The Effect of Tailings Characteristics on Cover System Success (or: What have we learned in 40 years?)

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Thanks to Freeport McMoRan, BHP Billiton, ASARCO

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Physical, Geochemical and Spatial Tailings Characteristics

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Physical Characteristics

- Tailings are poorly graded
  - Mostly silt size
  - No soil structure
- Highly erosive (high intensity precipitation/wind)
- Impoundment construction results in additional sorting and layering
  - beach (sands)
  - slimes (silts)
  - mixed areas
- Moisture retention and permeability varies by material types
- Variable saturation and drainage

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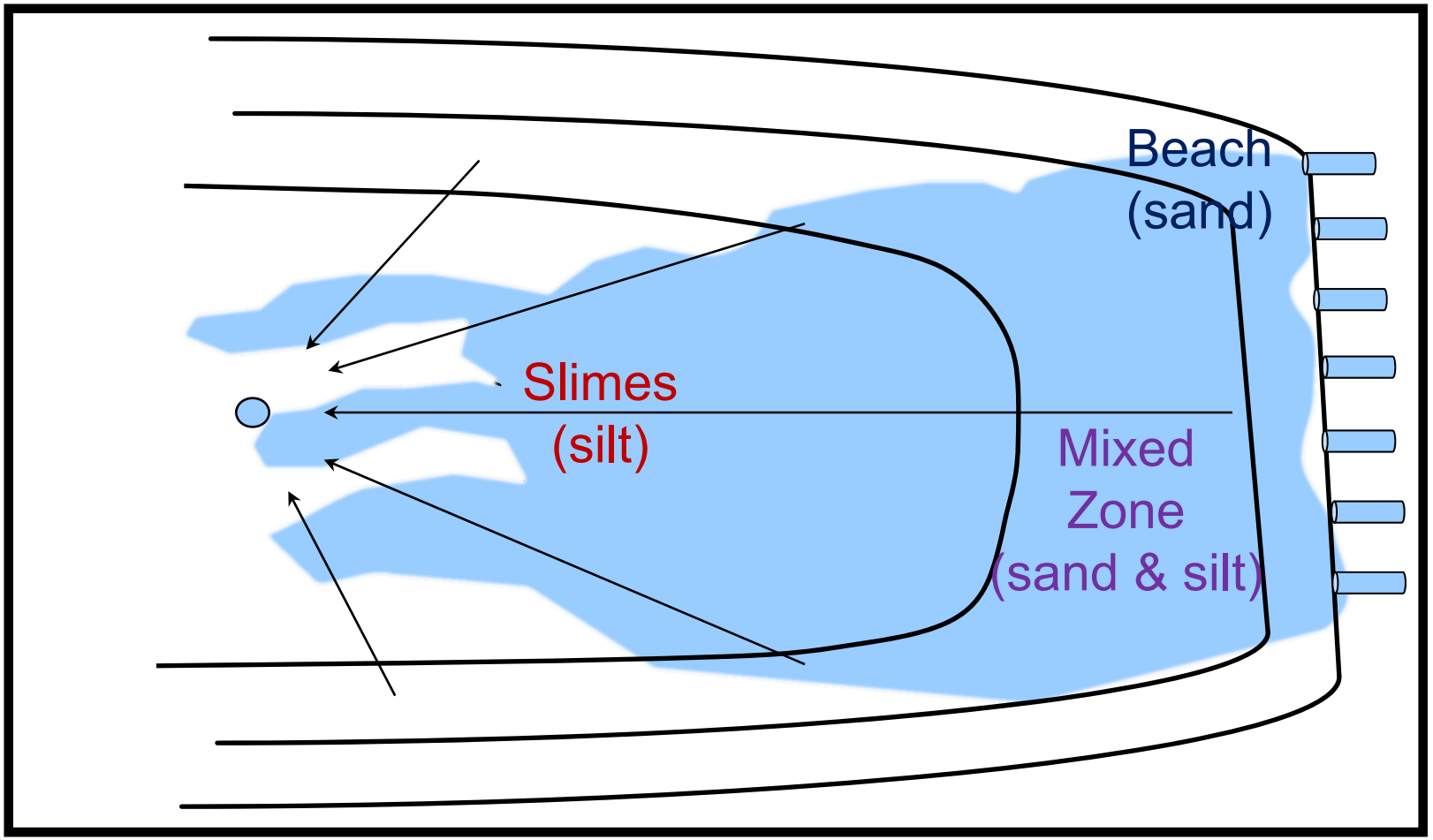
Tailings Segregation and Structure



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Geochemical Characteristics

- Can be moderately saline to hyper-saline
- Ore body mineralogy can result in:
  - High acid generation potential (and acidity) with high plant available metals (i.e. arsenic)
  - Moderate salts with no/ low plant-available metal content
- Typically low plant nutrient content
- Lack of organic matter and microbiota

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To Cap or Not To Cap?

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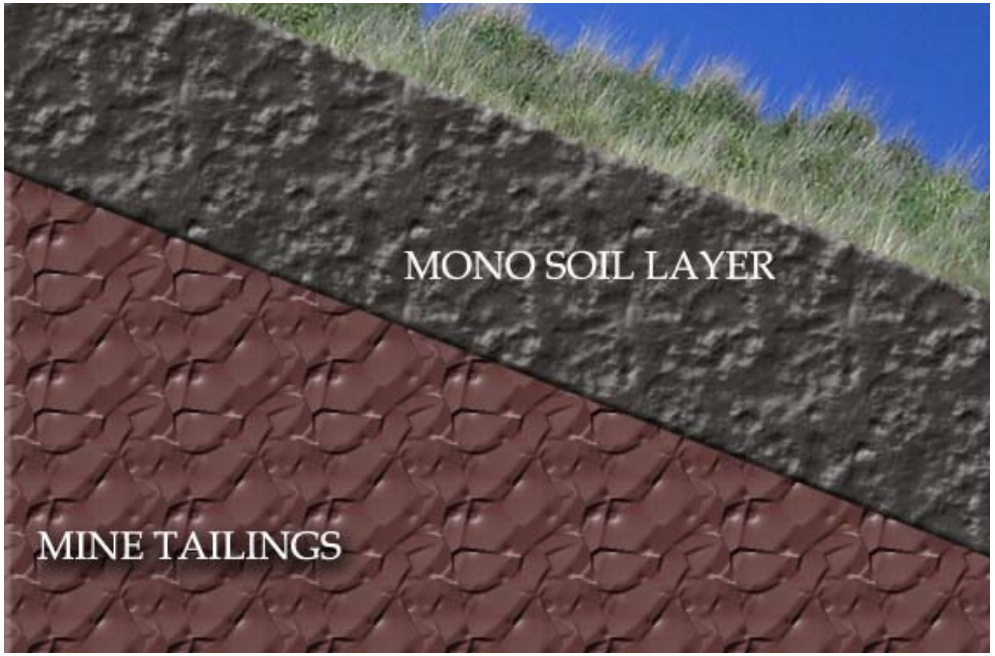
Reclamation Goals and Methods

Goals:

- Establish vegetation
- Minimize erosion and stabilize tailings
- Minimize deep percolation

Methods:

- Soil covers
- Direct revegetation w/ tailings amendments



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Previously Reclaimed Tailings Surfaces (in AZ)

- ASARCO Mission Tailings No. 6 (1983: 12-inch cover)
- ASARCO Mission San Xavier Tailings 1,2, 3 (2011: 12 inch cover)
- Eagle Pitcher Mill site (1960s, 1989-92: 12-inch cover)
- Twin Buttes Tailing No. 2 (1986: 12-inch cover)
- Phelps Dodge Sierrita Esperanza Tailings (1986: 12-inch cover)
- San Manuel PS Tailings Impoundment 1/2 (1991-92: 6 to 8 inches cover)
- San Manuel Tailing Impoundments 1-6 (2008: 12-inch cover)
- San Manuel PS experimental biosolid plots (1998: no cover)
- McCabe Mine Tailings (1996: 24 inch cover)
- Phelps Dodge Morenci Tailings NW exGeorgetown Plots (1997: 12 to 24-inch of cover)
- Freeport McMoran Copper Cobre TSA Tailings (2012: 24 inch cover)

Circumneutral

Potentially Acid Generating Acid

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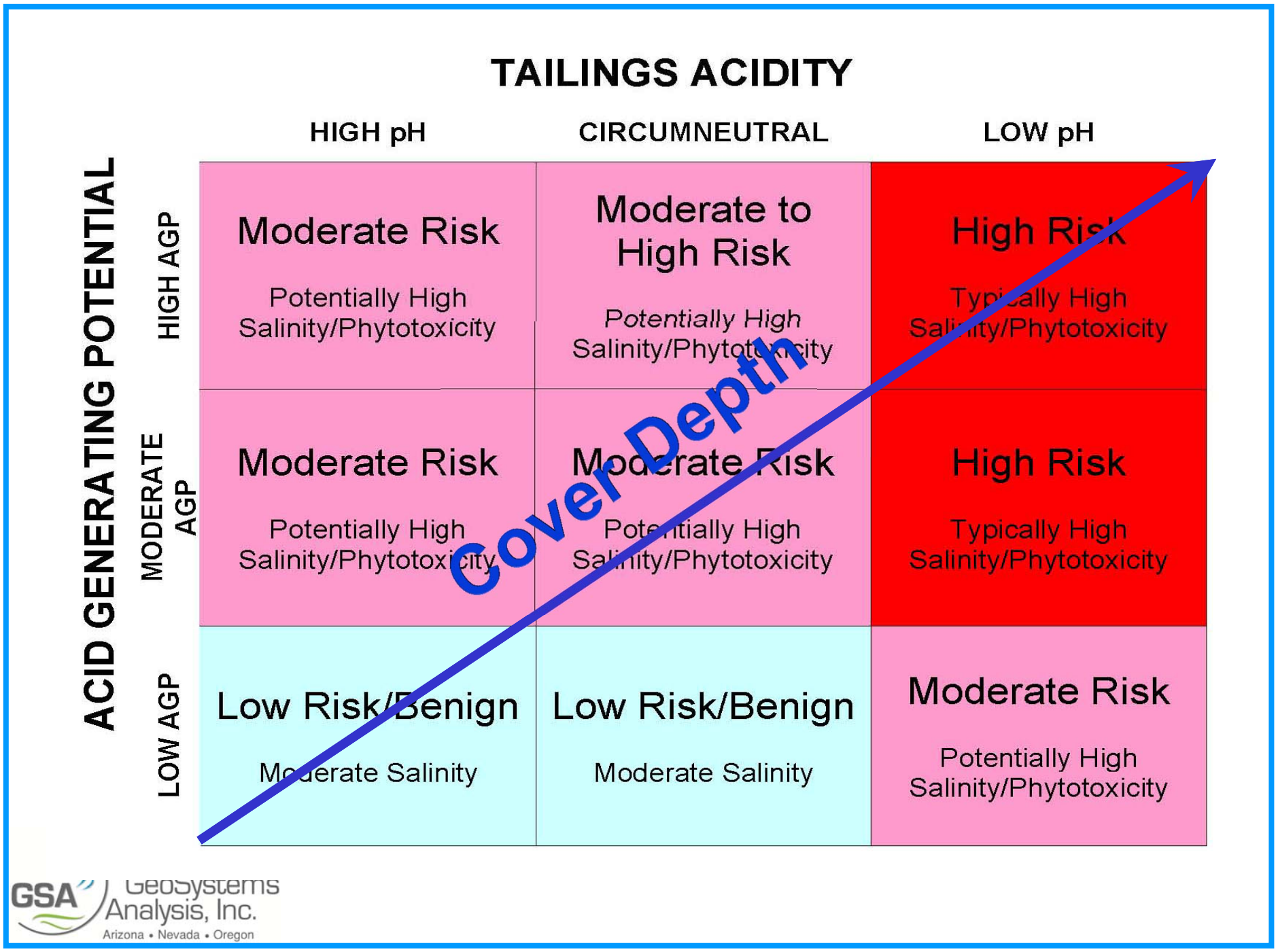

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Vegetation on Reclaimed Tailings

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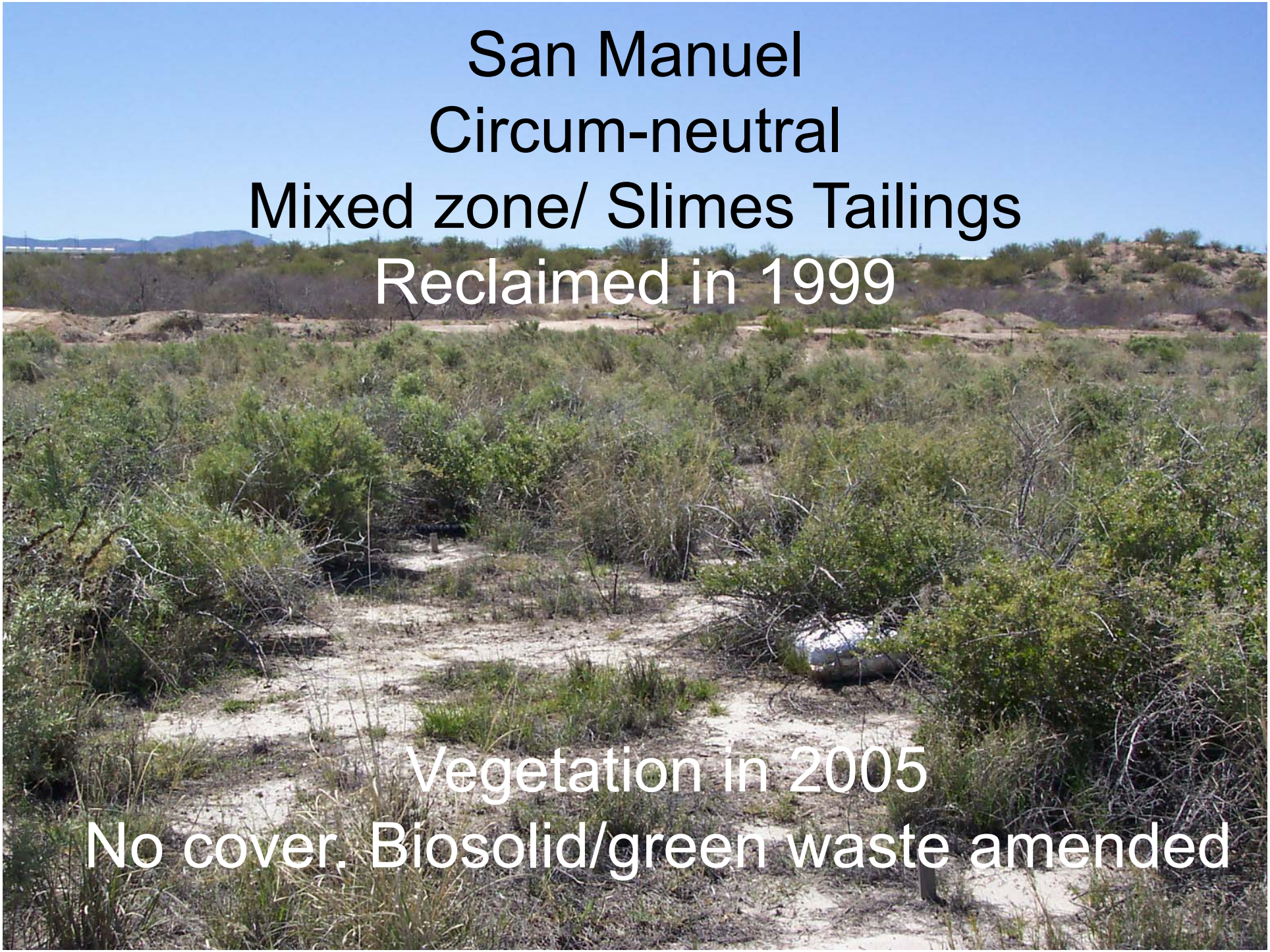
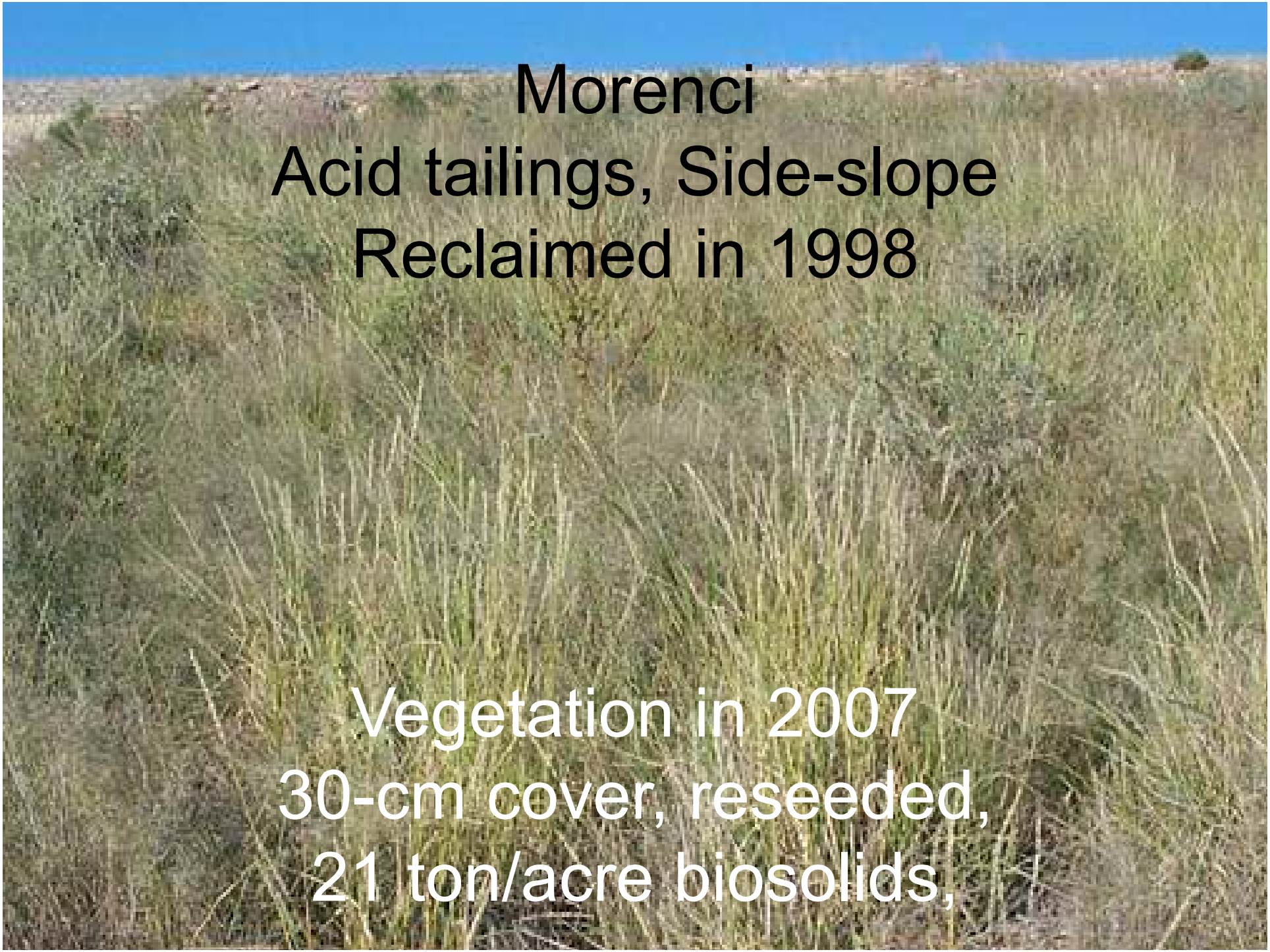
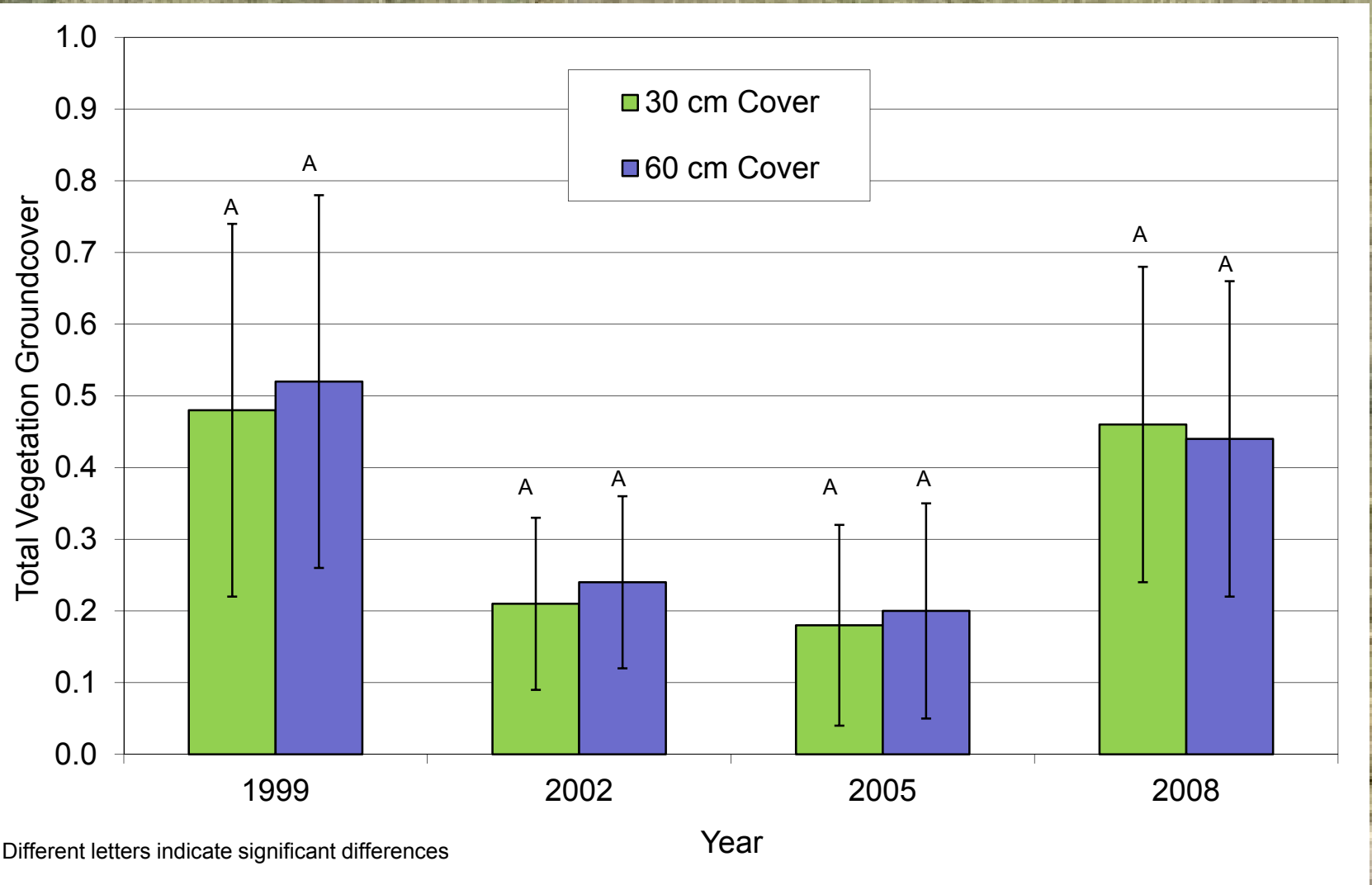
ASARCO Mission Tailings


San Manuel
Circum-neutral
Mixed zone/ Slimes Tailings
Reclaimed in 1999
Vegetation in 2005
No cover. Biosolid/green waste amended

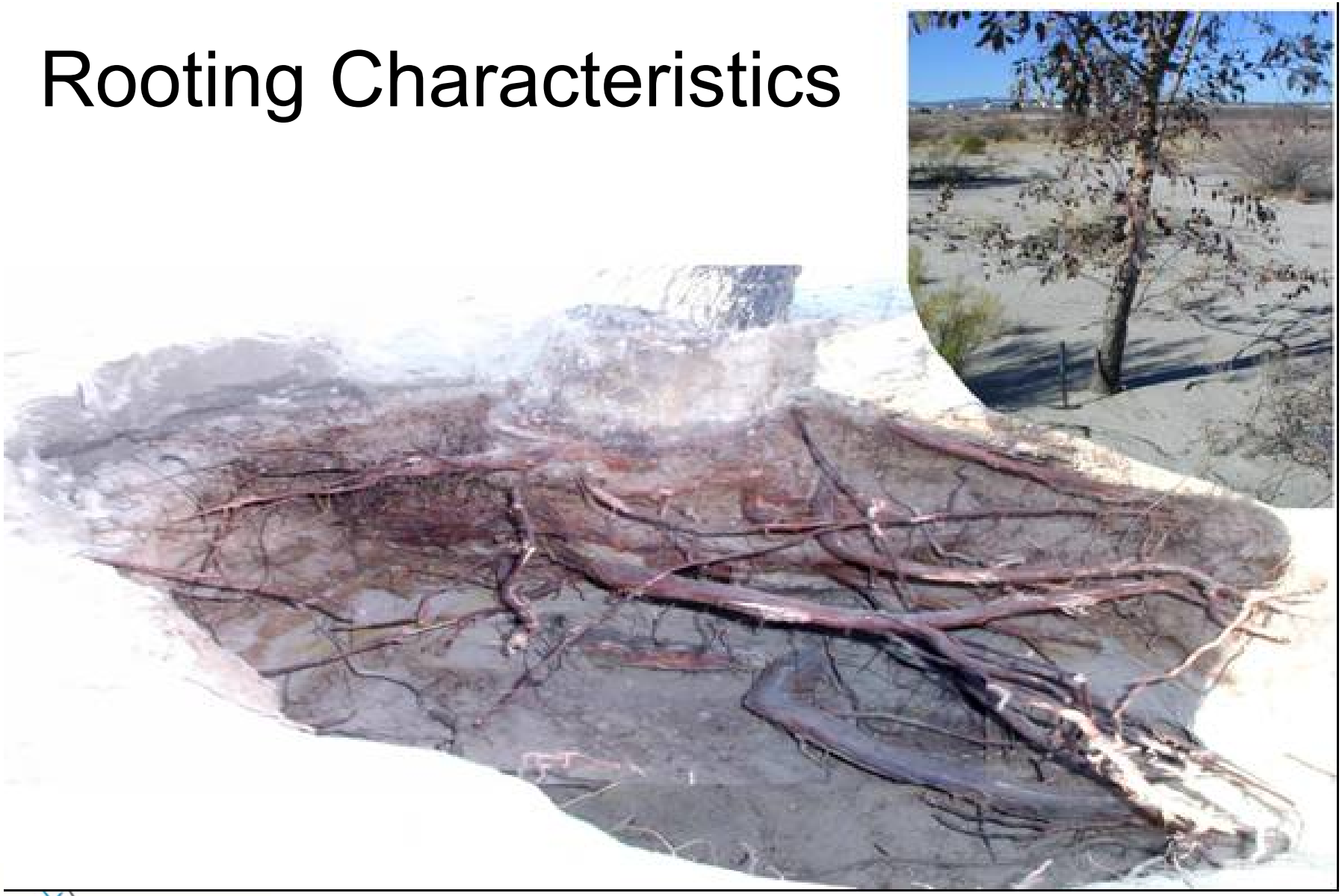

San Manuel
Circum-neutral Tailings,
Beach/Mixed
Reclaimed in 1999
Vegetation in 2005
30-cm cover, reseeding/mulching,
hand planting


Morenci
Acid tailings, Side-slope
Reclaimed in 1998
Vegetation in 2007
30-cm cover, reseeded,
21 ton/acre biosolids,

30 cm Cover vs. 60 cm Cover



Rooting Characteristics



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Vegetation Considerations

- Rooting characteristics:
  - Actively root into circum-neutral tailings
  - Minor rooting into moderately acid tailings, primarily limited to cover and upper one foot of tailings
  - Form dense root mat above cover/acid tailings contact
  - Affected by tailings permeability
- Vegetative success generally greater in mixed zone than in beach areas and slime areas
- Vegetation characteristics varies with location (e.g. slimes vs. sands)

Vegetation Considerations (cont'd)

- Effect of cover depth
  - Nominal differences in vegetative covers > 30 cm thick
  - BUT native species perform better on thicker covers
- Effect of organic amendments:
  - Can successfully reclaim raw tailings with a biosolids/green waste (compost) mix
  - Results in significantly greater mean vegetation cover; however, less species diversity
  - In some cases, observed effects sustained for over 10 years
- Side slopes may require rock armoring; only seeded cover material may not adequately stabilize slopes

Low-pH and Saline Solution Migration into Monolayer Covers?

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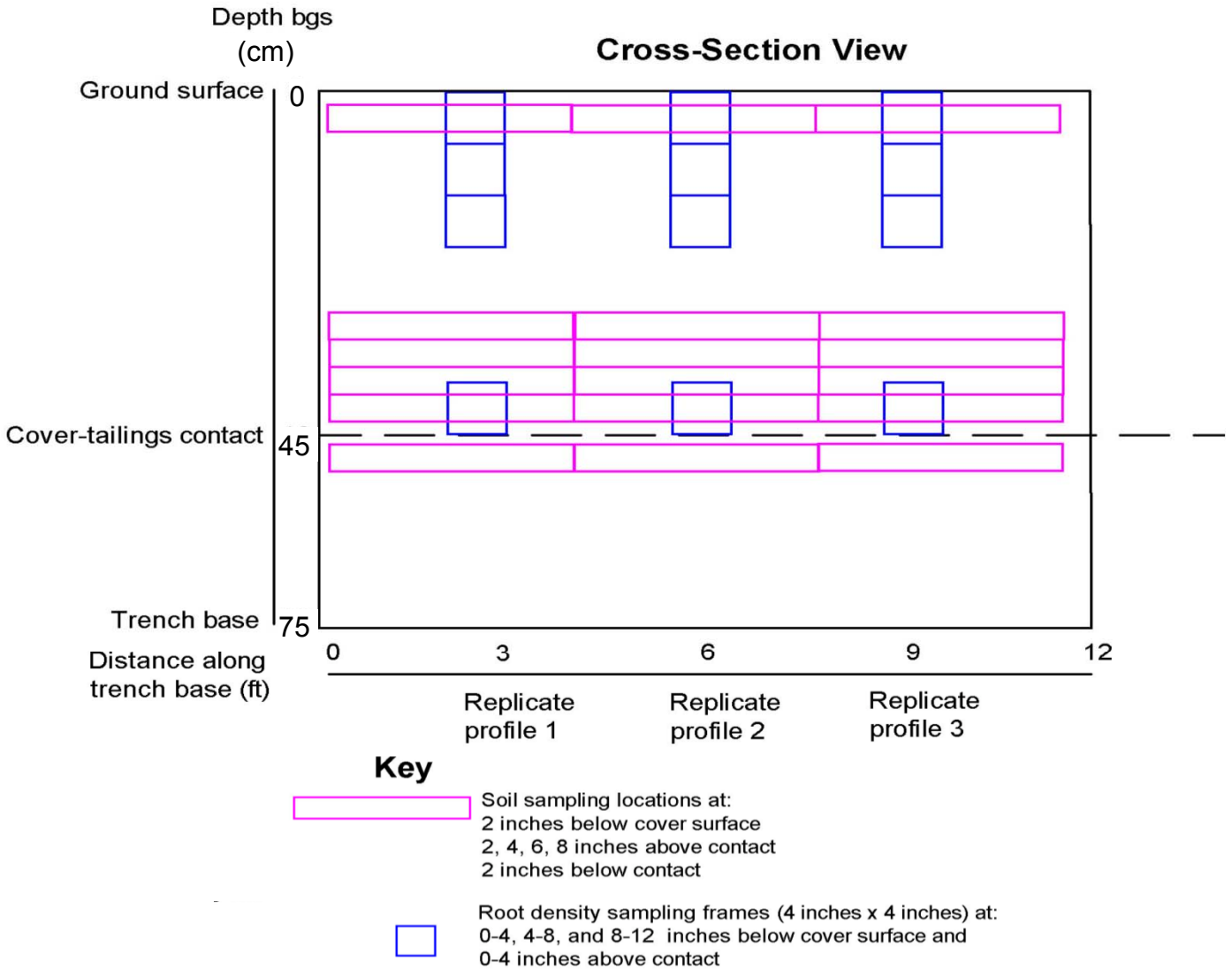
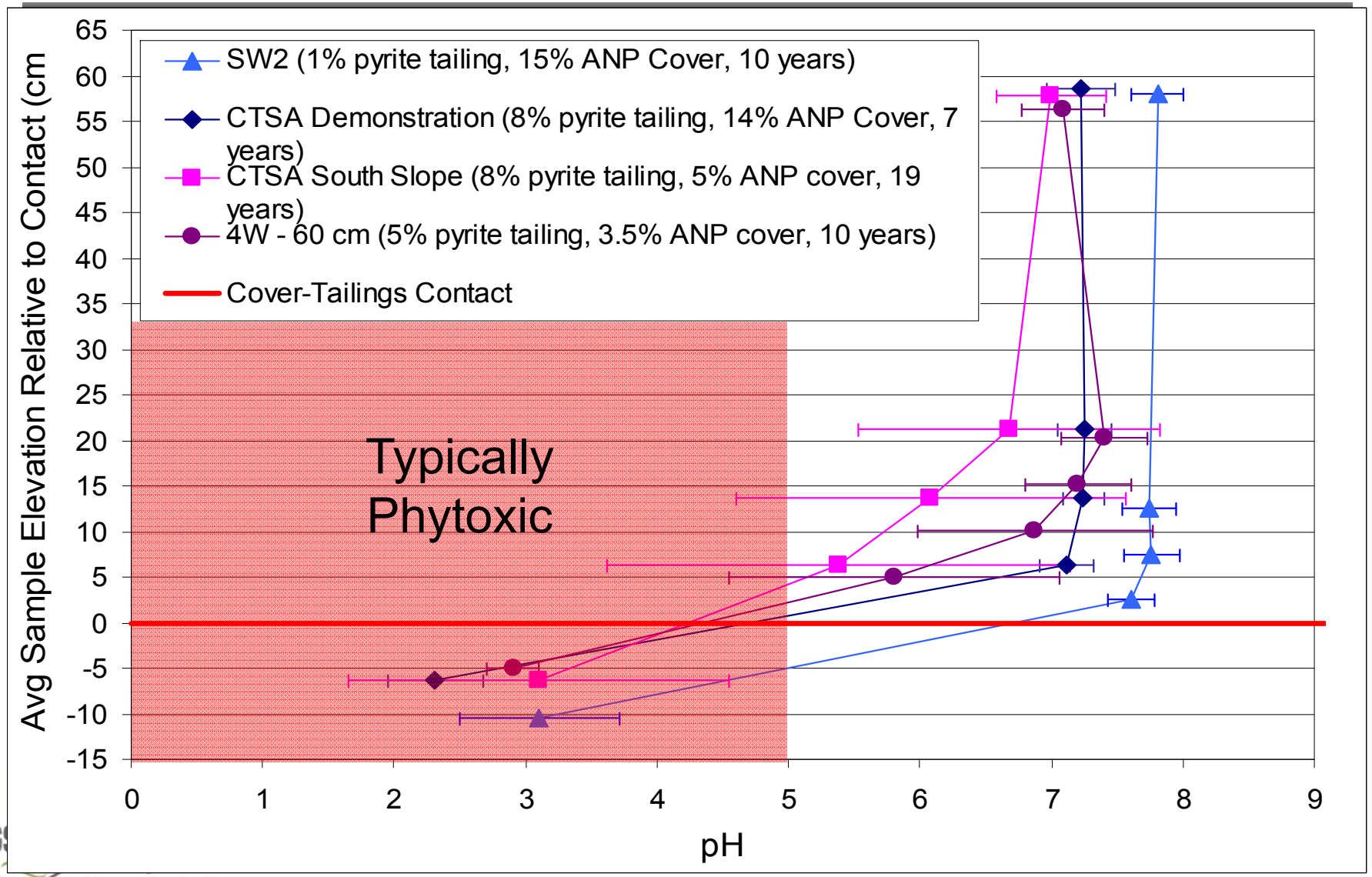
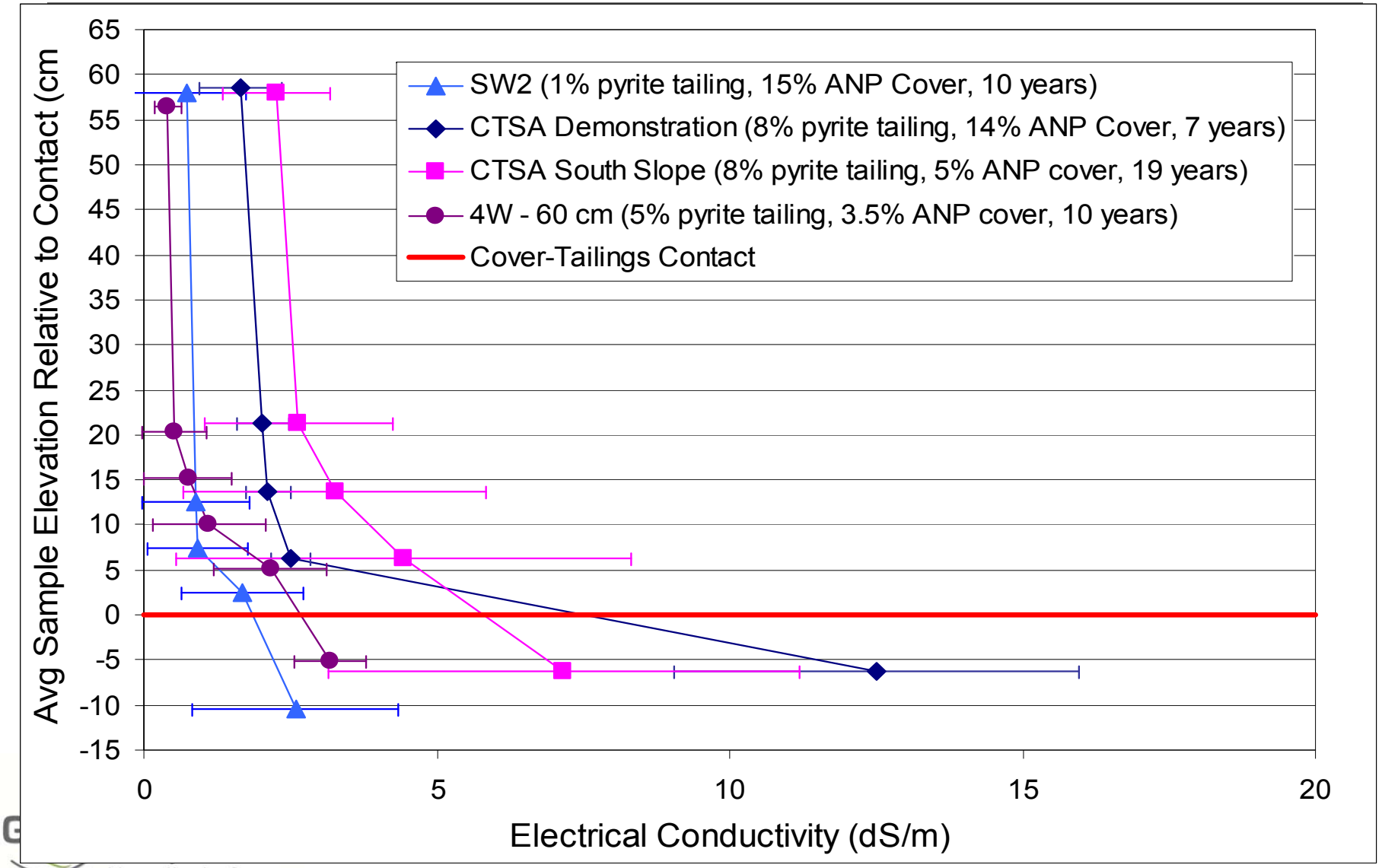
Trench Sample Design



pH Profiles


SW2 (1% pyrite tailing, 15% ANP Cover, 10 years)
CTSA Demonstration (8% pyrite tailing, 14% ANP Cover, 7 years)
CTSA South Slope (8% pyrite tailing, 5% ANP cover, 19 years)
4W - 60 cm (5% pyrite tailing, 3.5% ANP cover, 10 years)
Cover-Tailings Contact
Typically Phytoxic
Avg Sample Elevation Relative to Contact (cm
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
6
7
8
9
pH

EC Profiles


Avg Sample Elevation Relative to Contact (cm
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
0
5
10
15
20
Electrical Conductivity (dS/m)
SW2 (1% pyrite tailing, 15% ANP Cover, 10 years)
CTSA Demonstration (8% pyrite tailing, 14% ANP Cover, 7 years)
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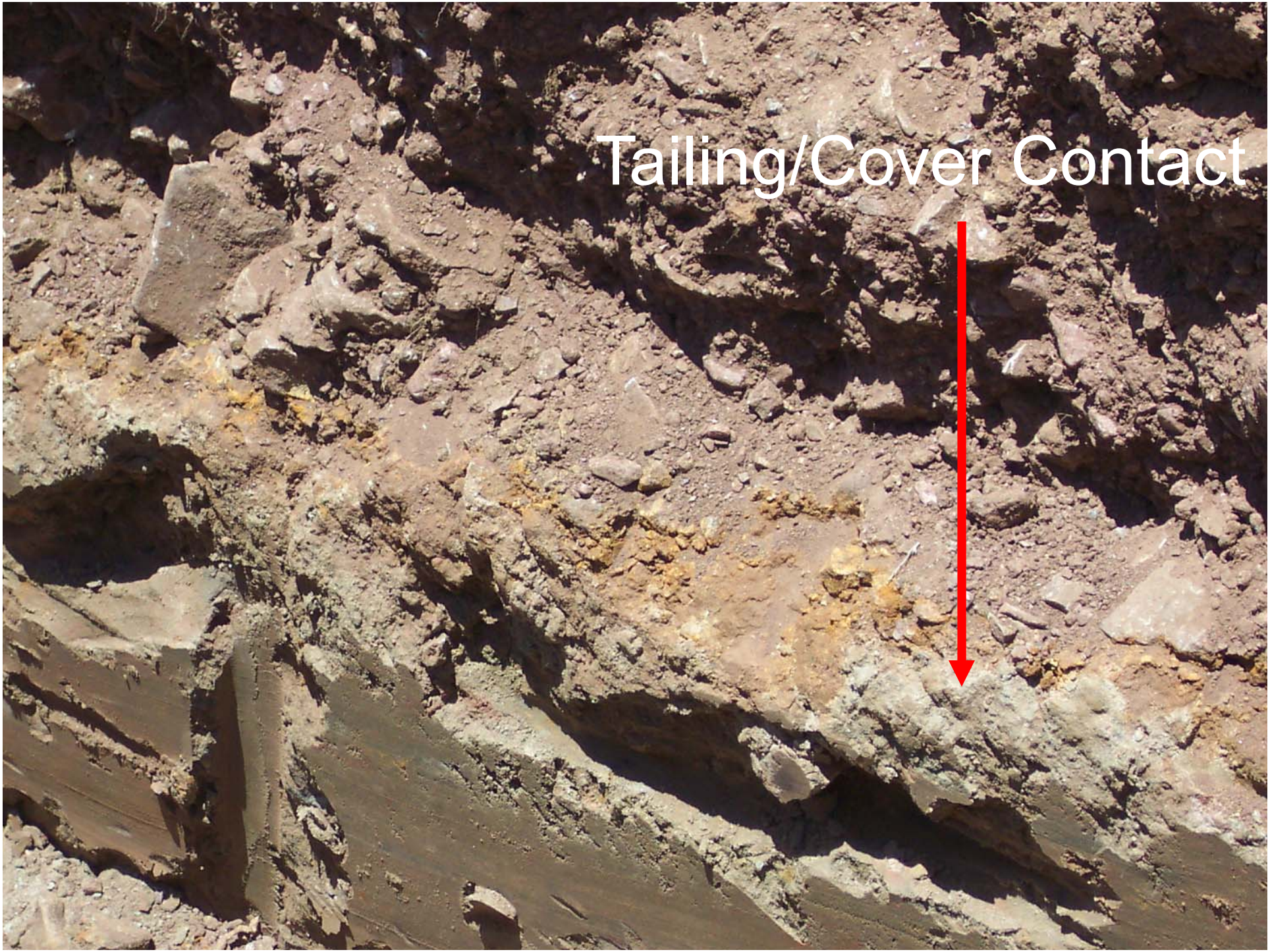
Cover-Tailings Contact


Tailing/Cover Contact

Acid and Salinity Migration Considerations

- In a semi-arid environment salinity and acid migration observed in Southwest US environment to be limited to ≈ 15 cm above contact
- Phytotoxic levels of pH and salinity in cover material generally absent ≈ 5 cm above contact
- Increased migration above contact with decreased cover thickness (30 vs. 60 cm)
- Acidity and salinity migration may be limited due to:
  - Unsaturated hydraulic conductivities and upward flux rates greatly diminish with distance above the contact
  - High calcium carbonate contents in the cover material can neutralize low-pH solution

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Infiltration/Net Percolation

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Calculated 1D Net Percolation Flux

Sensor Nest/Plot Location	Total Downward Flux (cm)	Annual Flux (cm/yr)	Annual Flux Rate (cm/s)	Estimated Flux as Percent of Precipitation
30 cm cover, low vegetation				
	3.23	0.37	1.16E-08	1.29%
	1.61	0.26	8.14E-09	1.04%
30 cm cover, high vegetation				
	0.84	0.12	3.80E-09	0.34%
	6.52	0.07	2.24E-09	0.30%
60 cm cover, low vegetation				
	4.20	0.55	1.74E-08	1.68%
	7.37	0.55	1.76E-08	1.35%
Average 60 cm cover, high vegetation				
	3.84	0.48	1.53E-08	1.53%
	3.10	0.29	9.13E-09	1.24%
Bare Tailings				
	0.17	0.02	6.56E-10	0.09%
	0.28	0.03	1.11E-09	0.16%

Shallower (30 cm) cover/ Lower permeability tailings

Deeper (60 cm) cover/ Higher permeability tailings

Low permeability bare tailings: > runoff, less infiltration

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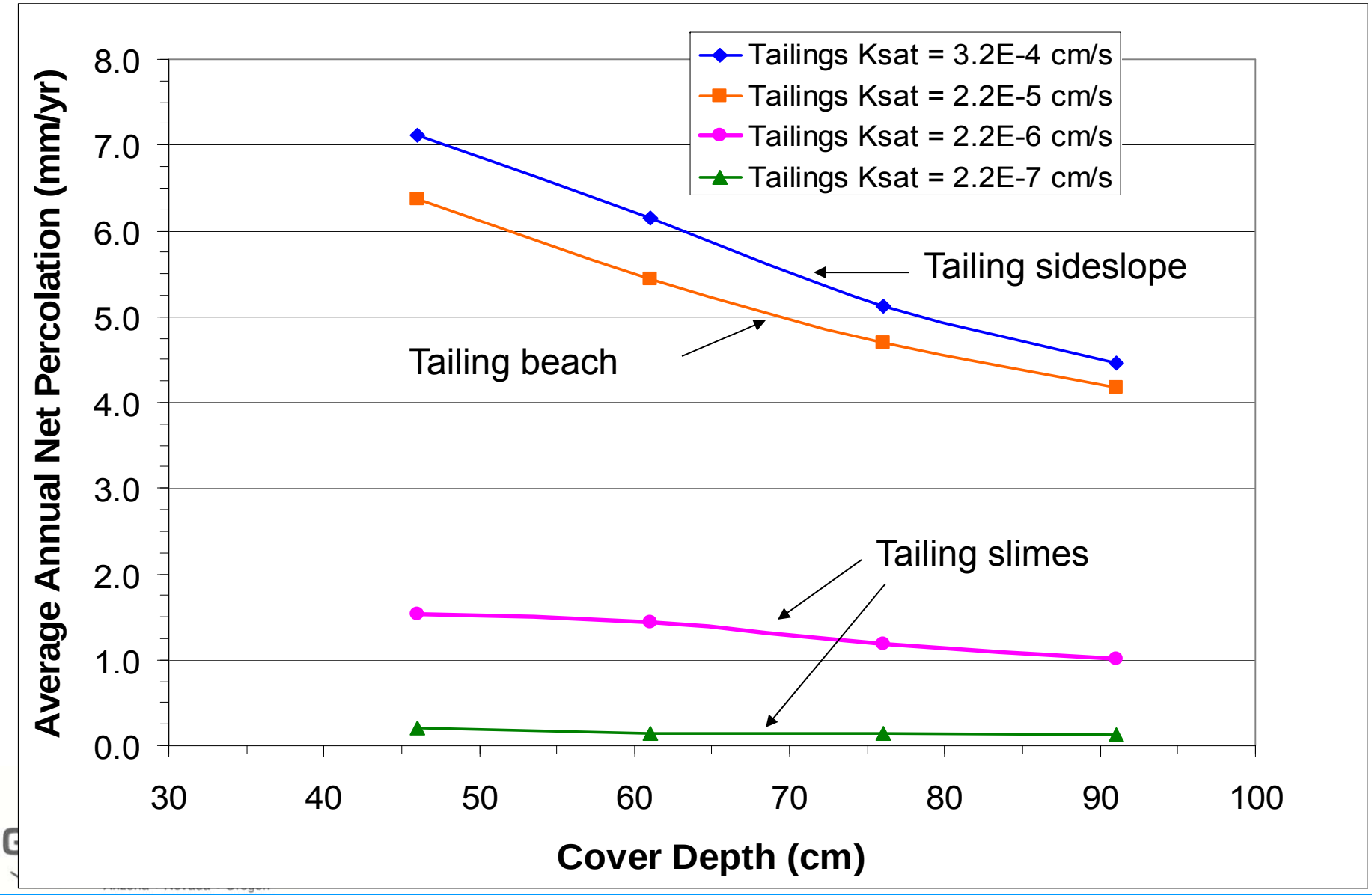
Predicted Effect of Increasing Cover Thickness



Net Percolation Considerations

- Lower permeability tailings reduce net percolation
- Increasing cover thickness can have less influence on net percolation than tailings characteristics
- Shallow covers or direct reclaimed tailings can have less net percolation than deeper covers
- **Tailings are an integral part of store and release cover systems and their influence should be considered during cover design**

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Conclusions

- Circumneutral tailings can be revegetated with organic amendments (if available); net percolation may actually decrease because of low permeability material at surface
- Low permeability tailings serve to slow down infiltration and retain water in cover; can have greater effect on net percolation than cover depth
- Revegetation seed mixes should consider differences between sand and slimes area; deeper covers are better for native seed mixes
- Cover system modeling should acknowledge ET depth into tailings
- Upward acidity and salinity migration into monolayer covers may be limited

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THANK YOU!

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