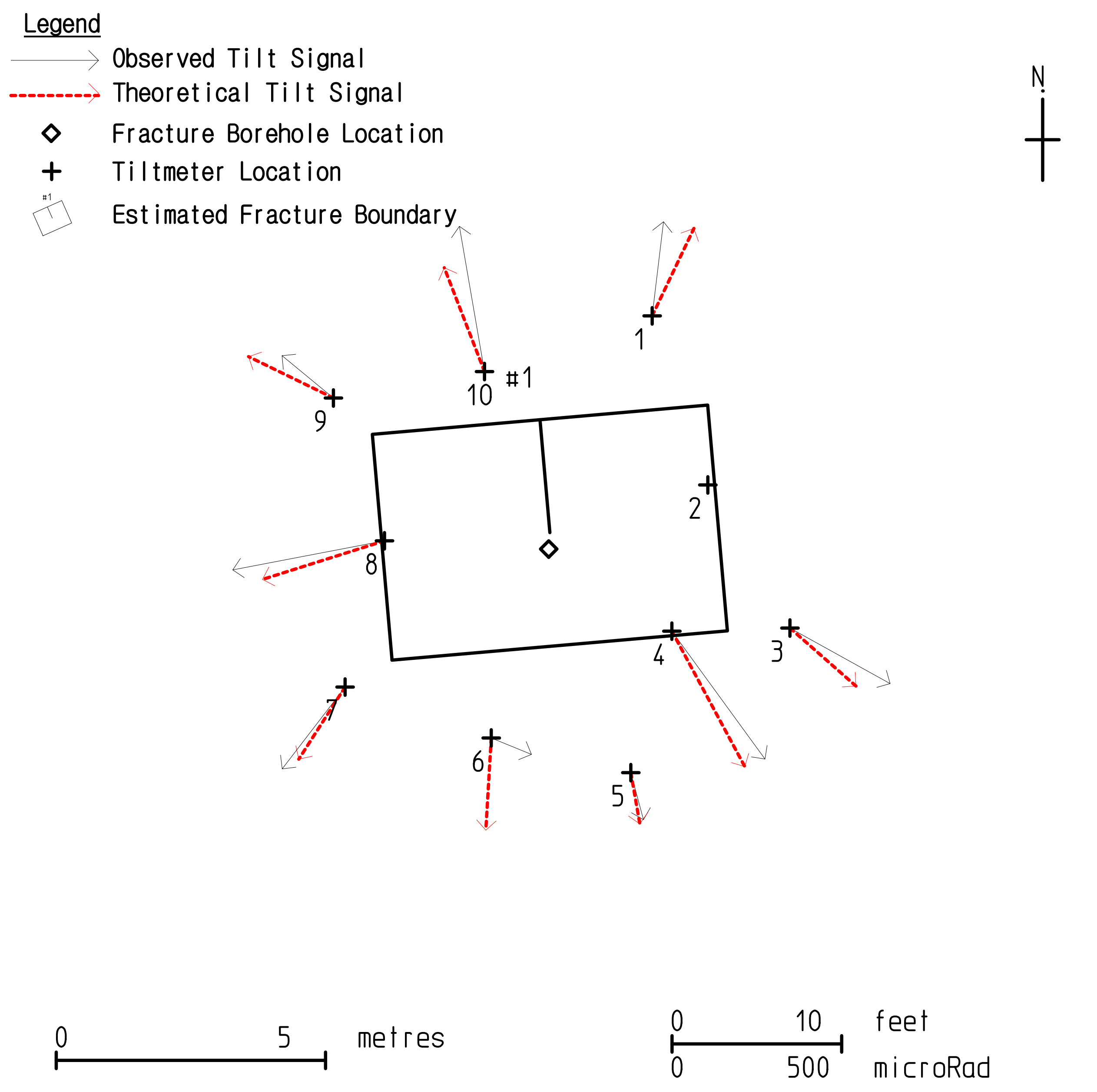


WELL: HIP-01-2a
DATE: 9/14/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	255	17	15	1.07	0	44%

Length = 16.5 ft, Width = 10.0 ft, Thickness = 0.016 ft
Normalized Vector Error = 0.088, RMS Error = 4.39E04 nRad

Geo Tactical 2017

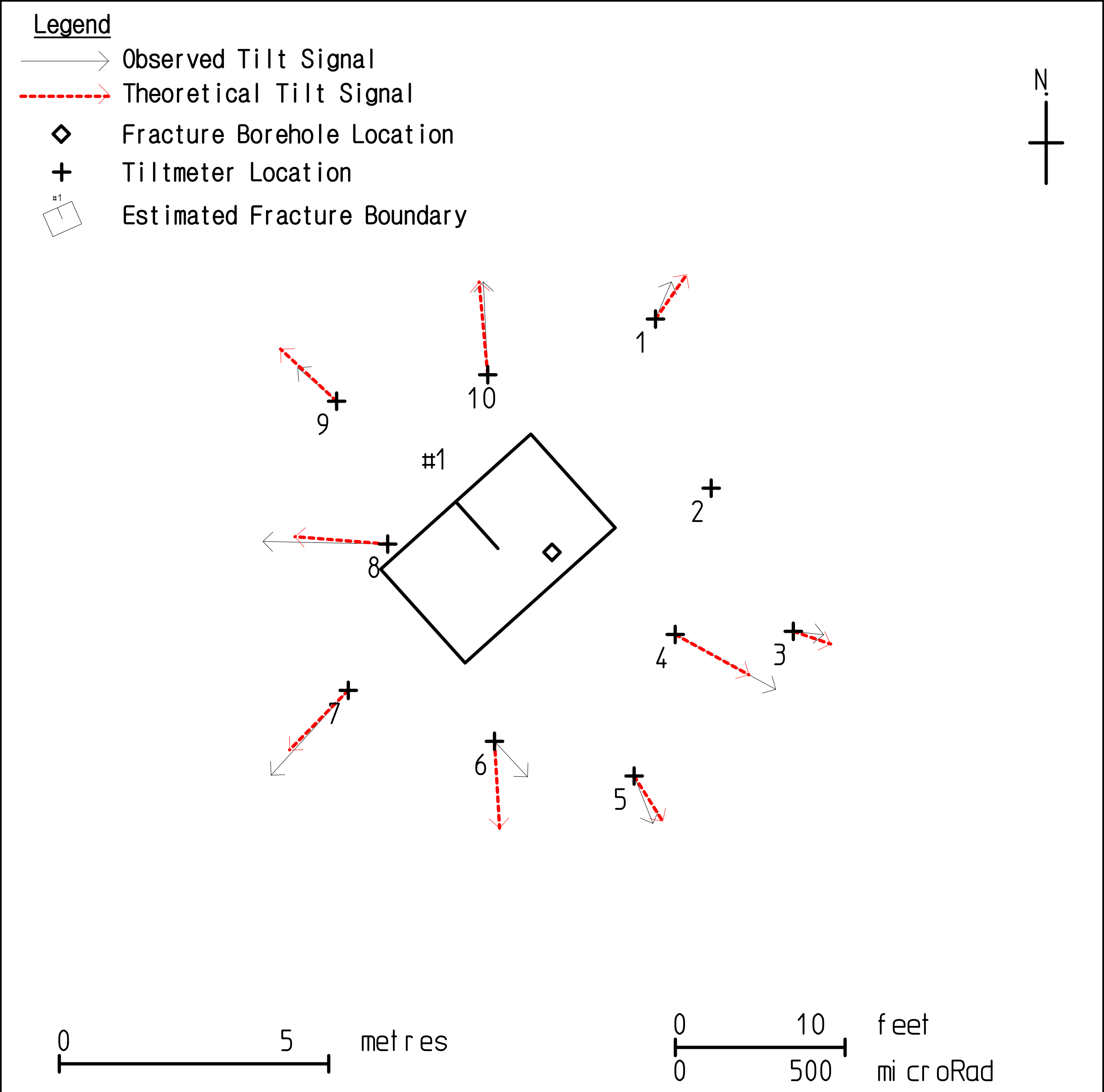


WELL: HIP-01-2b
DATE: 9/14/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	265	23	15	1.95	1	48%

Length = 20.5 ft, Width = 15.0 ft, Thickness = 0.017 ft
Normalized Vector Error = 0.133, RMS Error = 8.75E04 nRad

Geo Tactical 2017

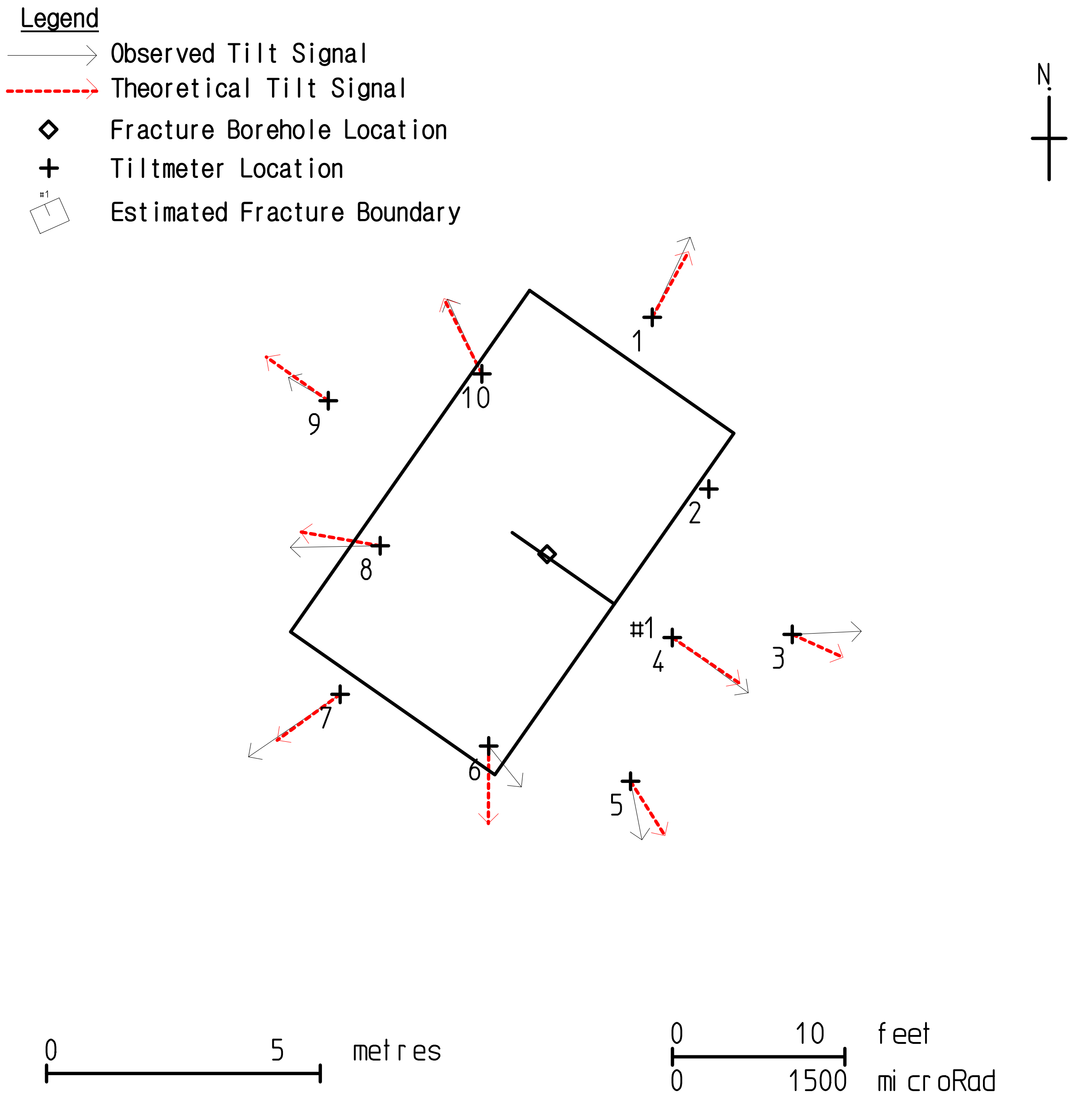


WELL: HIP-01-3a
DATE: 9/14/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	228	2	12.3	0.83	1	81%

Length = 12.3 ft, Width = 7.7 ft, Thickness = 0.040 ft
Normalized Vector Error = 0.124, RMS Error = 6.23E04 nRad

Geo Tactical 2017

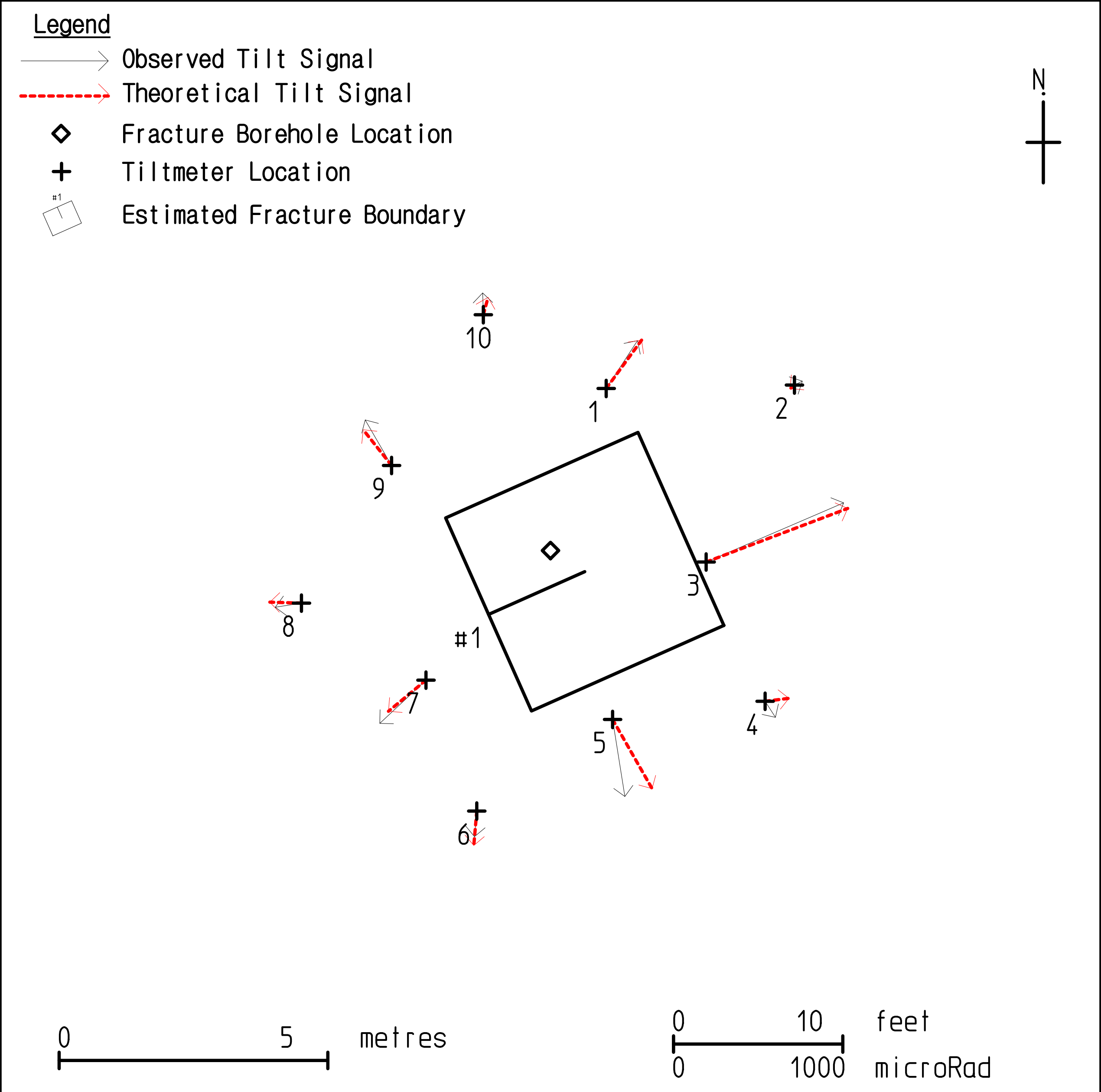


WELL: HIP-01-3b
DATE: 9/14/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	35	5	18.2	2.93	3	91%

Length = 25.0 ft, Width = 15.0 ft, Thickness = 0.040 ft
Normalized Vector Error = 0.118, RMS Error = 1.74E05 nRad

Geo Tactical 2017

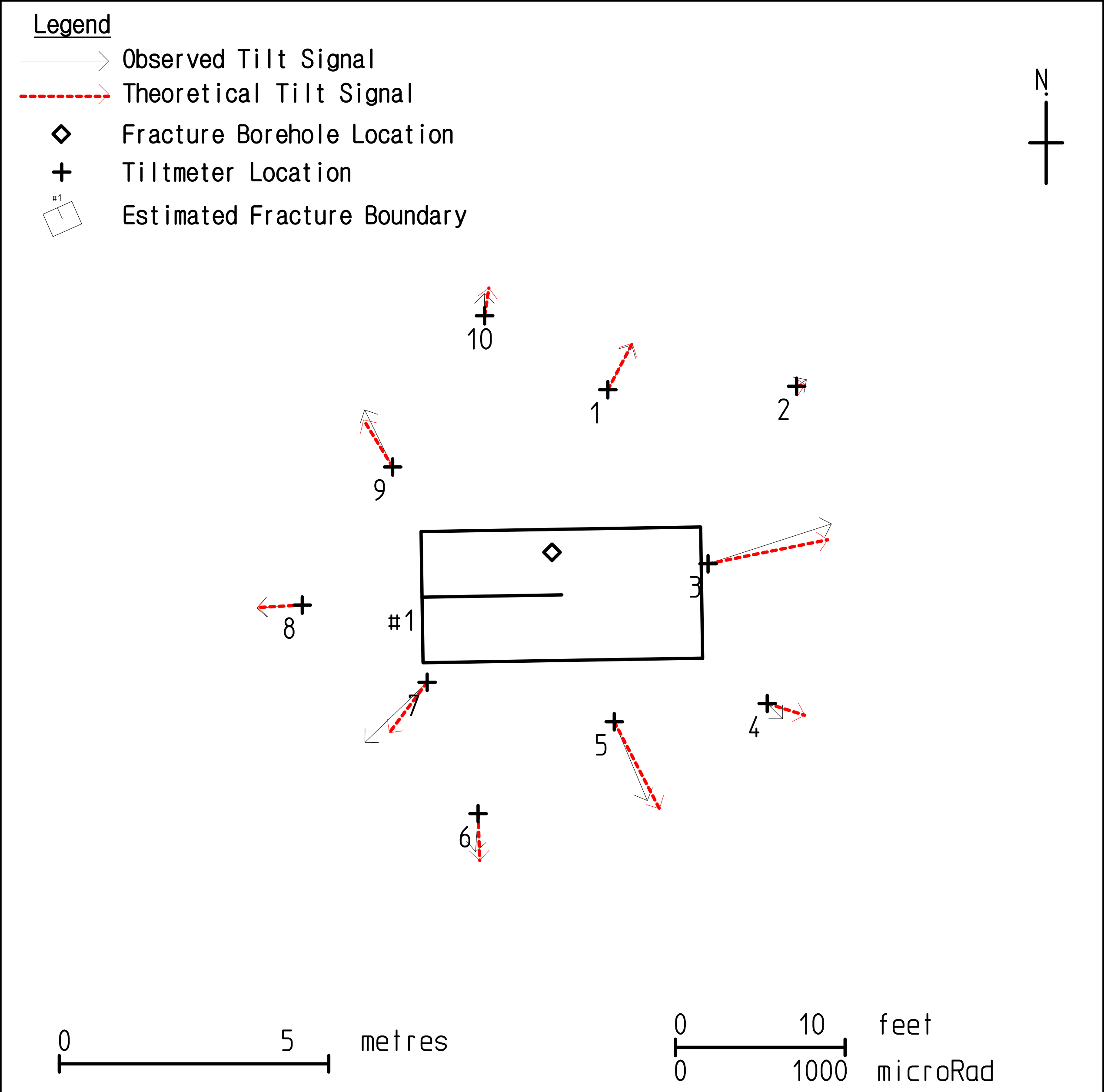


WELL: HIP-02-1
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	156	46	11.9	1.81	1	40%

Length = 12.9 ft, Width = 18.5 ft, Thickness = 0.017 ft
Normalized Vector Error = 0.052, RMS Error = 6.28E04 nRad

Geo Tactical 2017

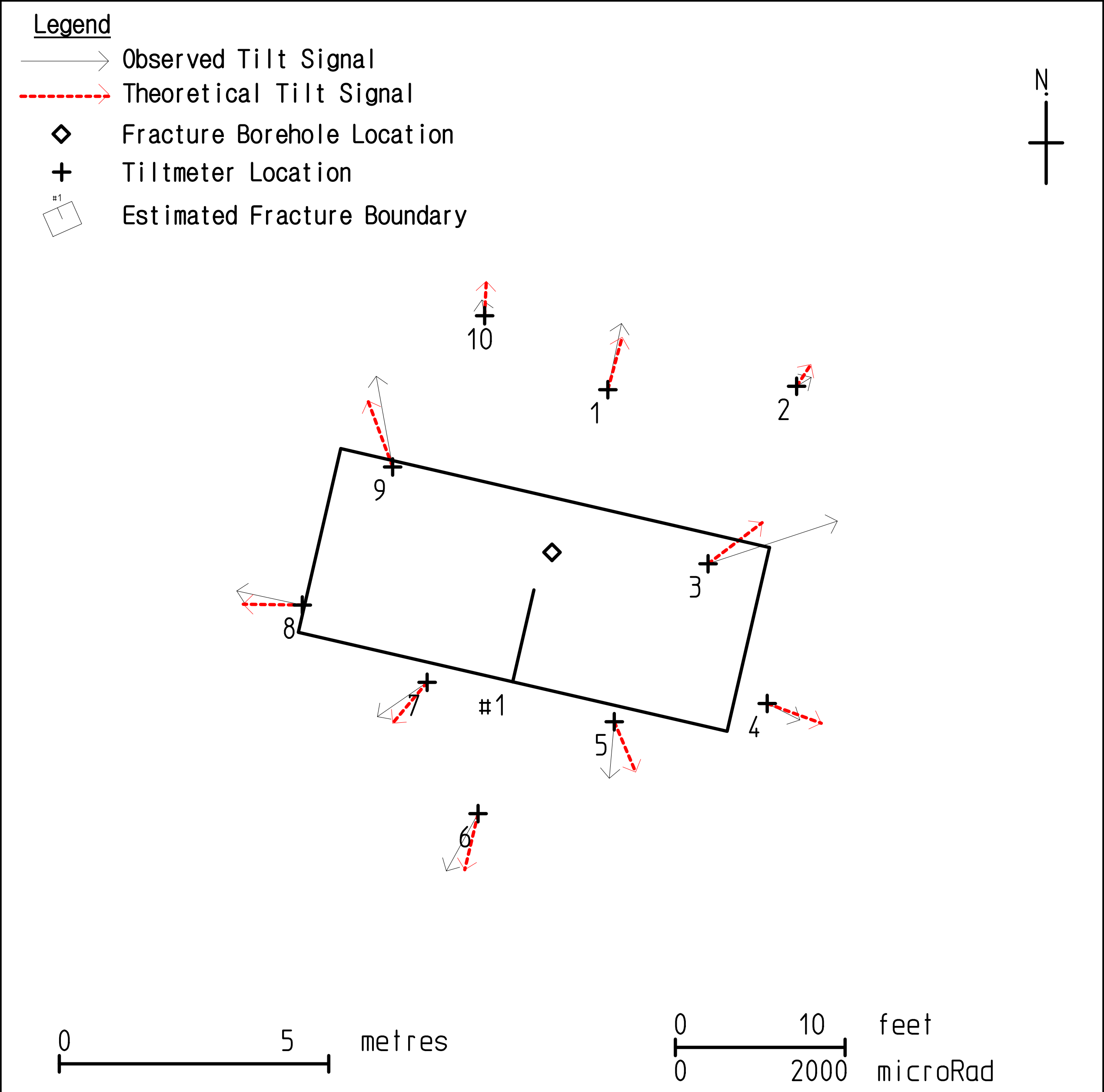


WELL: HIP-02-2
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	179	33	15	1.17	1	82%

Length = 8.0 ft, Width = 20.3 ft, Thickness = 0.033 ft
Normalized Vector Error = 0.046, RMS Error = 6.02E04 nRad

Geo Tactical 2017

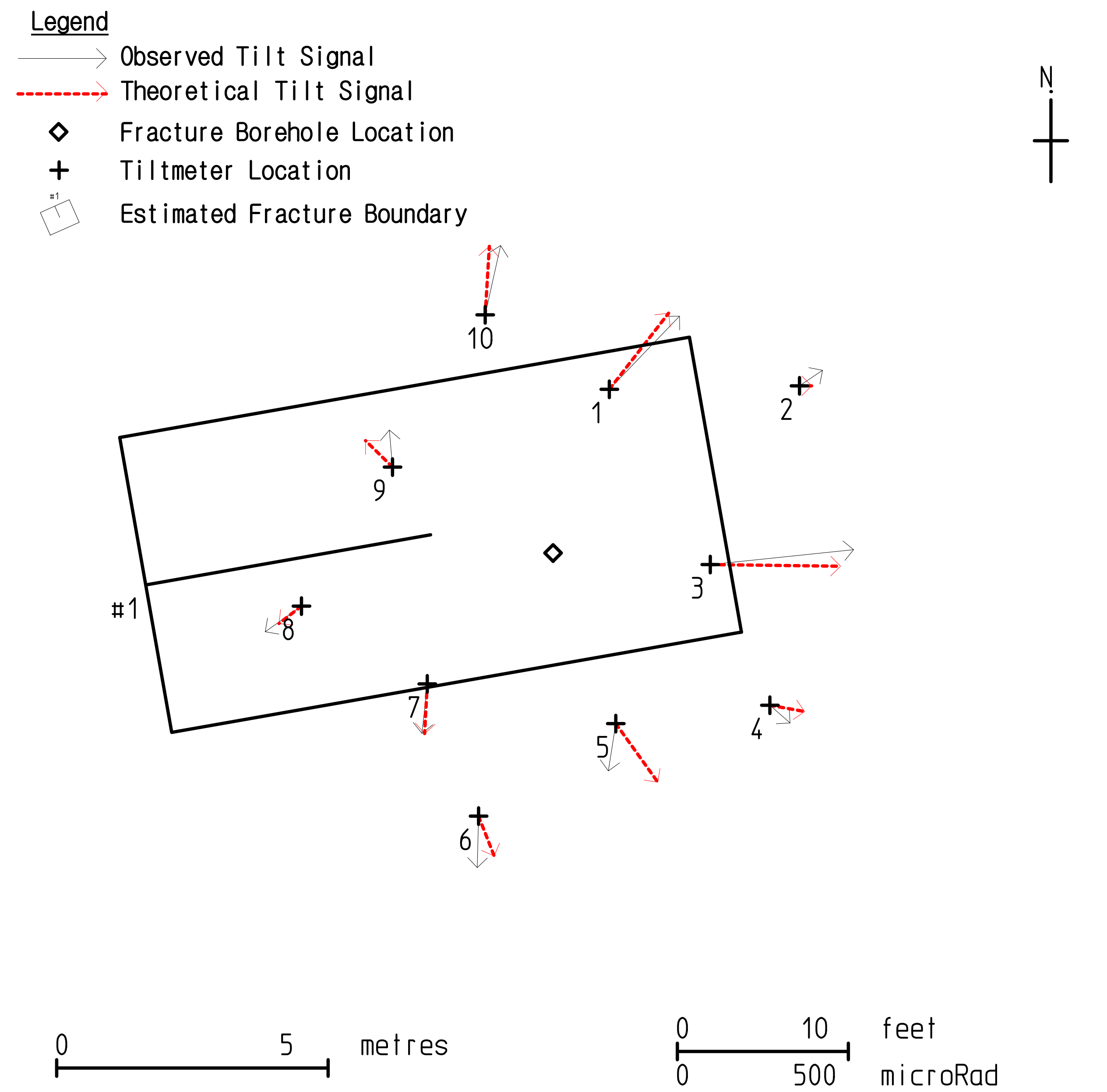


WELL: HIP-02-3
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	103	17	18	3.00	3	95%

Length = 26.8 ft, Width = 12.0 ft, Thickness = 0.050 ft
Normalized Vector Error = 0.185, RMS Error = 2.60E05 nRad

Geo Tactical 2017

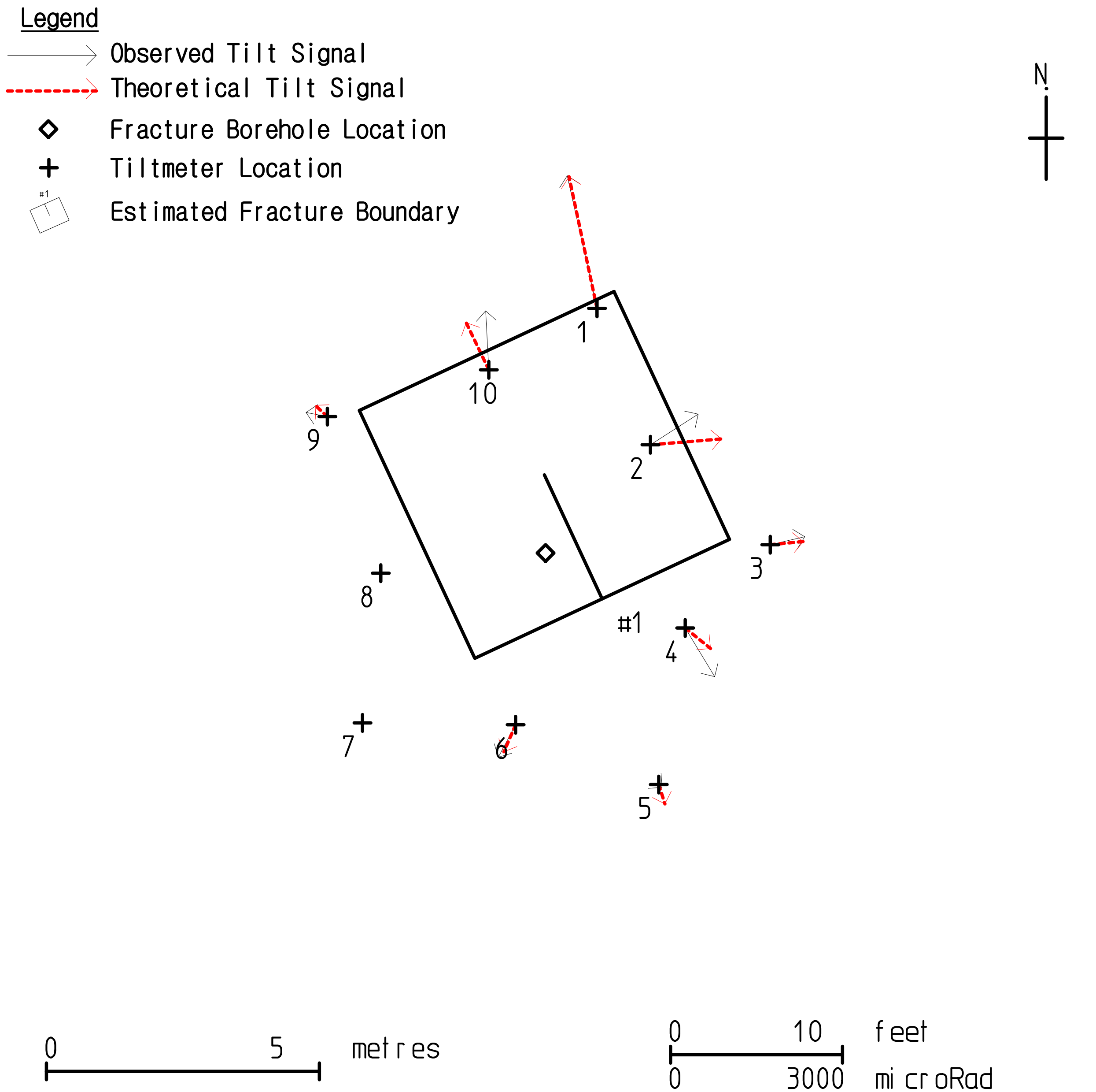


WELL: HIP-02-4
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	170	43	25	3.07	2	50%

Length = 18.1 ft, Width = 47.8 ft, Thickness = 0.010 ft
Normalized Vector Error = 0.110, RMS Error = 4.94E04 nRad

Geo Tactical 2017

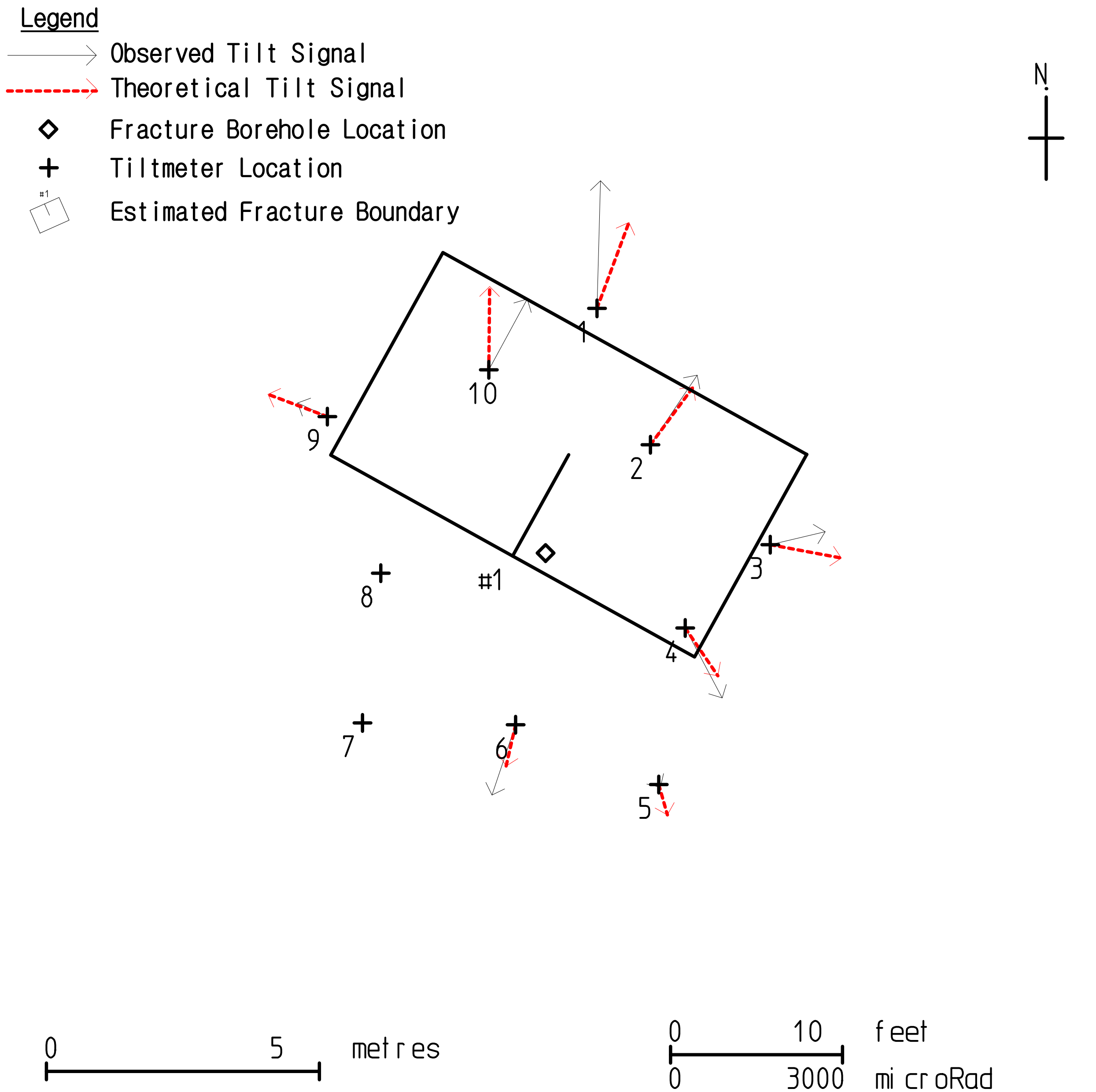


WELL: HIP-04-1
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	65	52	10.2	3.09	2	78%

Length = 16.9 ft, Width = 26.7 ft, Thickness = 0.030 ft
Normalized Vector Error = 0.095, RMS Error = 2.47E05 nRad

Geo Tactical 2017

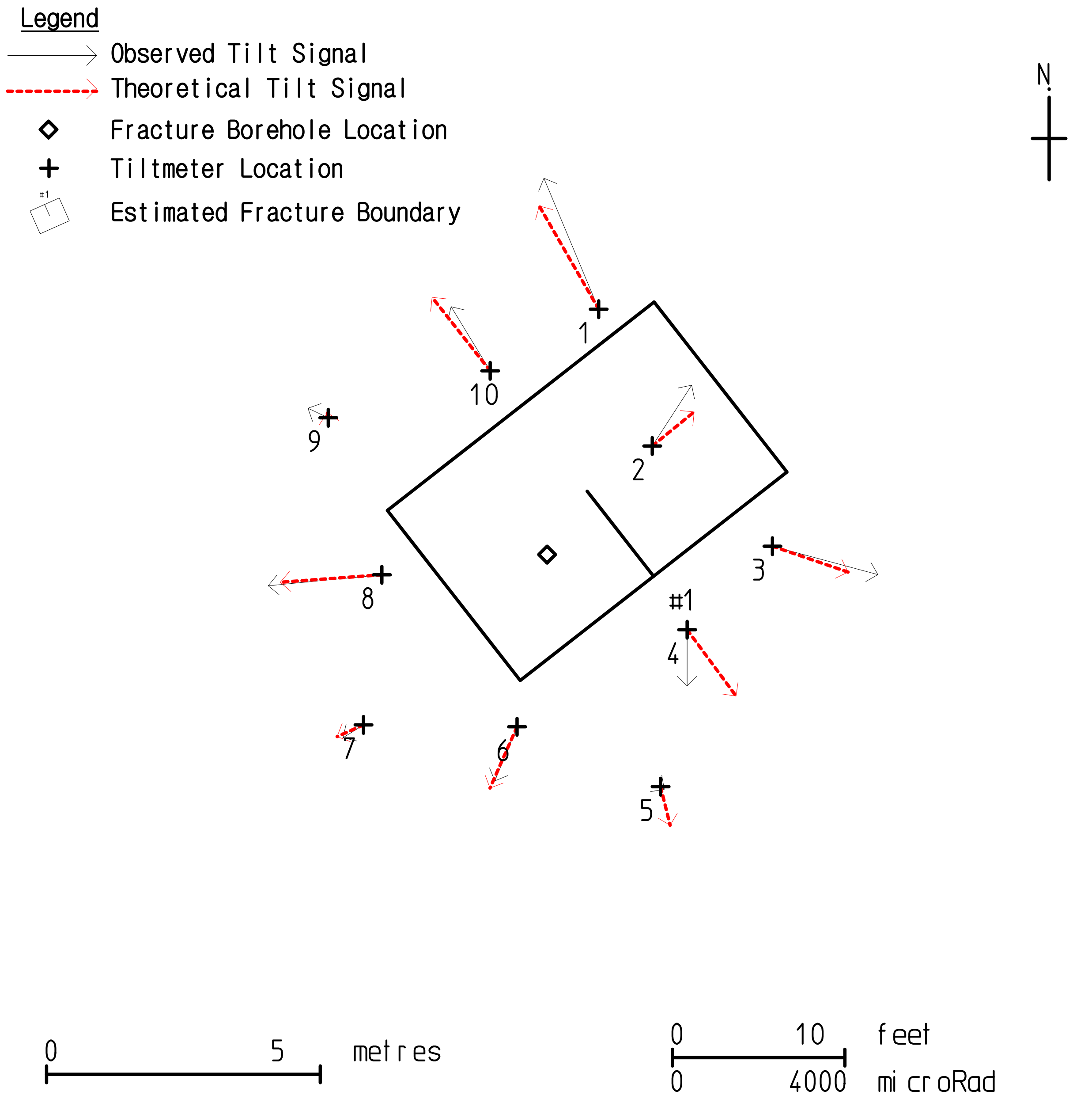


WELL: HIP-04-2
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	119	35	12.9	3.09	3	98%

Length = 25.0 ft, Width = 17.0 ft, Thickness = 0.040 ft
Normalized Vector Error = 0.202, RMS Error = 4.16E05 nRad

Geo Tactical 2017



WELL: HIP-04-3
DATE: 9/15/2016

FRAC #	AZ	DIP	DEPTH(FT)	INJECT. VOL.(bbl)	FRAC. VOL.	FRAC. EFF.
1	52	34	10.1	3.45	3	100%

Length = 20.3 ft, Width = 15.6 ft, Thickness = 0.061 ft
Normalized Vector Error = 0.115, RMS Error = 4.60E05 nRad

Geo Tactical 2017

APPENDIX III

SUBSURFACE DISTRIBUTION OF LACTOIL® FRACTURES

Fracture Boreholes at Grand Forks AFB Site

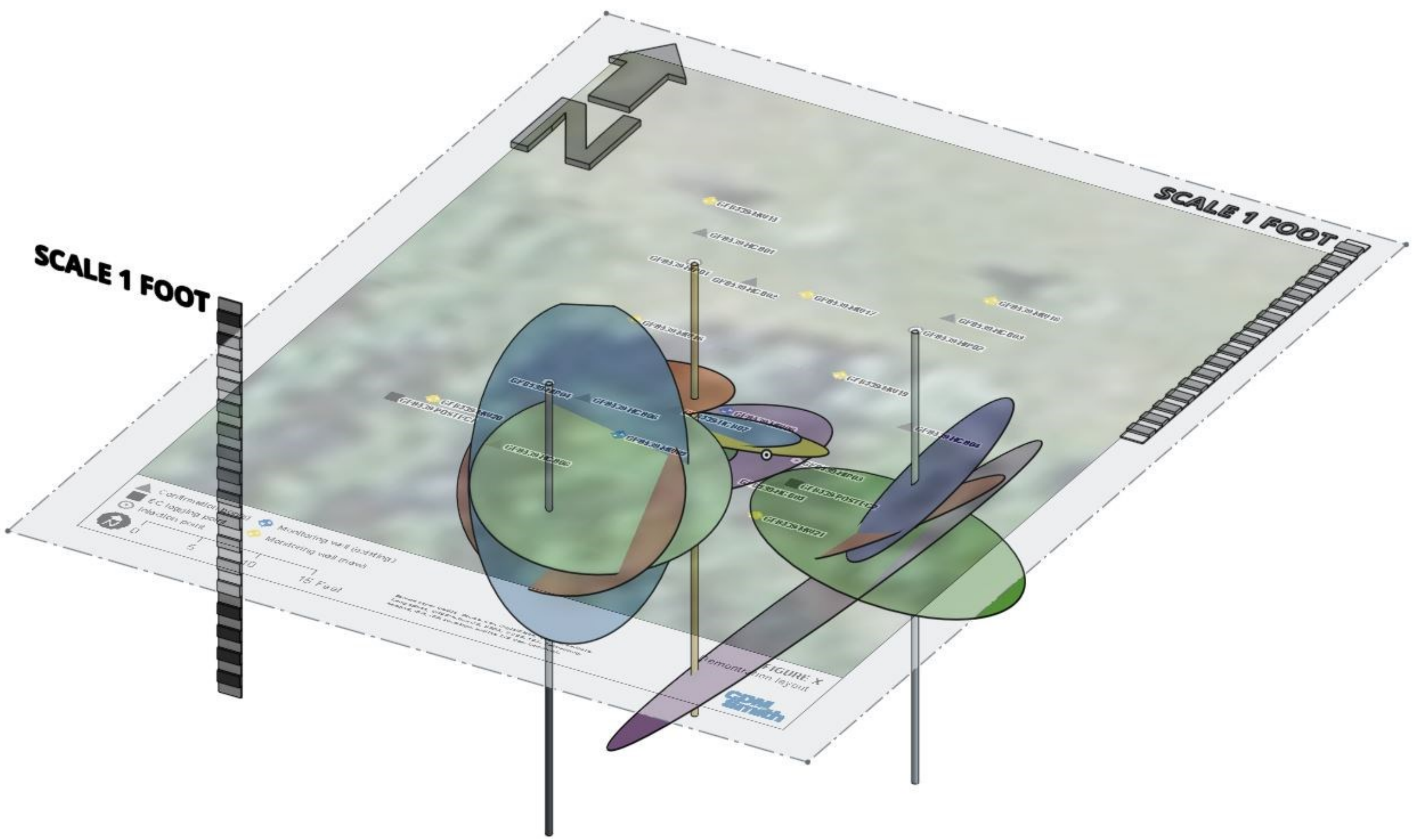


Figure III-1

Three dimensional representation of LactOil® distribution in the subsurface at the site

GeoTactical Remediation

Fracture Borehole HIP-01

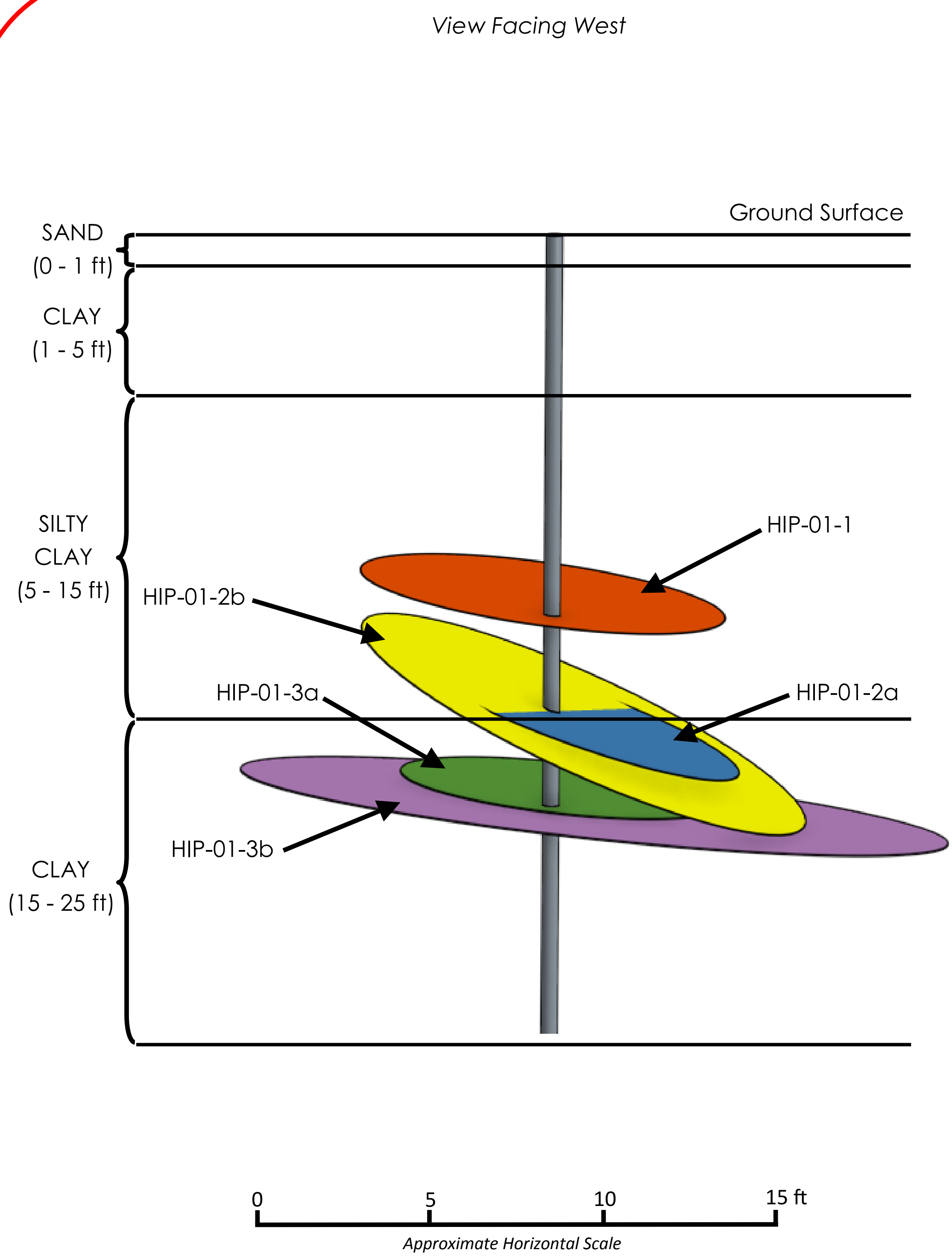


Figure III-2

Three dimensional representation of LactOil® distribution in the subsurface at HIP-01

GeoTactical Remediation

Fracture Borehole HIP-02

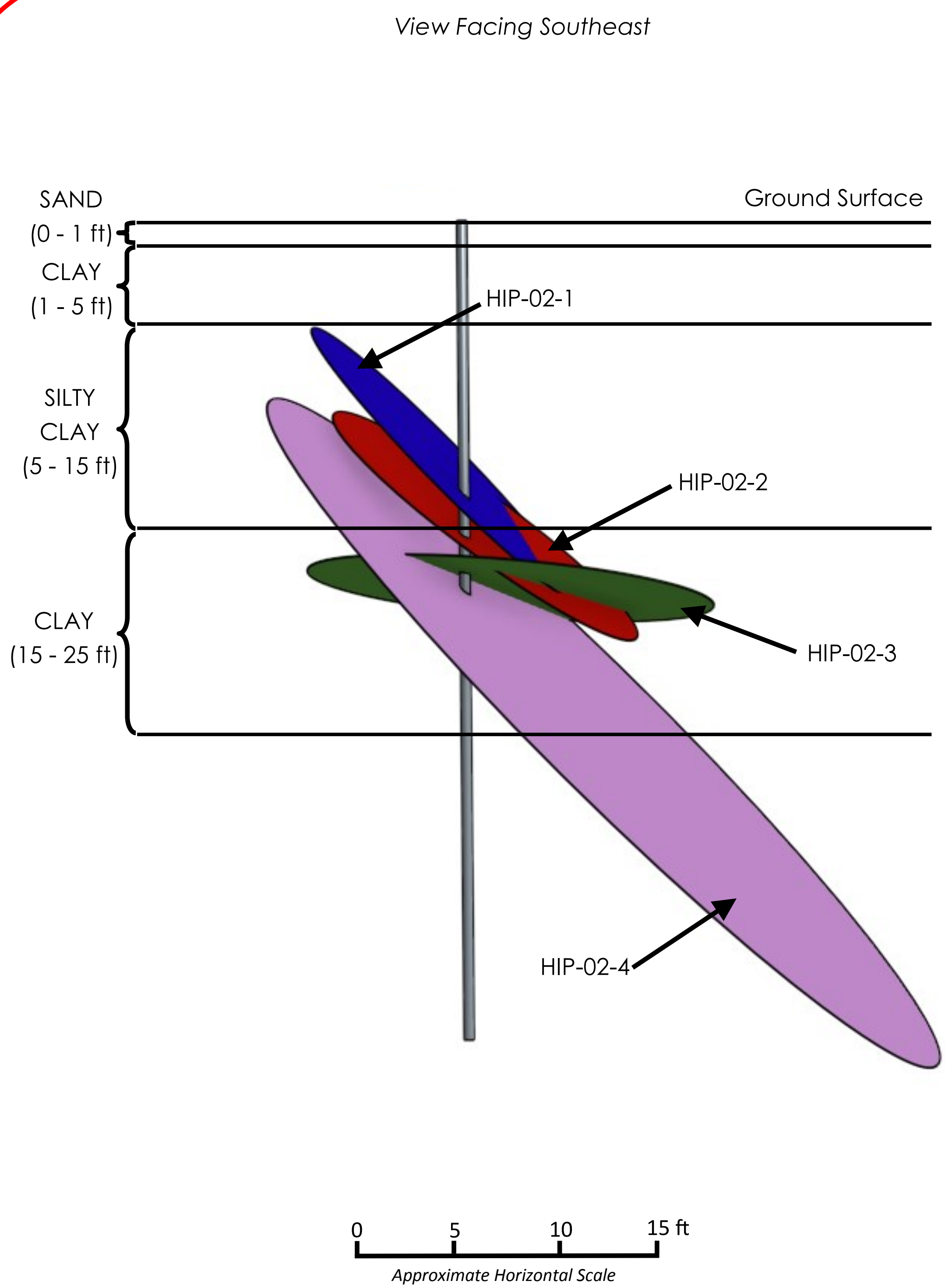


Figure III-3

Three dimensional representation of LactOil® distribution in the subsurface at HIP-02

GEOTACTICAL REMEDIATION

Fracture Borehole HIP-04

View Facing Northeast

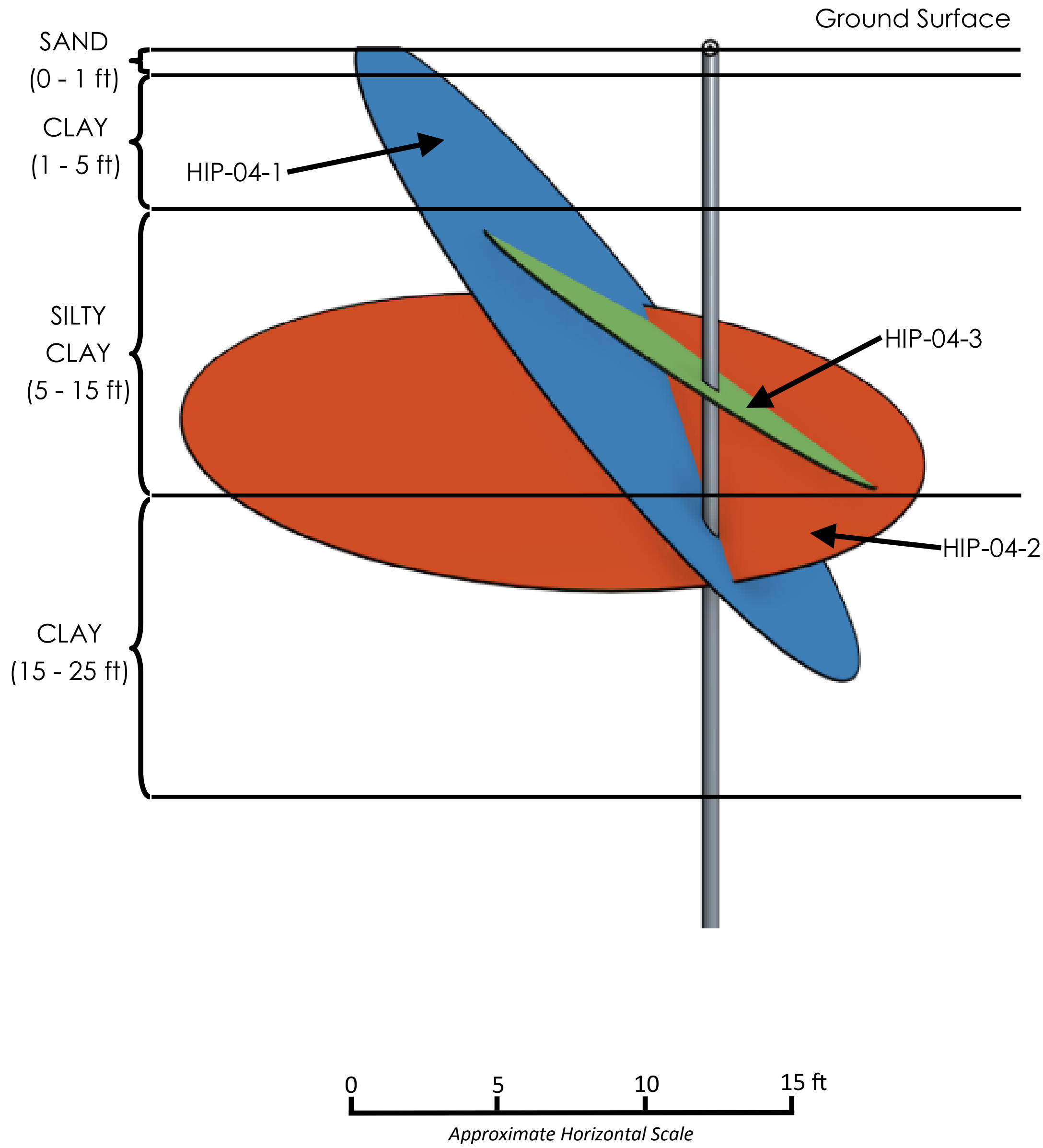


Figure III-4

Three dimensional representation of LactOil® distribution in the subsurface at HIP-04

GEOTACTICAL REMEDIATION

Pneumatic Fracturing Technology - Implementation Summary
ATK Lake City Munitions Plant – Independence, MO

Prepared For: CDM Smith Environmental, Inc.

Prepared By: Zebra Technical Services, LLC.

Date: May 27th, 2016

INTRODUCTION

This memorandum summarizes the **Pneumatic Fracturing (PF)** and amendment injection activities conducted at the Lake City Munitions Plant in Independence MO. Zebra Technical Services, LLC (ZTS) was contracted by CDM Smith to pneumatically fracture the site lithology and inject a combination of water, Lactoil and a salt tracer. This work was conducted as part of an ESTCP study into the application of PF and its effectiveness in comparison to other fracture-based remedial technologies.

The work scope entailed the injection of 110 gals of Lactoil and 187.5 lbs of salt tracer into three (3) injection points designated as PIW-01, PIW-02, and PIW-03. ZTS drilled the injection points utilizing a Geoprobe 7822 Drill. Each location was drilled to the bottom of the targeted treatment zone and addressed in a "bottom up" injection approach. 4.25 inch outer diameter (OD) solid flight augers were advanced to four feet below the target depth. A 3.4 inch O.D. packer string, with packers above and below the nozzle (called a "straddle-packer" configuration) was lowered into the borehole. The four feet of over-drill allowed for the use of the packer below the nozzle in the bottom of hole, thereby isolating a discrete fracture interval. This procedure was applied at all locations. The design treatment depth for each of the three points was 20' – 35'. The vertical treatment zone was divided into five lifts, 3 feet thick each, called intervals. Each injection point contained 5 intervals.

Field operations took place from March 22nd thru March 23rd. PF was successfully applied at all intervals in all 3 injection points. The designed dosage of Lactoil and salt was emplaced into the fractures at all intervals in all three injections.

PF AND INJECTION SUMMARY

The following is a concise description of the injection activities at each of the three injection points as completed in chronological order.

Injection Point PIW-02

Fracture initiation pressures ranged from 150 to 250 PSI with maintenance pressures of 130 to 200 PSI. **Appendix A** displays the pressure vs time fracture curves for all five PF events in PIW-02. Within a few seconds of fracture initiation, blow-by of gas and groundwater occurred from within the borehole during each PF event. The PF events for intervals 2, 3, and 4 displayed distinct peaks of initiation pressure, which correspond to fracture creation and propagation. The PF events for intervals 1 and 5 displayed low peaks or flat pressure curves which correspond to zones of the formation where there was higher permeability.

Pressure influence during PF events was monitored at adjacent monitoring wells and injection points for all intervals. Pressure influence data indicates that fractures were propagated in all directions. Strong pressure influence between injection point and all nearby monitoring wells was observed with a maximum pressure of 26.5 PSI at PMW-2during PF of the deepest interval in PIW-02. **Appendix B** displays pressure influence data for all intervals addressed in PIW-02.

Ground surface heave was measured utilizing two heave rods in different directions around each PF location. Surface heave was detected during PF events out to a distance of 12 ft. during PF events in the deepest two intervals of PIW-02. Due to the blow-by of gas during the PF events, the duration of gas application was reduced for all subsequent PF events in PIW-02, thereby leading to reduction in observable surface heave. **Appendix B** displays the surface heave data for all intervals addressed in PIW-02.

Amendment injection of Lactoil and salt was completed in all 5 intervals of PIW-02. Target volume was achieved with a flow rate of 7 to 11 GPM and injection pressure of 5 – 20 PSI. Very minimal daylighting of amendment was observed from the injection borehole. The daylighting was stopped by adjusting the flow rate of the amendment.

Injection Point PIW-03

Fracture initiation pressures ranged from 175 to 225 PSI with maintenance pressures of 165 to 195 PSI. **Appendix A** displays the pressure vs time fracture curves for all five PF events in PIW-03. Within a few seconds of fracture initiation, blow-by of gas and groundwater occurred from within the borehole during each PF event. The PF events for intervals 2, 3, 4, and 5 displayed distinct peaks of initiation pressure, which correspond to fracture creation and propagation. The PF event for interval 1 displayed low peaks or flat pressure curves which correspond to a zone of the formation where there was higher permeability.

Pressure influence during PF events was monitored at adjacent monitoring wells and injection points for all intervals. Pressure influence data indicates that fractures were propagated in all directions. Strong pressure influence between injection point and all nearby monitoring wells was observed with a maximum pressure of 19 PSI at PMW-04 during PF of the deepest interval in PIW-03. Strong pressure influence between PIW-03 and the completed location PIW-02 was observed during all PF events in PIW-03. **Appendix B** displays pressure influence data for all intervals addressed in PIW-03.

Ground surface heave was measured utilizing two heave rods in different directions around each PF location. Due to the blow-by of gas during the PF events, the duration of gas application was reduced for all PF events in PIW-03, thereby leading to reduction in observable surface heave. **Appendix B** displays the surface heave data for all intervals addressed in PIW-03.

Amendment injection of Lactoil and salt was completed in all 5 intervals of PIW-03. Target volume was achieved with a flow rate of 10 to 11 GPM and injection pressure of 5 – 10 PSI. No daylighting of amendment was observed.

<u>Injection Point PIW-01</u>

Fracture initiation pressures ranged from 150 to 205 PSI with maintenance pressures of 145 to 175 PSI. **Appendix A** displays the pressure vs time fracture curves for all five PF events in PIW-01. Within a few seconds of fracture initiation, blow-by of gas and groundwater occurred from within the borehole during each PF event. The PF events for intervals 2, 3, 4, and 5 displayed moderate to distinct peaks of initiation pressure, which correspond to fracture creation and propagation. The PF event for interval 1 displayed low peaks or flat pressure curves which correspond to a zone of the formation where there was higher permeability.

Pressure influence during PF events was monitored at adjacent monitoring wells and injection points for all intervals. Pressure influence data indicates that fractures were propagated in all directions. Pressure influence between injection point and all nearby monitoring wells was observed with a maximum pressure of 7.2 PSI at 16MW76 during PF of the third interval in PIW-01. Pressure influence between PIW-01 and the completed locations of PIW-3 and PIW-02 was observed during all PF events in PIW-01. The magnitude of this influence was low due to formation collapse through the vertical treatment zone the competed locations. **Appendix B** displays pressure influence data for all intervals addressed in PIW-03.

Ground surface heave was measured utilizing two heave rods in different directions around each PF location. Due to the blow-by of gas during the PF events, the duration of gas application was reduced for all PF events in PIW-01, thereby leading to reduction in observable surface heave. **Appendix B** displays the surface heave data for all intervals addressed in PIW-01.

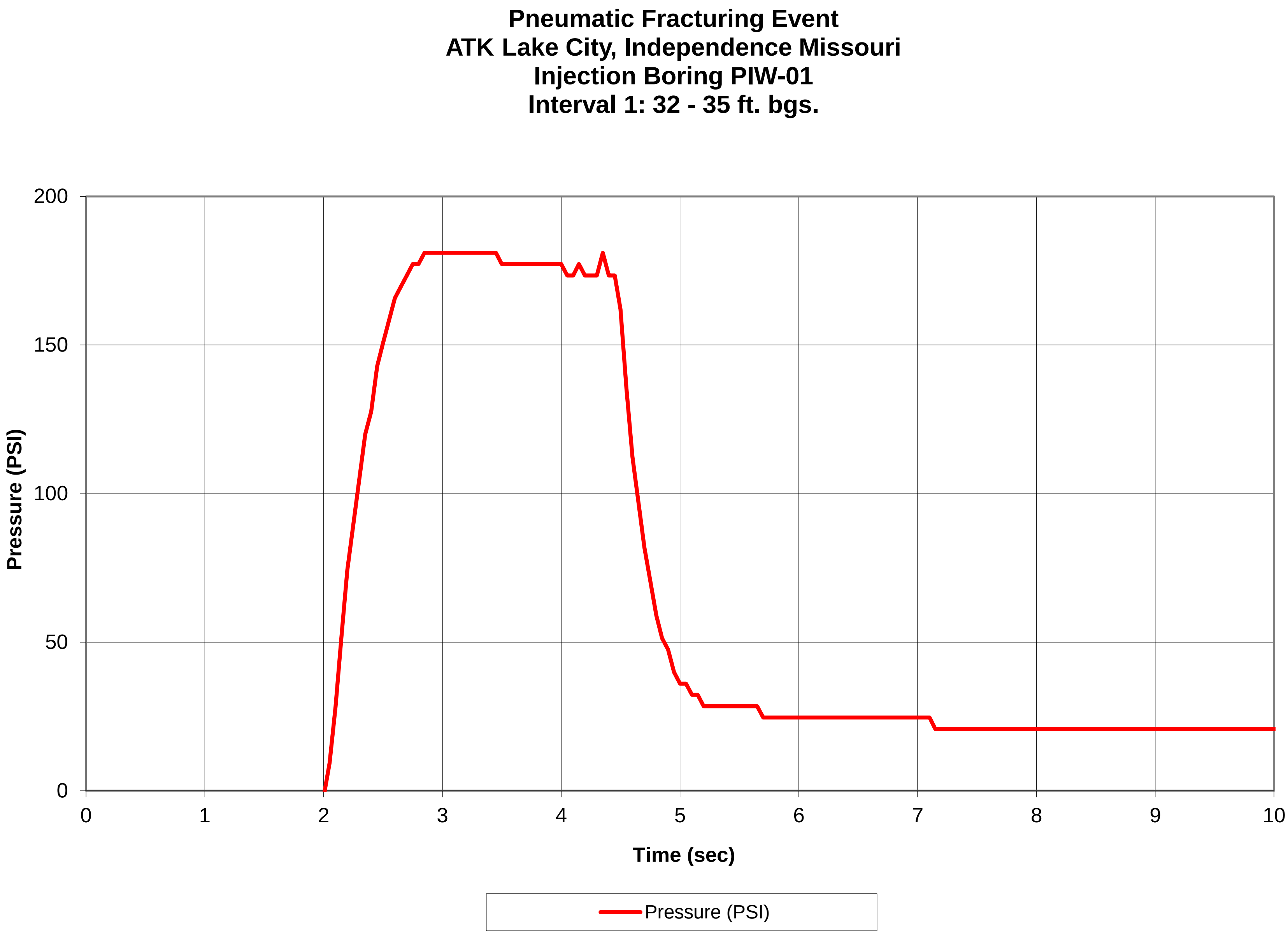
Amendment injection of Lactoil and salt was completed in all 5 intervals of PIW-01. Target volume was achieved with a flow rate of 10 to 11 GPM and injection pressure of 5 – 10 PSI. No daylighting of amendment was observed.

NOTES AND OBSERVATIONS

PF was successfully applied to all intervals in all selected injection locations. Pressure influence at the surrounding wells indicate a uniform radial distribution of fractures with an average Radius of Influence (ROI) of 12 – 14 feet. Pressure influence detected between injection points indicates that a fracture network connectingall three locations has been created.

The blow-by of gas during PF events in all intervals was due primarily to the soft and maleable nature of the formation above the targeted treatment zone. Despite the blow-by, the packers used to seal the formation were effect enough to allow for fracture creation, propogation and strong prersure influenc at surrounding wells.

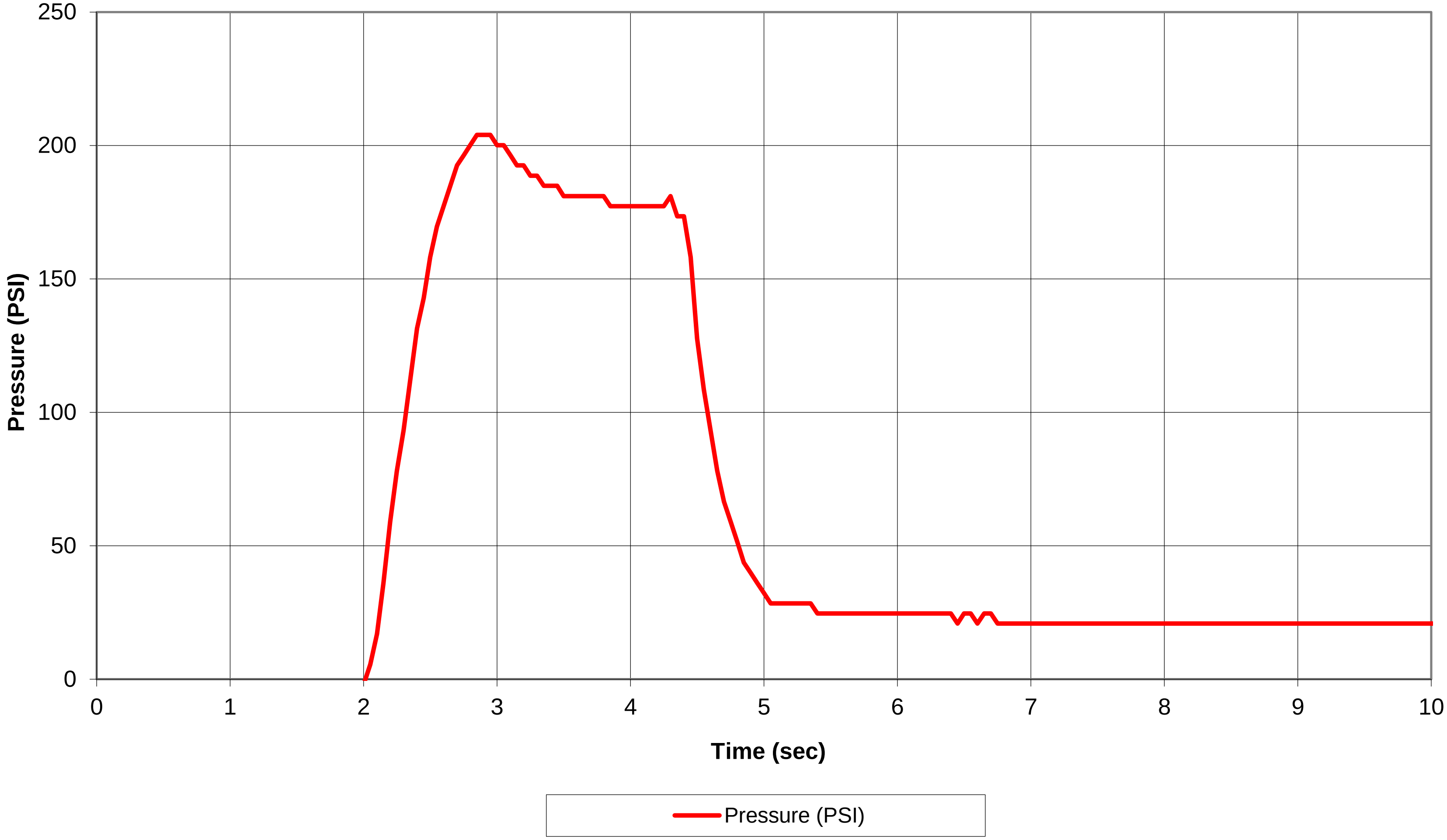
The targeted volume of Lactoil and salt was applied to all intervals in all injetcion locations with no loss of product due to daylighting. After fracturing, a consistant flow rate of 10 GPM could be maintained in most intervals.



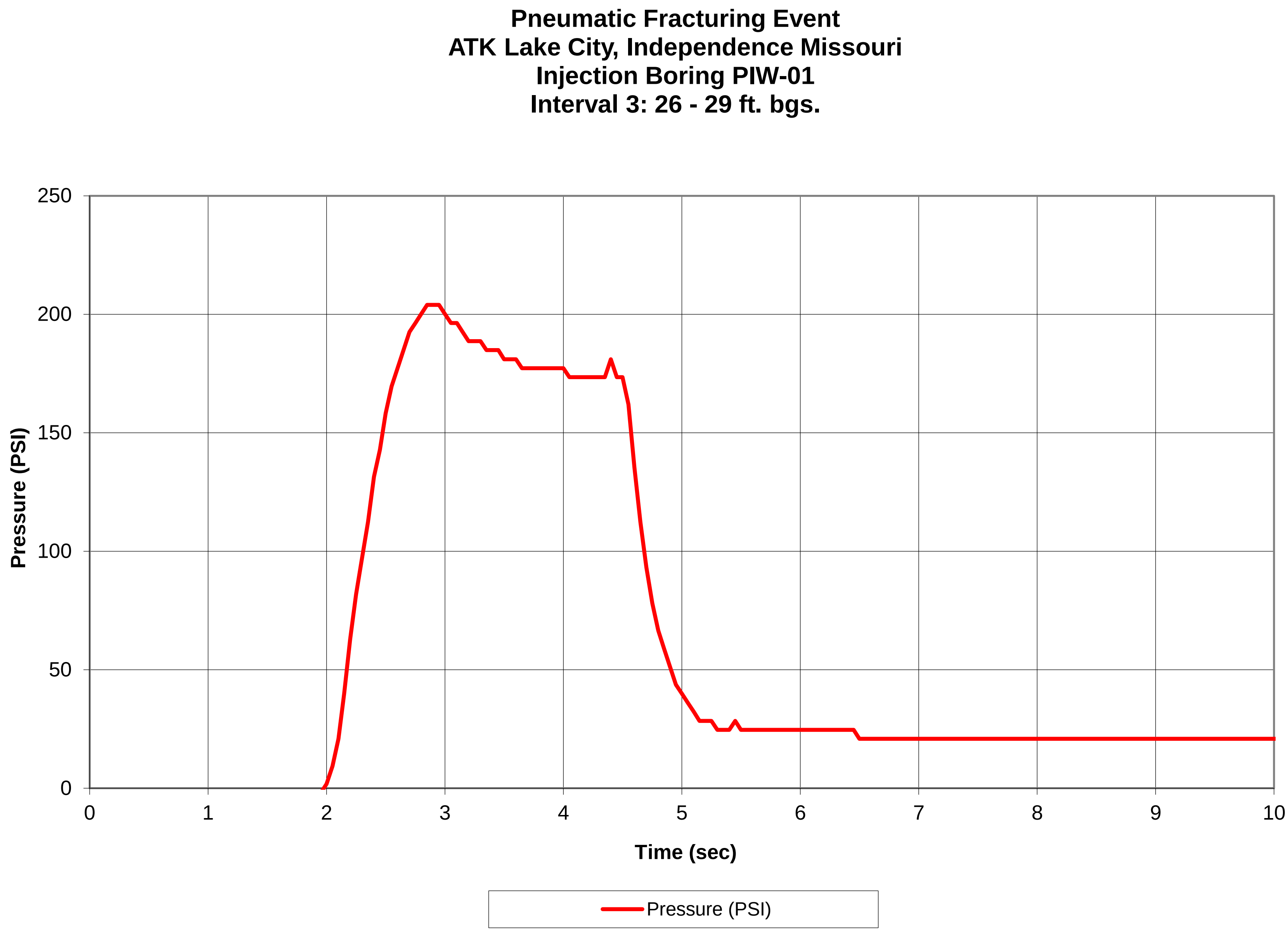
Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-01
Interval 1: 32 - 35 ft. bgs.
200
150
100
50
0
Pressure (PSI)
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-01-1F

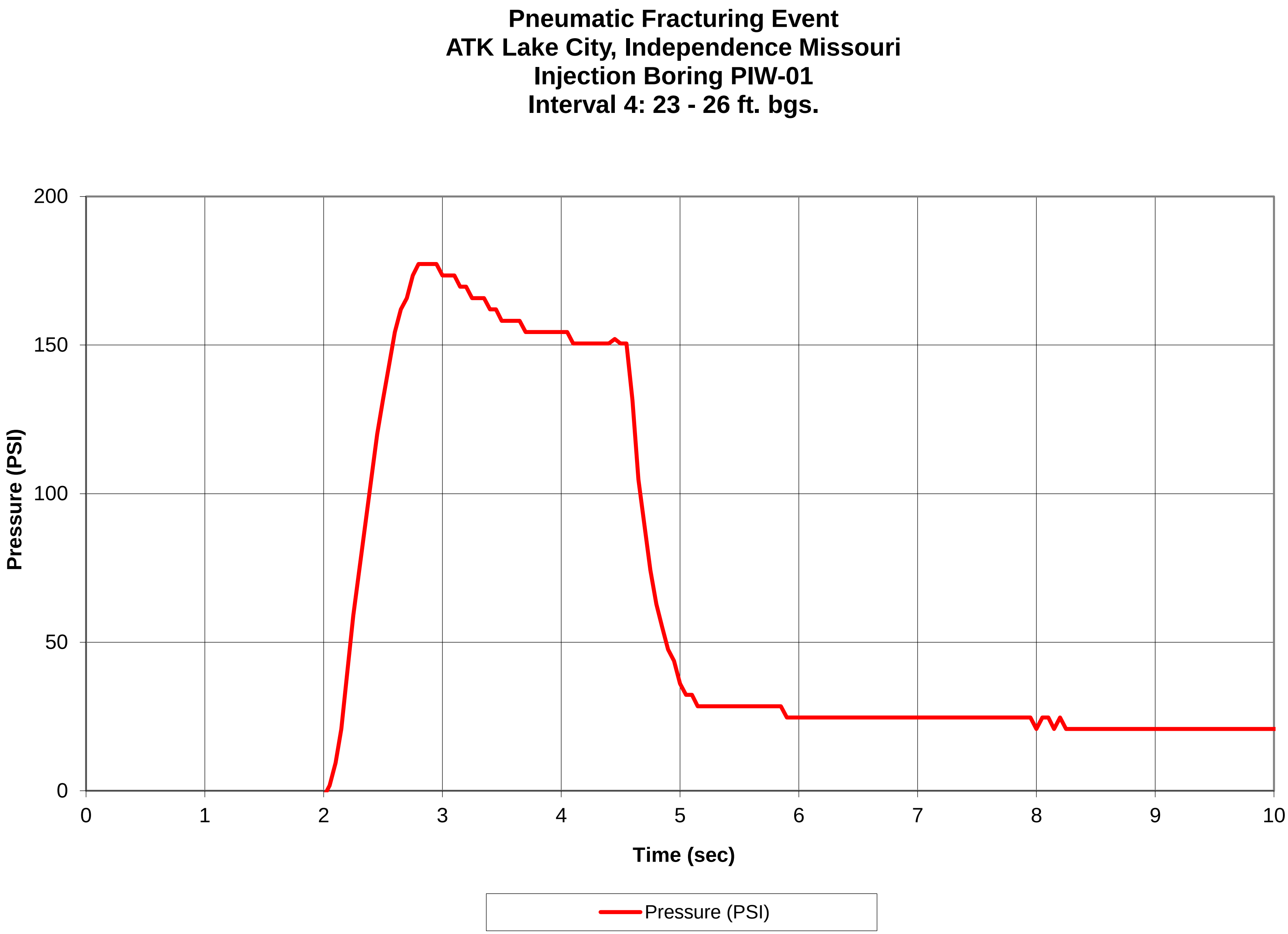
Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-01
Interval 2: 29 - 32 ft. bgs.



PIW-01-2F


Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-01
Interval 3: 26 - 29 ft. bgs.
Pressure (PSI)
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

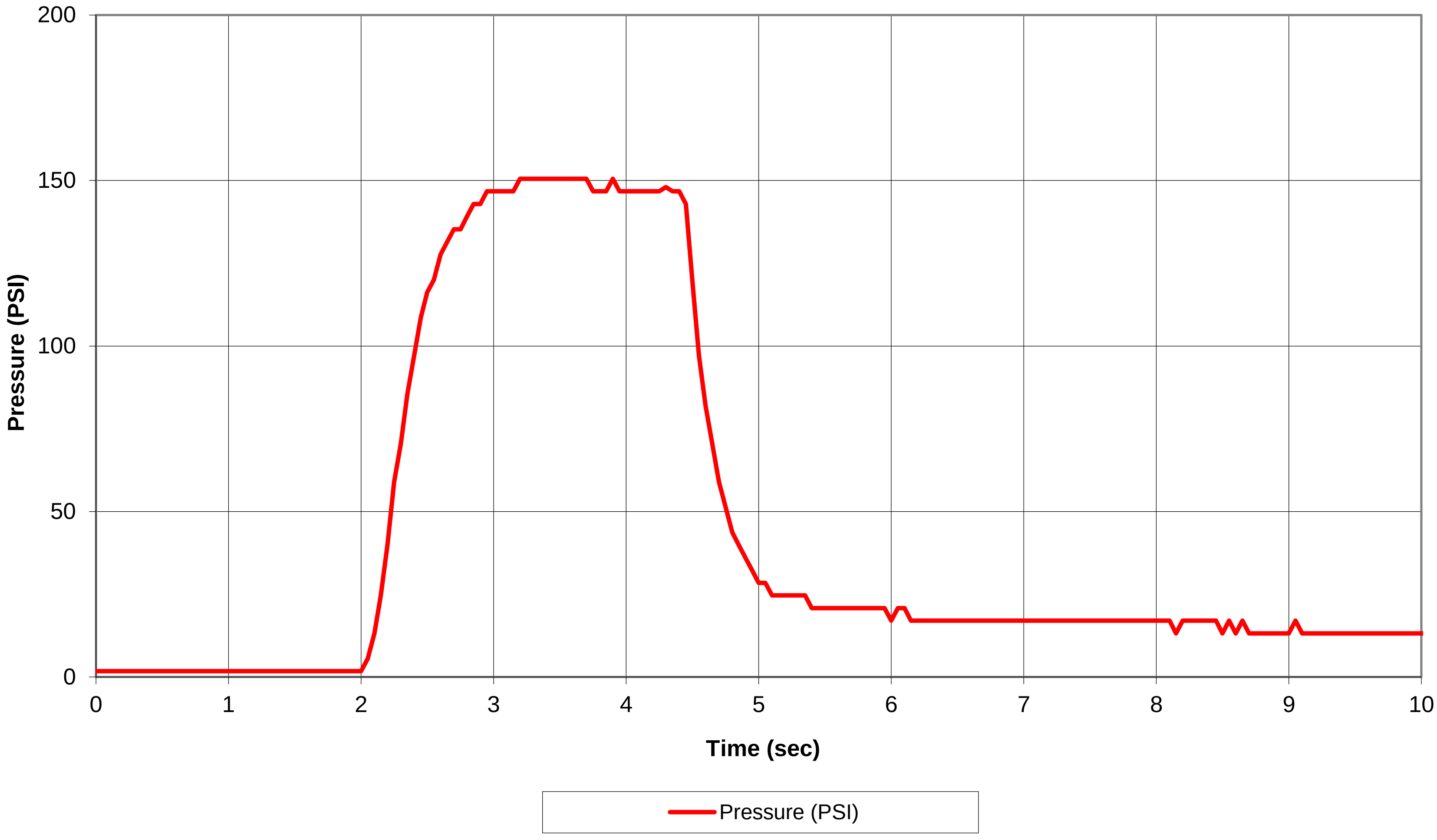
PIW-01-3F



Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-01
Interval 4: 23 - 26 ft. bgs.
200
150
100
50
0
Pressure (PSI)
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

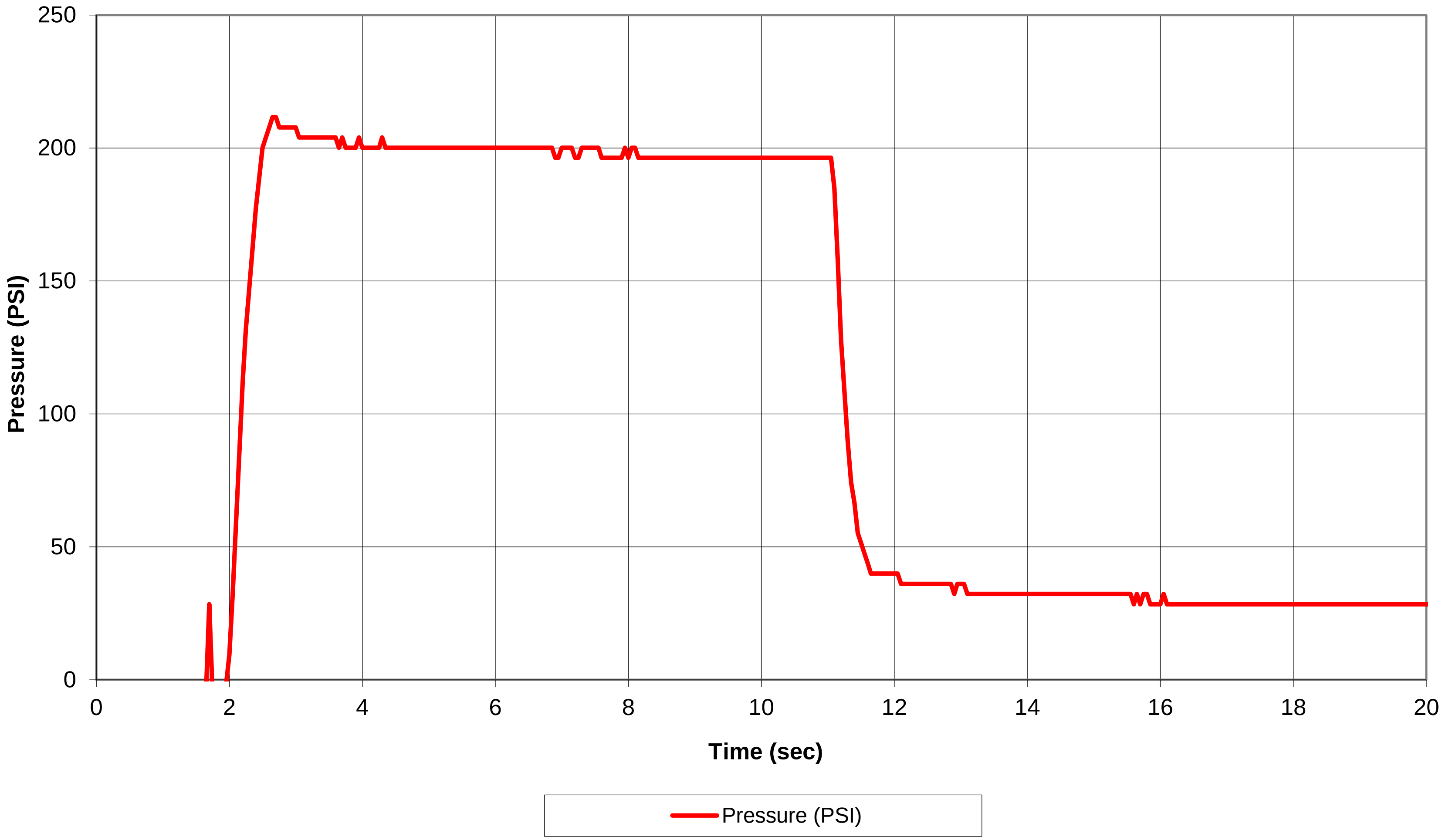
PIW-01-4F

Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-01
Interval 5: 20 - 23 ft. bgs.

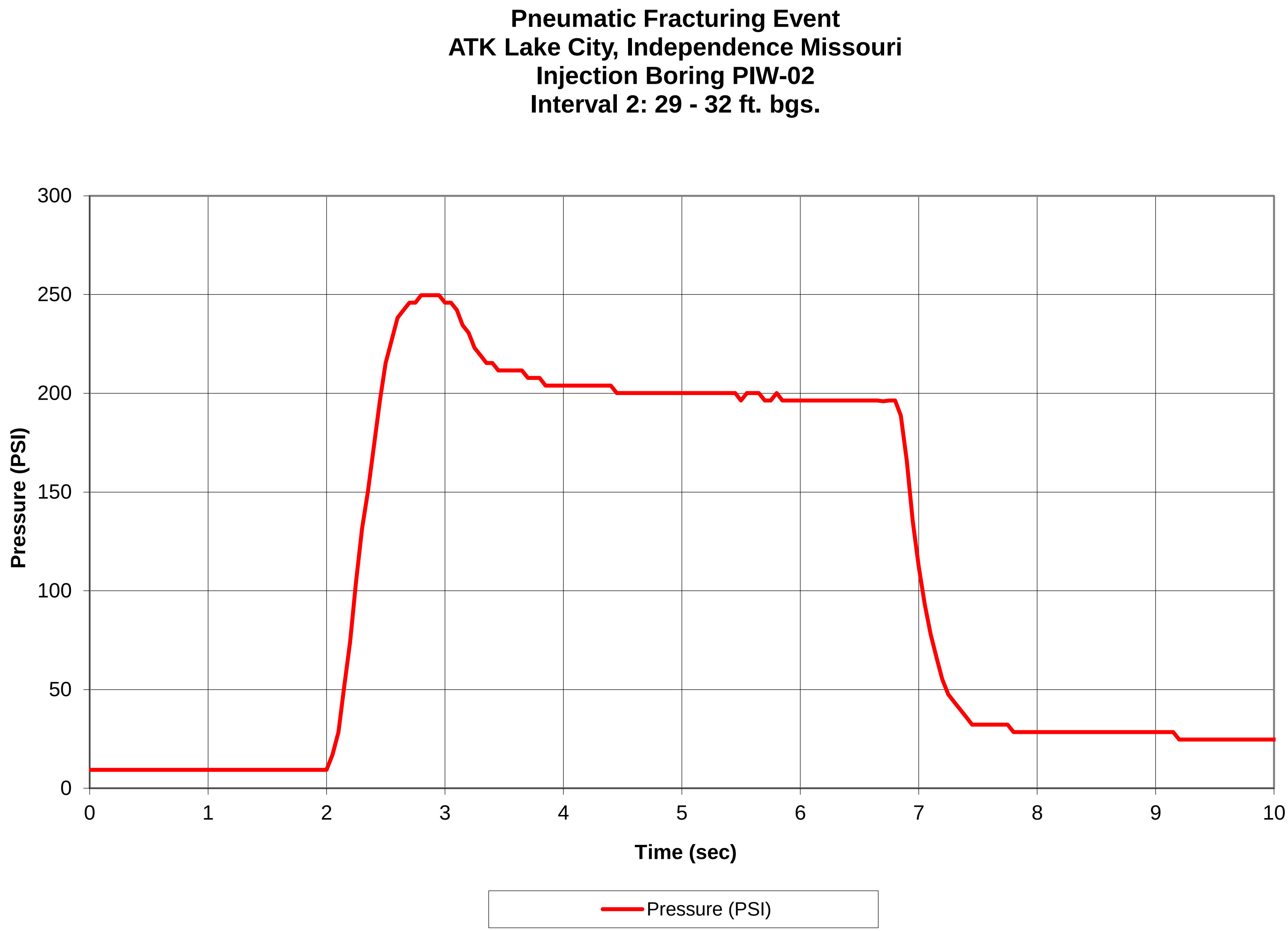


PIW-01-5F

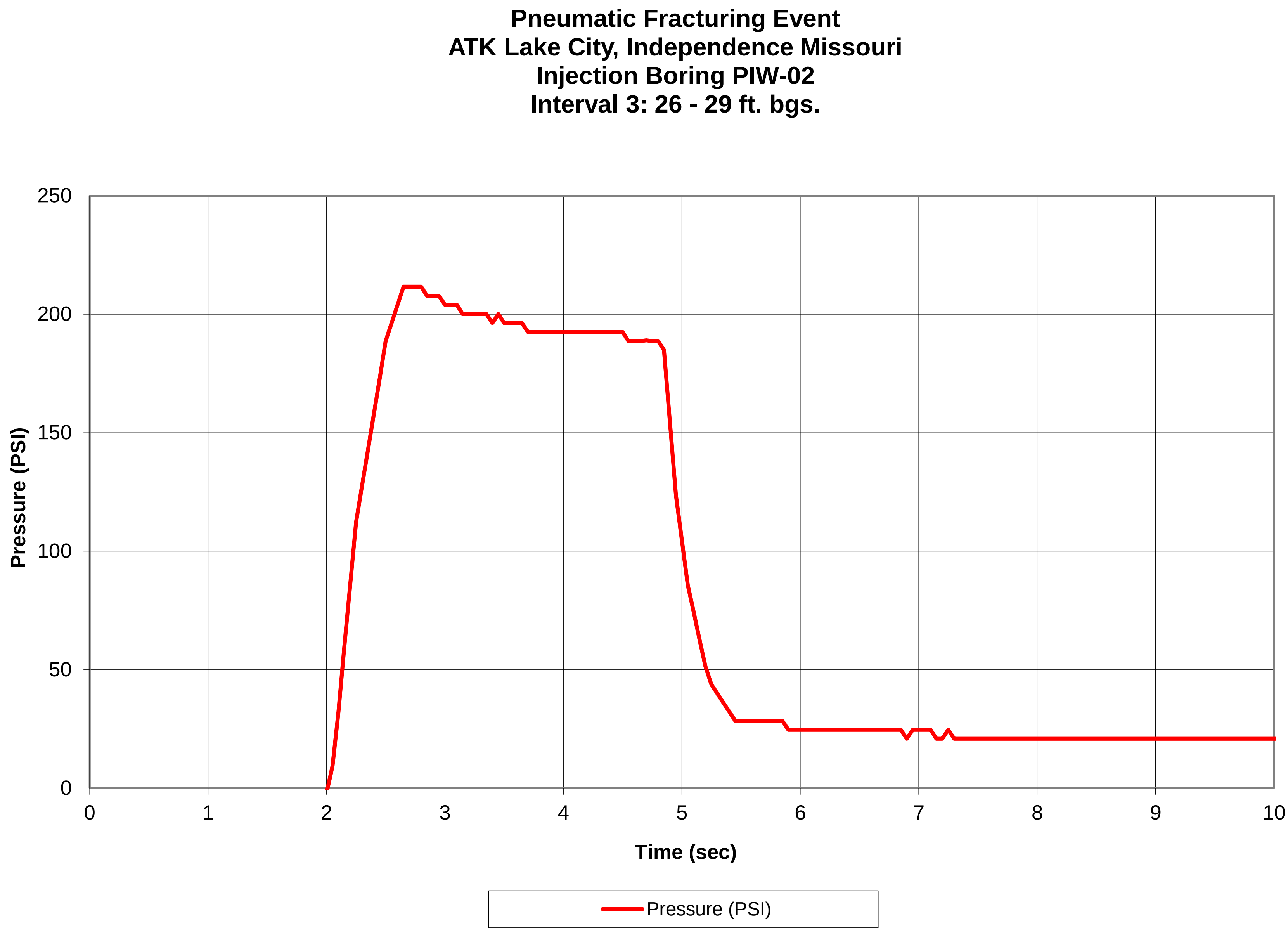
Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-02
Interval 1: 32 - 35 ft. bgs.



PIW-02-1F

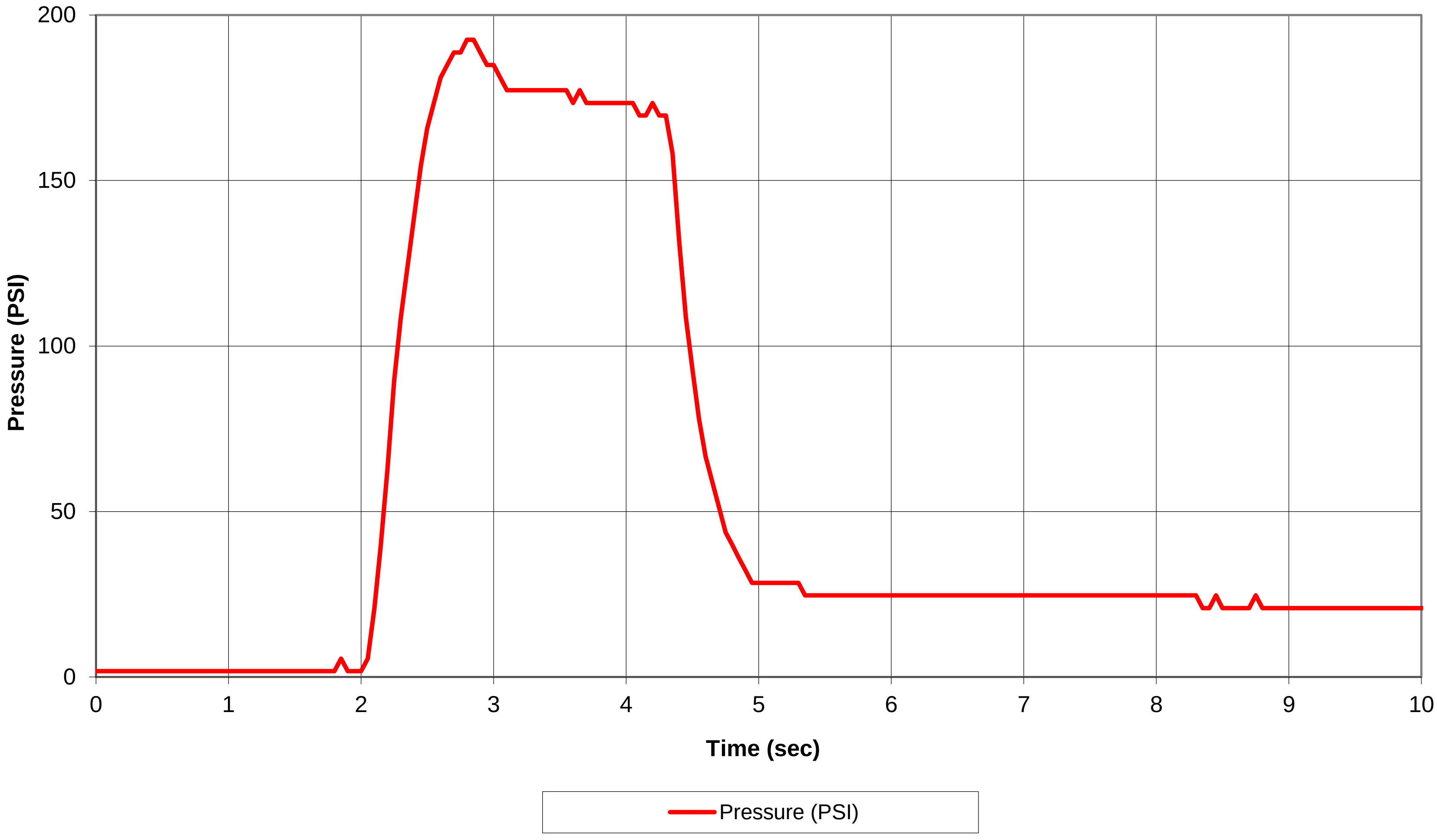

Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-02
Interval 2: 29 - 32 ft. bgs.
Pressure (PSI)
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-02-2F

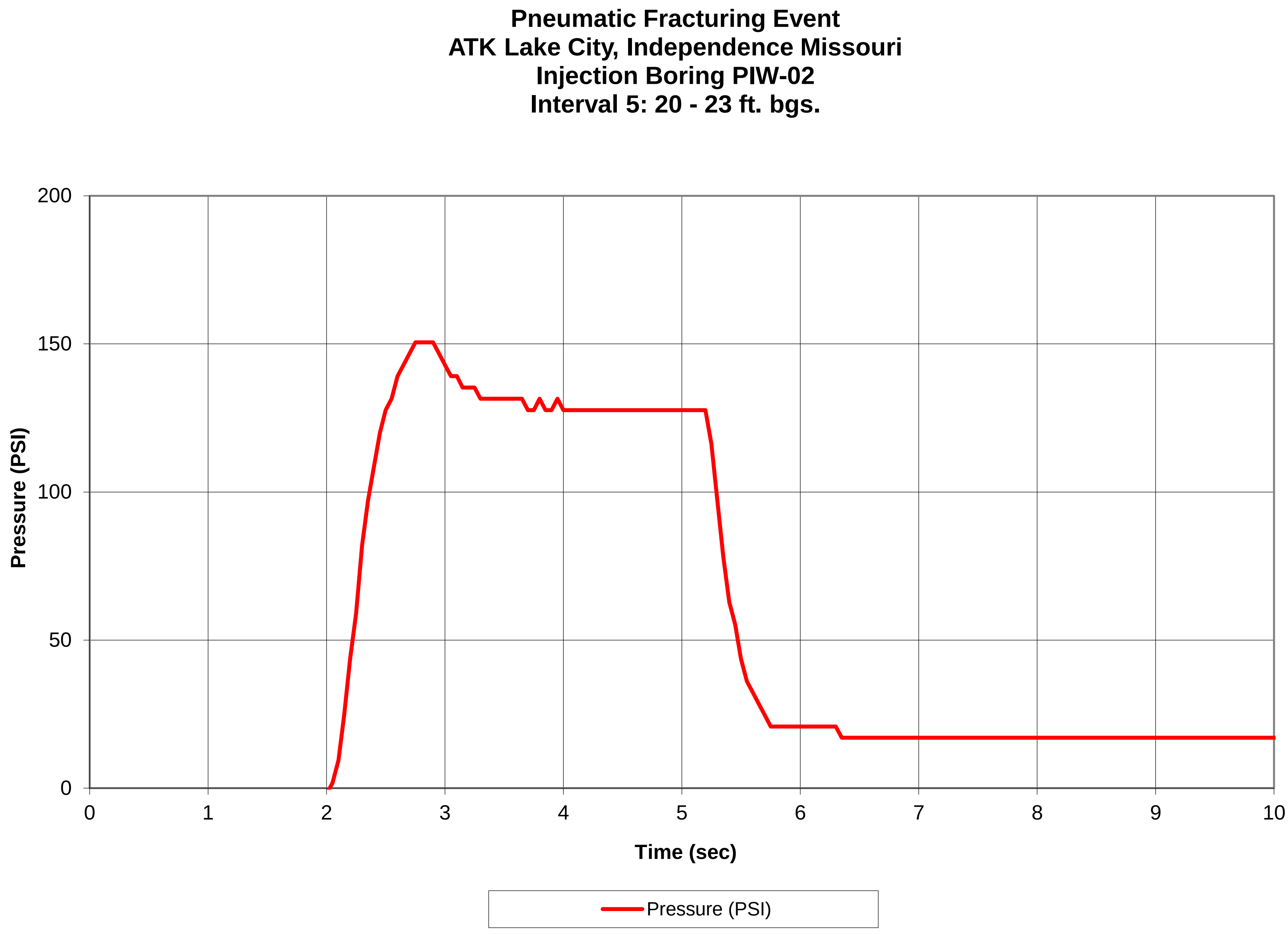

Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-02
Interval 3: 26 - 29 ft. bgs.
250
200
150
100
50
0
Pressure (PSI)
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-02-3F

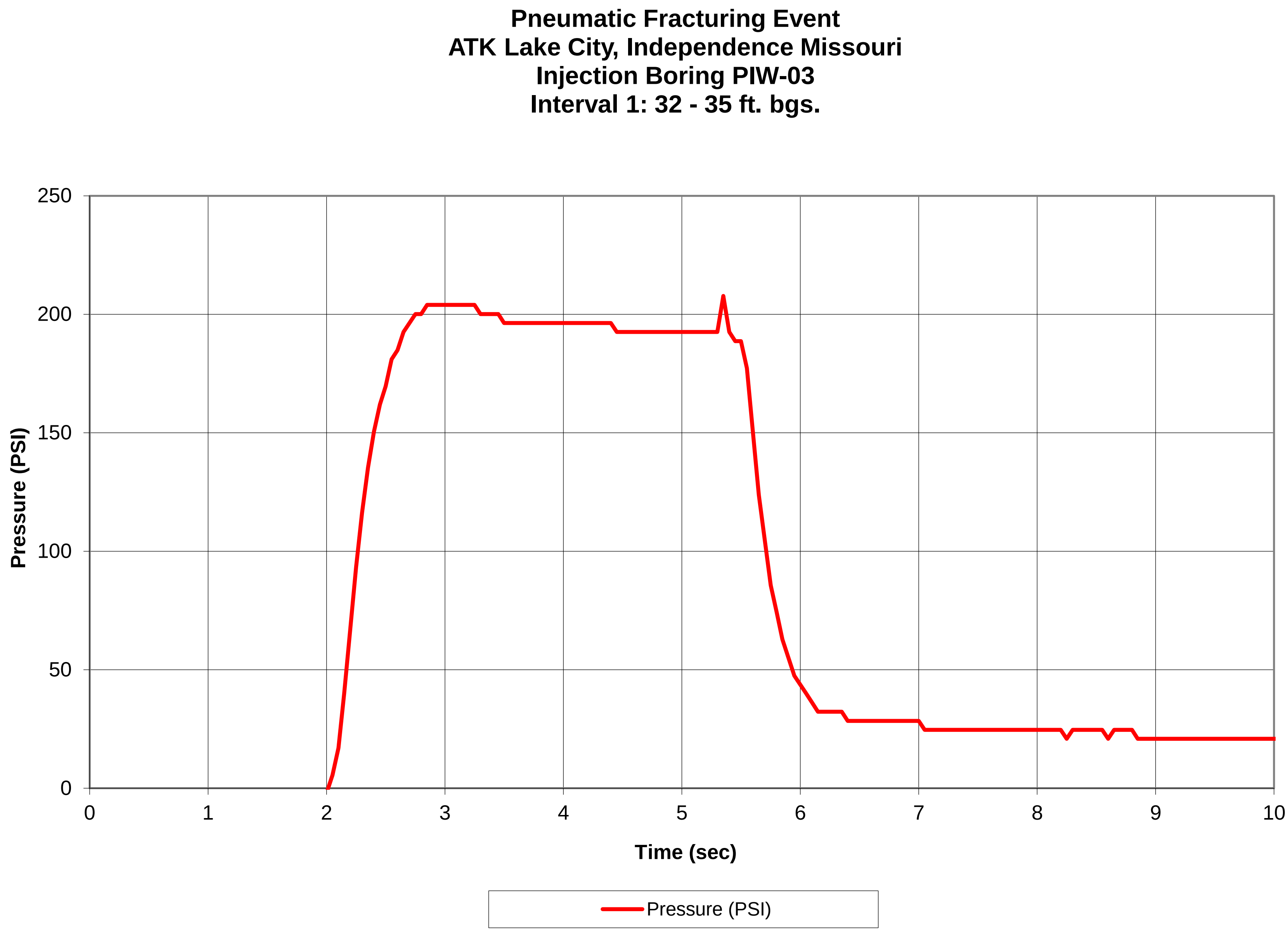
Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-02
Interval 4: 23 - 26 ft. bgs.



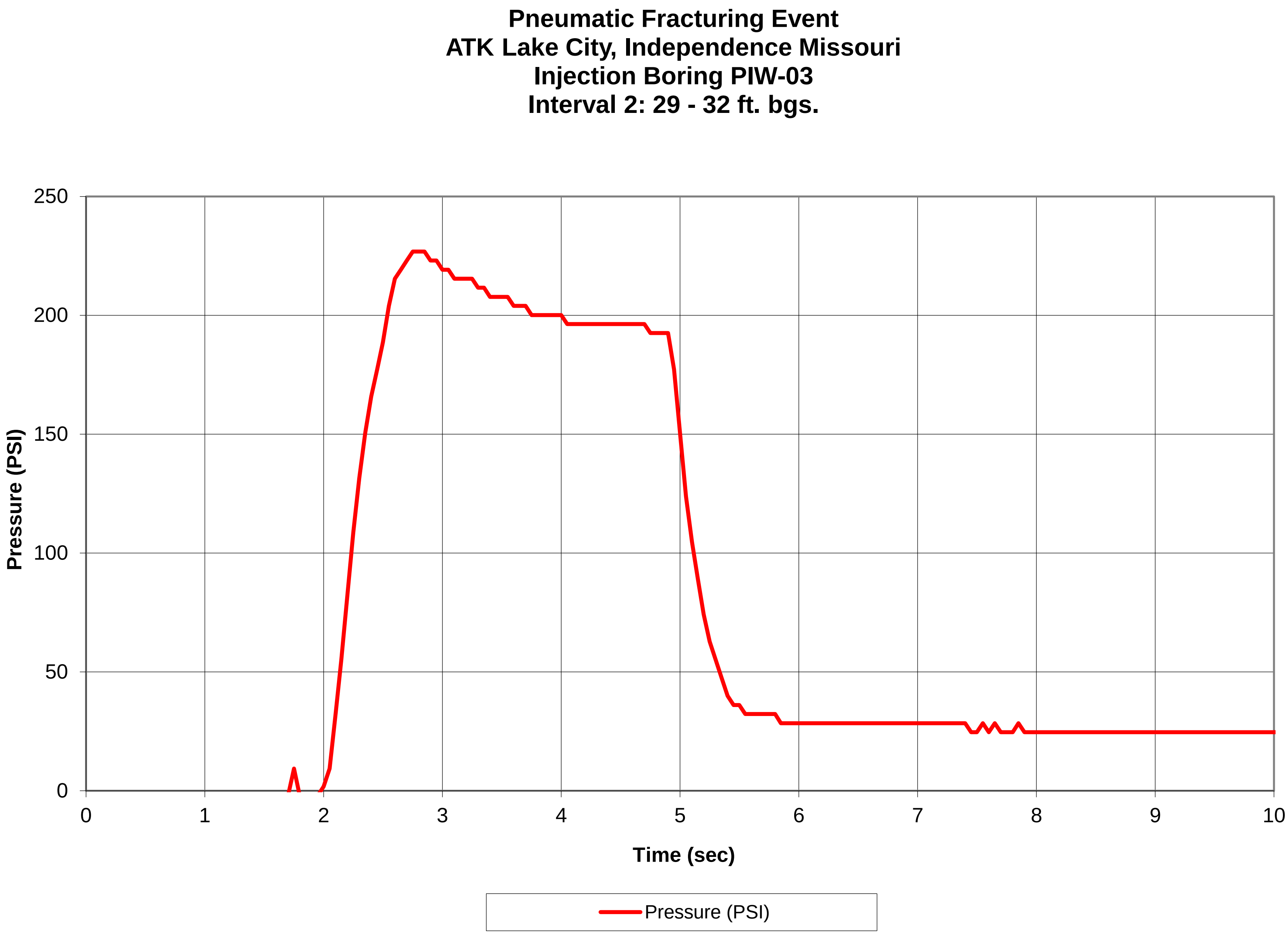
PIW-02-4F


Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-02
Interval 5: 20 - 23 ft. bgs.
200
150
100
50
0
Pressure (PSI)
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

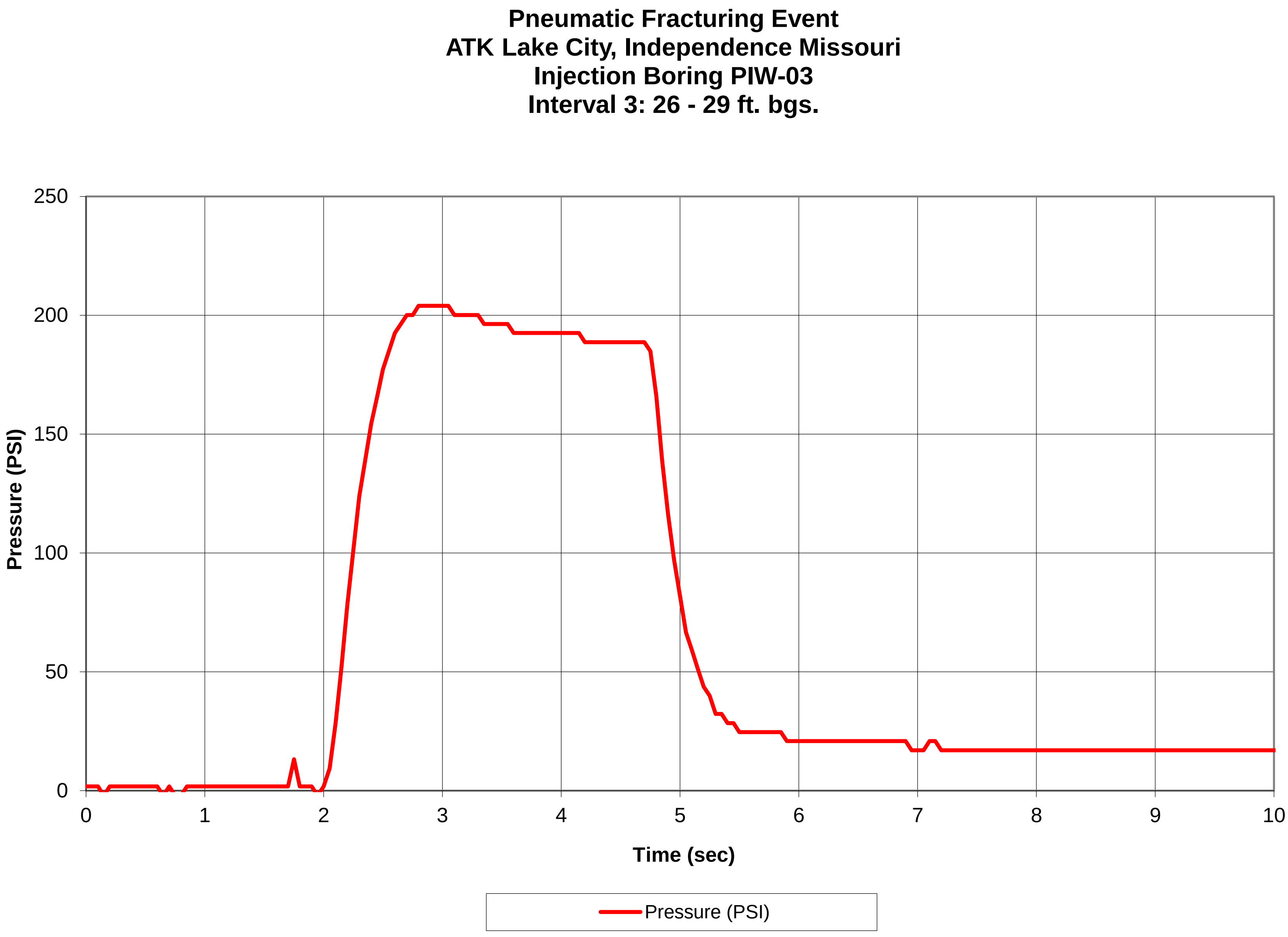
PIW-02-5F


Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-03
Interval 1: 32 - 35 ft. bgs.
Pressure (PSI)
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

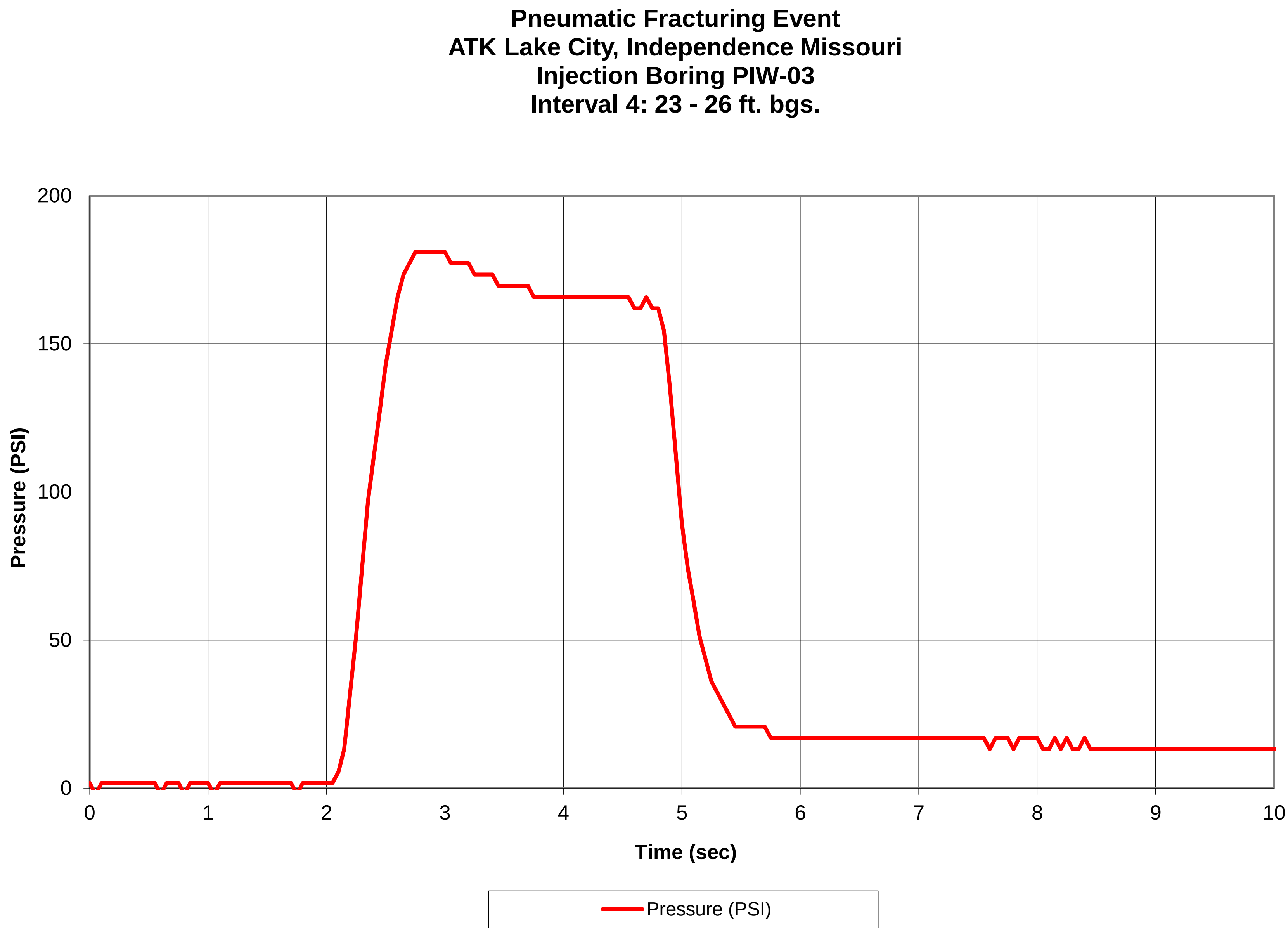
PIW-03-1F


Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-03
Interval 2: 29 - 32 ft. bgs.
250
200
150
100
50
0
Pressure (PSI)
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-03-2F

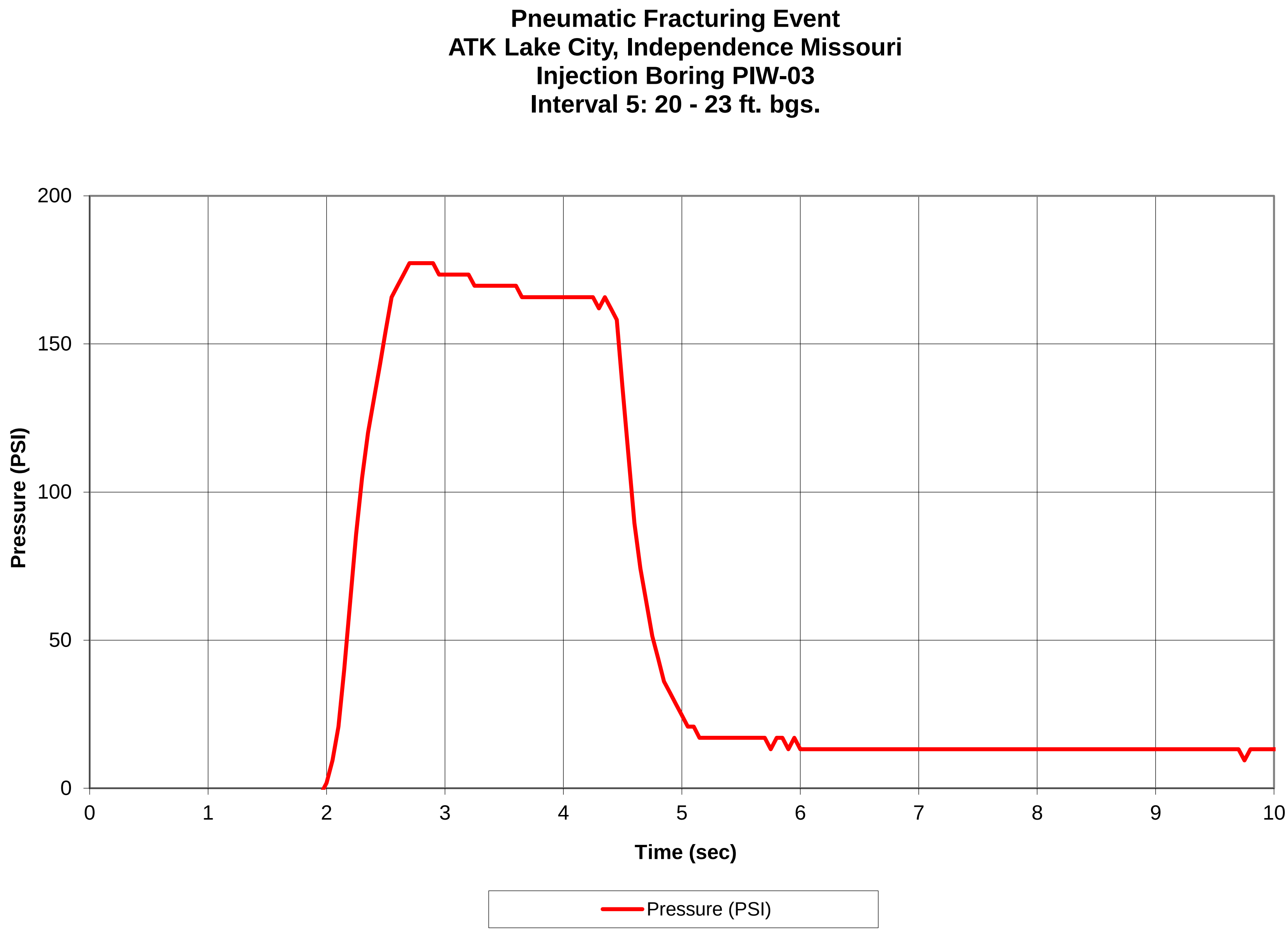

Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-03
Interval 3: 26 - 29 ft. bgs.
Pressure (PSI)
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-03-3F



Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-03
Interval 4: 23 - 26 ft. bgs.
200
150
100
50
0
Pressure (PSI)
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-03-4F


Pneumatic Fracturing Event
ATK Lake City, Independence Missouri
Injection Boring PIW-03
Interval 5: 20 - 23 ft. bgs.
Pressure (PSI)
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
Pressure (PSI)

PIW-03-5F

Pneumatic Fracturing and Lactoil/Salt Injection Summary Data Sheet

CDM Smith, Independence Missouri

Date	Borehole	Int, ft bgs	Fracture Data		Surface Heave Max / Res Inches		Batch Data			Injection Data				Monitoring Data									Comments
			Initiation Pressure, PSI	Maintenance Pressure, PSI	Heave Pt 1	Heave Pt 2	Water, gal	EVO, gal	Tracer Salt, lbs	Flow Rate, gpm	Injection Pressure, PSI	Solution Injected, gals	Solution Remaining, gals										
					8.5' NE	12'SW								PMW-01	PMW-02	PMW-03	PMW-04	16IW13	16MW76	16MW77			
3-22-16	PIW-02	32 - 35	215	195	.25 / .25	.10 / .00	200	6	12.5	10.7	10 - 20	215.00	0	>0	26.5	5.5	21.5	6.5	3.2	0			Blowby out of BH during frak and purge. Frak duration shortened.
		29 - 32	250	200	.25 / .25	.00 / .00	200	6	12.5	10.7	10 - 20	223.00	0	>0	10.5	1.8	21	1.5	2.5	0			Blowby out of BH during frak and purge. Frak duration shortened.
3-23-16		26 - 29	210	190	.00 / .00	.00 / .00	200	6	12.5	9	10 - 20	225.00	0	>0	4.0	>0	19.5	>0	1.5	0			Blowby out of BH during frak and purge. Frak duration shortened.
		23 - 26	195	175	.00 / .00	.00 / .00	200	6	12.5	7 - 11	5 - 10	215.00	0	0	1.5	>0	3.5	>0	0.5	0			Blowby out of BH during frak and purge. Frak duration shortened.
		20 - 23	150	130	.00 / .00	.00 / .00	200	6	12.5	7 - 8	5 - 10	220.00	0	0	13.5	>0	4.0	>0	>0	0			Blowby out of BH during frak and purge. Frak duration shortened.
					9' NW	12' SE								PMW-01	PMW-02	PMW-03	PMW-04	16IW13	16MW76	16MW77	PIW-02		
3-23-16	PIW-03	32 - 35	205	195	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	208.00	0	>0	1.0	6.5	19.0	>0	>0	0	10.0		Blowby out of BH during frak and purge. Frak duration shortened.
		29 - 32	225	195	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	206.00	0	0	0.5	3.3	7.5	>0	1.7	0	1.2		Blowby out of BH during frak and purge. Frak duration shortened.
		26 - 29	205	195	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	212.00	0	0	>0	2.0	5.0	>0	>0	0	>0		Blowby out of BH during frak and purge. Frak duration shortened.
		23 - 26	180	165	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	212.00	0	0	0	1.5	1.5	>0	>0	0	>0		Blowby out of BH during frak and purge. Frak duration shortened.
		20 - 23	175	165	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	212.00	0	0	0	>0	18.5	>0	>0	0	4.0		Blowby out of BH during frak and purge. Frak duration shortened.
					12' E	11' N								PMW-01	PMW-02	PMW-03	PMW-04	16IW13	16MW76	16MW77	PIW-02	PIW-03	
3-23-16	PIW-01	32 - 35	180	175	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	205.00	0	2.0	1.0	1.5	2.0	1.0	3.6	0	>0	>0	Blowby out of BH during frak and purge. Frak duration shortened.
		29 - 32	205	175	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	216.00	0	2.7	0	1.5	2.5	2.0	7.0	0	>0	1.0	Blowby out of BH during frak and purge. Frak duration shortened.
		26 - 29	205	175	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	212.00	0	2.2	0	1.1	6.0	3.5	7.2	0	1.0	1.2	Blowby out of BH during frak and purge. Frak duration shortened.
		23 - 26	175	150	.00 / .00	.00 / .00	200	6	12.5	10 - 11	5 - 10	218.00	0	2.8	0	1.0	5.0	4.5	6.7	0	1.5	1.2	Blowby out of BH during frak and purge. Frak duration shortened.
		20 - 23	150	145	.00 / .00	.00 / .00	200	26	12.5	10 - 11	5 - 10	250.00	0	2.4	0	1.0	4.0	5.0	7.2	0	>0	1.5	Blowby out of BH during frak and purge. Frak duration shortened.