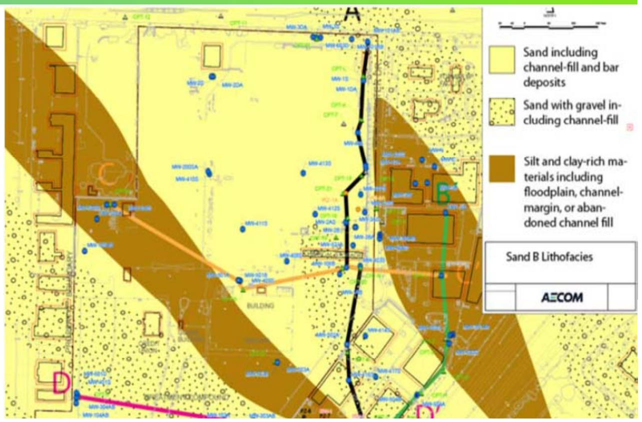
Focus on Geology to Define Subsurface Migration Pathways



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December 2, 2015

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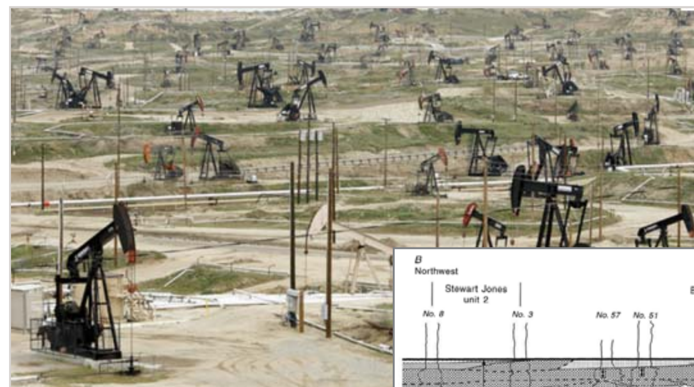
Outline

- Introduction
  - Why does geology matter?
  - What is Environmental Sequence Stratigraphy?
  - Proof of concept
- The technology
- Case Studies

Technology Established in the Oil Industry

In the early days of exploration and production, once oil reservoir was discovered, production was limited by facilities capacity (engineering focus).

As technology improved and fields matured, the "easy stuff" had been recovered. Problems such as water production became critical. Understanding the geology and predicting reservoir architecture became increasingly critical for economical operations.



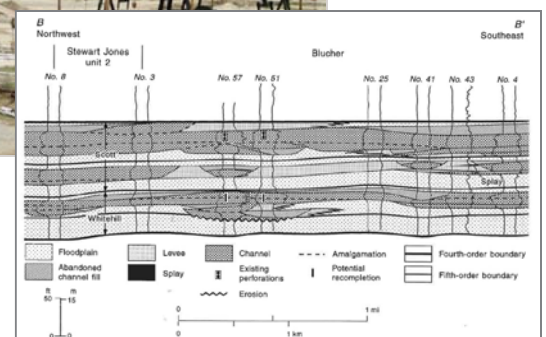
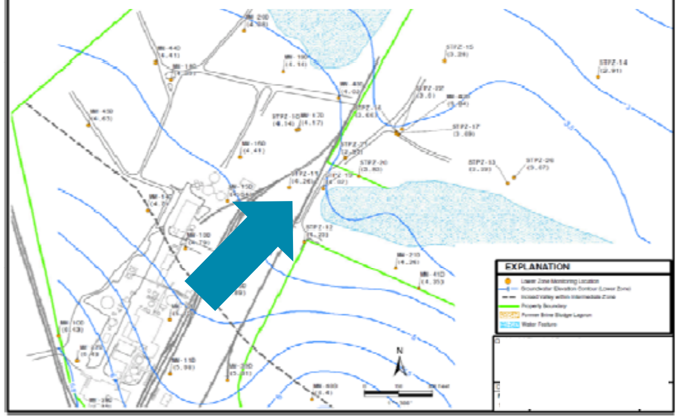


Figure 3. Dip-oriented stratigraphic cross section B-B' through amalgamated channel sandstones and floodplain shales in the Scott/Whitehill intermediate-frequency unit in T-C-B field. Note that the four high-frequency units, the lower and upper Whitehill and the lower and upper Scott, exhibit a successive increase in thickness from the lower Whitehill to the upper Scott. See Figure 4a for location. From Knox and McRae (1995).

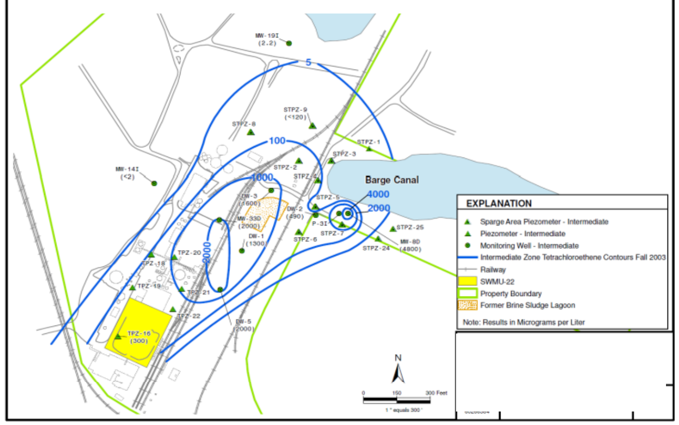
Subsurface Heterogeneity and Groundwater Remediation

- Historically, simplifying assumptions of aquifer **homogeneity and isotropy** applied to designing and implementing groundwater remediation programs – the “water supply legacy”
- While heterogeneity was recognized, it was thought that we could **“engineer around geology”**

Groundwater gradient



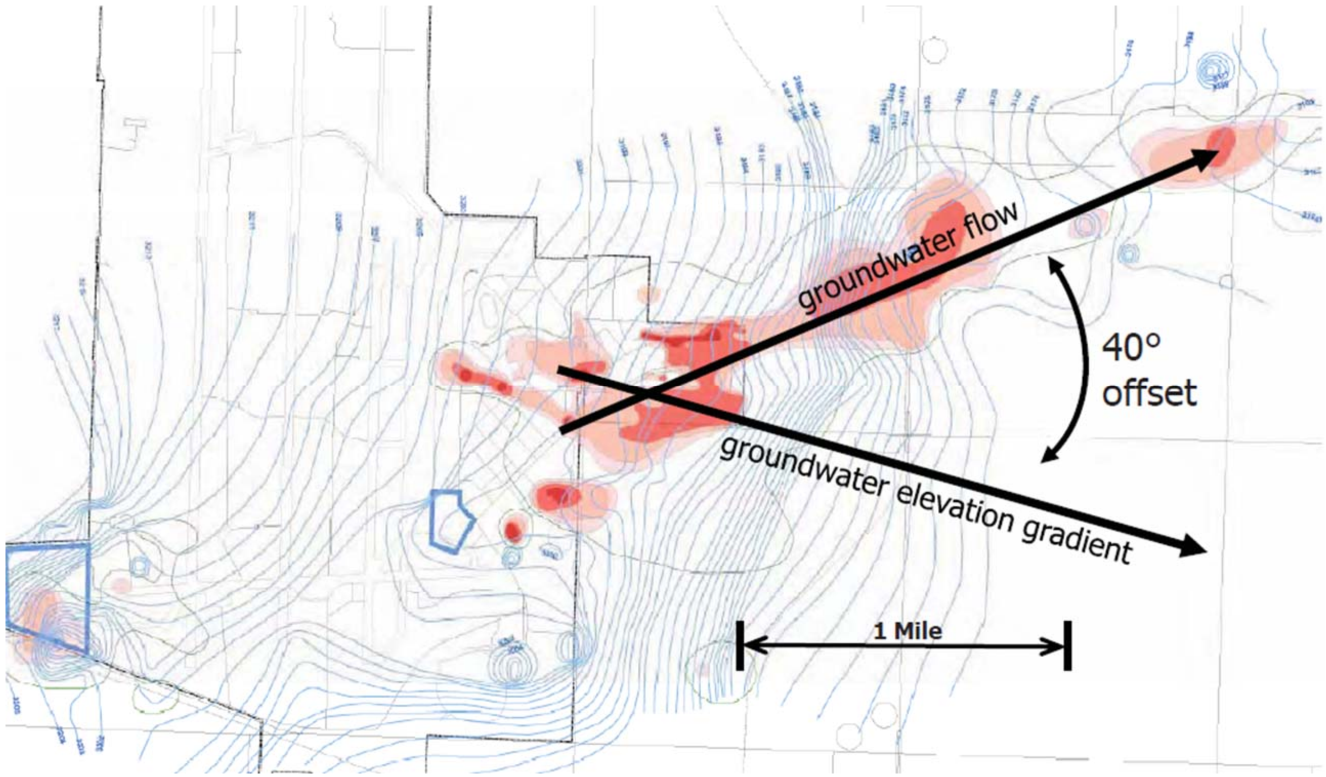
Contaminant plume



Subsurface Heterogeneity and Groundwater Remediation

With heterogeneous geology groundwater flow may not match gradient and result in:

- *Off-gradient contaminant migration*
- *Poor distribution of in situ reagents*
- *Production of byproducts during in situ injection*
- *Poor pump-and-treat performance*



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Why Geology Matters

- At least 126,000 sites across the U.S. have contaminated groundwater that requires remediation
- Over **12,000** of these sites are considered "complex"
- “There is general agreement among practicing remediation professionals, however, that there is a substantial population of sites, where, due to **inherent geologic complexities**, restoration within the next 50-100 years is likely not achievable.”

Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites
National Academy of Sciences Committee on Future Options for Management in the Nation's Subsurface Remediation Effort, 2013

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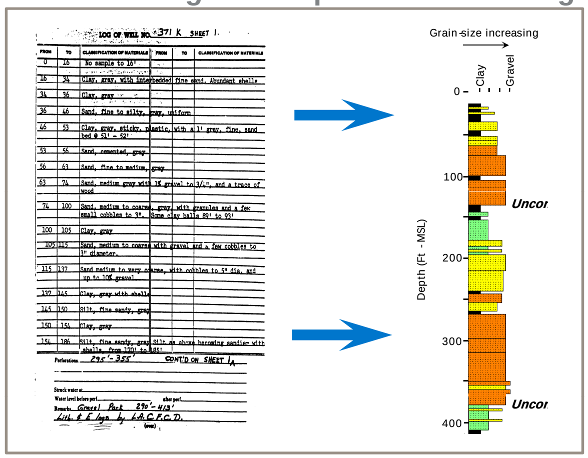
Environmental Sequence Stratigraphy (ESS) Process

1

Determine depositional environment which is the foundation to the ESS evaluation

Borehole Log to Graphic Grainsize Log

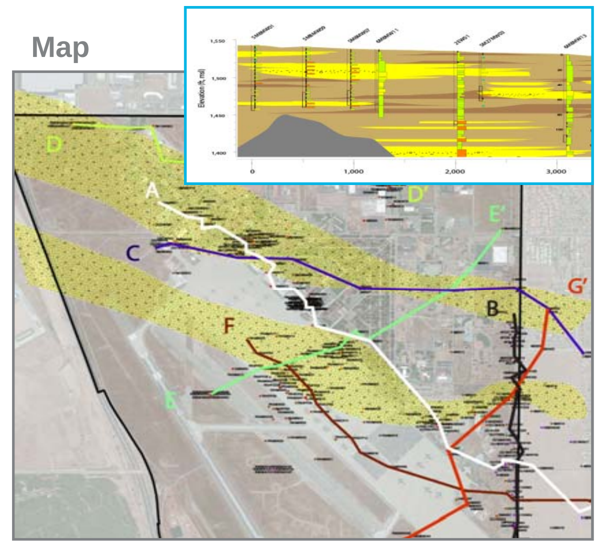


2

Leverage existing lithology data to identify vertical grain size trends and correlate between boreholes

Cross Section

Map

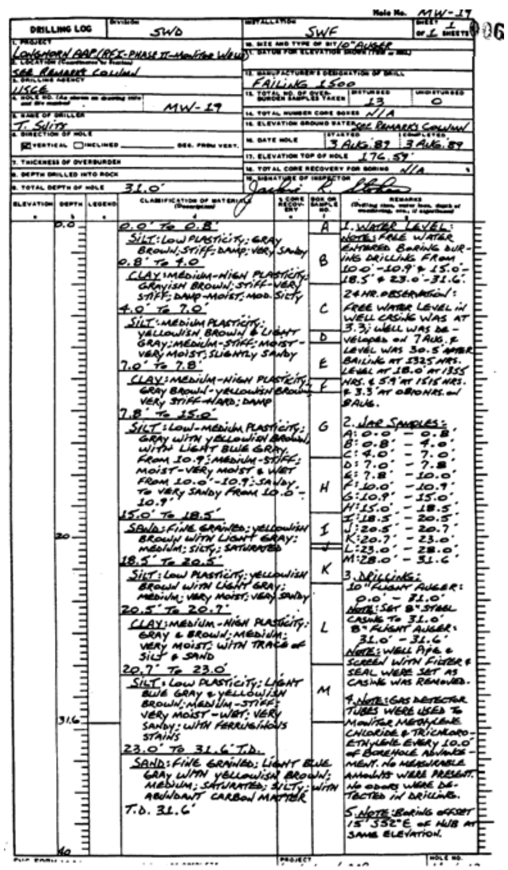


3

Map the permeability architecture to predict contaminant migration

All sites currently have high resolution data…

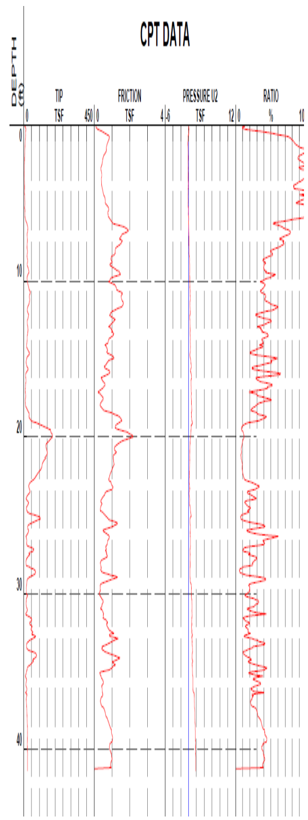
Boring Logs


DRILLING LOG | Division SWD | Installation SWF | Sheet 1 of 1 sheets | Hole No. MW-17

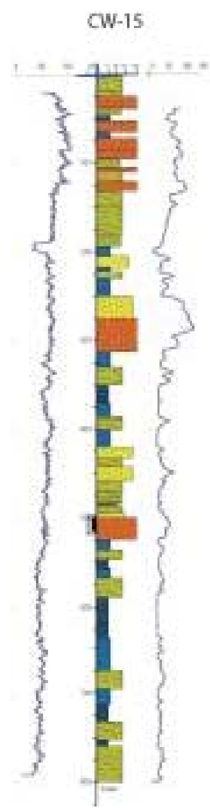
1. Project: LONGHORN AAP (REX-PHASE II-MONITOR WELLS)
2. Location: SEE REMARKS COLUMN
3. Drilling Agency: USCE
4. Hole No.: MW-17
5. Name of Driller: T. SMITH
6. Direction of Hole: VERTICAL
7. Thickness of Overburden
8. Depth Drilled into Rock
9. Total Depth of Hole: 31.0'
10. Size and Type of Bit: 10" AUGER
12. Manufacturer's Designation of Drill: FAILING 1500
13. Total No. of Over-Burden Samples Taken: Disturbed 13, Undisturbed 0
14. Total Number Core Boxes: N/A
15. Elevation Ground Water: SEE REMARKS COLUMN
16. Date Hole: Started 3 AUG. 87, Completed 3 AUG. 87
17. Elevation Top of Hole: 176.59'
18. Total Core Recovery for Boring: N/A
19. Signature of Inspector

Elevation	Depth	Legend	Classification of Materials	% Core Recovery	Box or Sample No.	Remarks
	0.0		0.0' TO 0.8' SILT: LOW PLASTICITY; GRAY BROWN; STIFF; DAMP; VERY SANDY		A	1. WATER LEVEL: NOTE: FREE WATER ENTERED BORING DURING DRILLING FROM 10.0'-10.9' & 15.0'-18.5' & 23.0'-31.6'. 24 HR. OBSERVATION: FREE WATER LEVEL IN WELL CASING WAS AT 3.3; WELL WAS DEVELOPED ON 7 AUG. & LEVEL WAS 30.5' AFTER BAILING AT 1325 HRS. LEVEL AT 18.0' AT 1355 HRS. & 5.9' AT 1516 HRS. & 3.3' AT 0800 HRS. ON 8 AUG.
			0.8' TO 4.0' CLAY: MEDIUM-HIGH PLASTICITY; GRAYISH BROWN; STIFF-VERY STIFF; DAMP-MOIST; MOD. SILTY		B	
			4.0' TO 7.0' SILT: MEDIUM PLASTICITY; YELLOWISH BROWN & LIGHT GRAY; MEDIUM-STIFF; MOIST-VERY MOIST; SLIGHTLY SANDY		C, D	
			7.0' TO 7.8' CLAY: MEDIUM-HIGH PLASTICITY; GRAY BROWN-YELLOWISH BROWN; VERY STIFF-HARD; DAMP		E, F	
			7.8' TO 15.0' SILT: LOW-MEDIUM PLASTICITY; GRAY WITH YELLOWISH BROWN; WITH LIGHT BLUE GRAY. FROM 10.9' MEDIUM-STIFF; MOIST-VERY MOIST & WET FROM 10.0'-10.9'; SANDY, TO VERY SANDY FROM 10.0'-10.9'		G, H	2. JAR SAMPLES: A: 0.0'-0.8'; B: 0.8'-4.0'; C: 4.0'-7.0'; D: 7.0'-7.8'; E: 7.8'-10.0'; F: 10.0'-10.9'; G: 10.9'-15.0'; H: 15.0'-18.5'; I: 18.5'-20.5'; J: 20.5'-20.7'; K: 20.7'-23.0'; L: 23.0'-28.0'; M: 28.0'-31.6'
			15.0' TO 18.5' SAND: FINE GRAINED; YELLOWISH BROWN WITH LIGHT GRAY; MEDIUM; SILTY; SATURATED		I	
	20		18.5' TO 20.5' SILT: LOW PLASTICITY; YELLOWISH BROWN WITH LIGHT GRAY; MEDIUM; VERY MOIST; VERY SANDY		J, K	3. DRILLING: 10" FLIGHT AUGER: 0.0'-31.0'. NOTE: SET 8" STEEL CASING TO 31.0'. 8" FLIGHT AUGER: 31.0'-31.6'. NOTE: WELL PIPE & SCREEN WITH FILTER & SEAL WERE SET AS CASING WAS REMOVED.
			20.5' TO 20.7' CLAY: MEDIUM-HIGH PLASTICITY; GRAY & BROWN; MEDIUM; VERY MOIST; WITH TRACE OF SILT & SAND		L	
			20.7' TO 23.0' SILT: LOW PLASTICITY; LIGHT BLUE GRAY & YELLOWISH BROWN; MEDIUM-STIFF; VERY MOIST-WET; VERY SANDY; WITH FERRUGINOUS STAINS		M	4. NOTE: GAS DETECTOR TUBES WERE USED TO MONITOR METHYLENE CHLORIDE & TRICHLOROETHYLENE EVERY 10.0' OF BOREHOLE ADVANCEMENT. NO MEASURABLE AMOUNTS WERE PRESENT. NO ODORS WERE DETECTED IN DRILLING.
	31.6		23.0' TO 31.6' T.D. SAND: FINE GRAINED; LIGHT BLUE GRAY WITH YELLOWISH BROWN; MEDIUM; SATURATED; SILTY; WITH ABUNDANT CARBON MATTER. T.D. 31.6'			5. NOTE: BORING OFFSET 15' 352°E OF HUB AT SAME ELEVATION.

CPT Logs



Geophysical Logs



…lithology data that is not being used to its full capacity.

Environmental Sequence Stratigraphy (ESS)

Beauty of this approach is that the **data are already paid for** and the **Oil Industry has already invested billions** in developing the technology.

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Where is Environmental Sequence Stratigraphy applied?

ESS

Fractured rock?

Karst limestone?

Clastic (sand/silt/clay mixtures) sedimentary deposits?

YES

- River deposits
- Desert systems
- Coastal settings
- Marine deposits
- Glacial deposits

Focus on geology improves site characterization throughout the remediation life cycle:

- Data gaps investigations, high-resolution site characterization programs
- Optimizing groundwater monitoring programs
- Contaminant source identification for comingled plumes
- Mass flux/mass discharge analysis (contaminant transport vs contaminant storage zones)
- In situ remediation (optimize distribution)
- Optimizing pump and treat programs
- Alternative endpoint analysis

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Proof of Concept

Base-Wide Conceptual Site Models

Have successfully applied this technology to assess groundwater contaminant pathways at several Air Force facilities.

Proposed EPA Ground Water Issue Paper on ESS

EPA Ground Water Forum

Co-chairs 2014
Ben Bentkowski, Region 4
61 Forsyth St., S.W., Atlanta GA 30303-8960
404.562.5807
Katie Mishkin, Region 2
290 Broadway, 18th Floor
New York, NY, 10007-1866
212.637.4449

GROUND WATER FORUM ISSUE PAPER PROPOSAL

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Date prepared: 3.27.2014

Problem Statement

Historic environmental site characterization efforts, in many cases, have resulted in conceptual site models (CSMs) which do not adequately incorporate the geologic framework, depositional environments, and lithologic heterogeneity of aquifers. The geology underlying the site is the primary control of groundwater flow and contaminant pathways. Accurate characterization of groundwater contamination and effective site strategies require knowledge of the geologic characteristics of the aquifers.

Purpose of Issue Paper: The purpose of this issue paper is to provide practical guidance to remediation project teams on methods to integrate existing and future site geologic information to develop robust CSMs using sequence stratigraphic methods. Guidance will be presented on how to develop a CSM that address lithologic heterogeneity at the appropriate scale to select successful remedies.

Sequence stratigraphy is a method for understanding and predicting permeability architecture of sedimentary deposits. This method was developed in the petroleum industry, based on knowledge that sediments are organized into repeated, predictable patterns (i.e, sequences) which control permeability architecture in the subsurface.

Target Audience: EPA technical support and RPMs along with the regulated community.

Outline of Pertinent Questions and Objectives to be addressed:

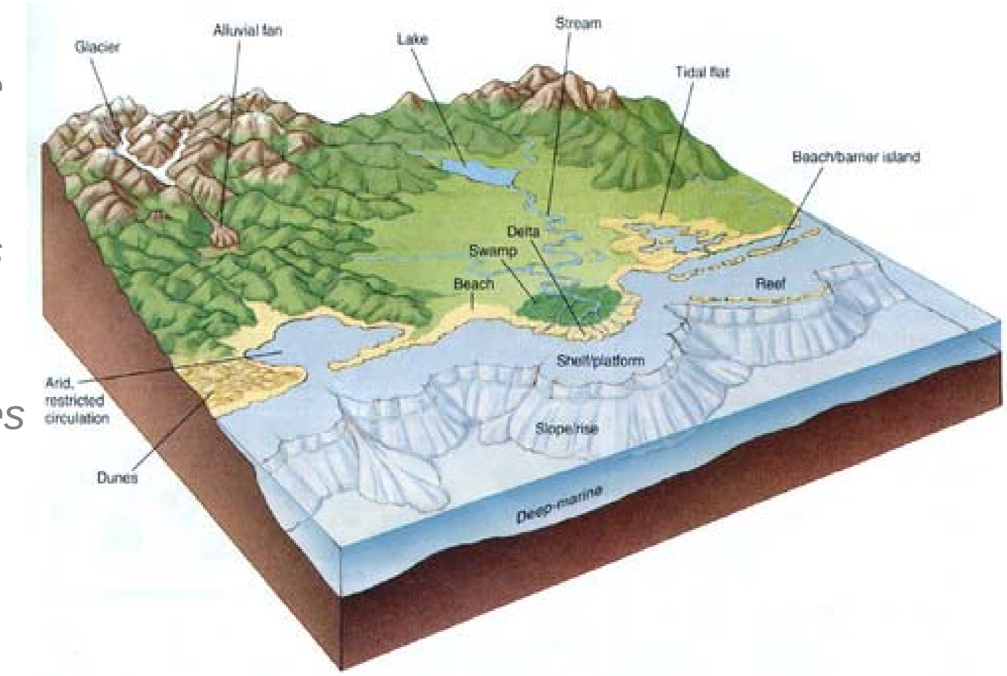
Applying sequence stratigraphic methods to environmental groundwater sites results in:

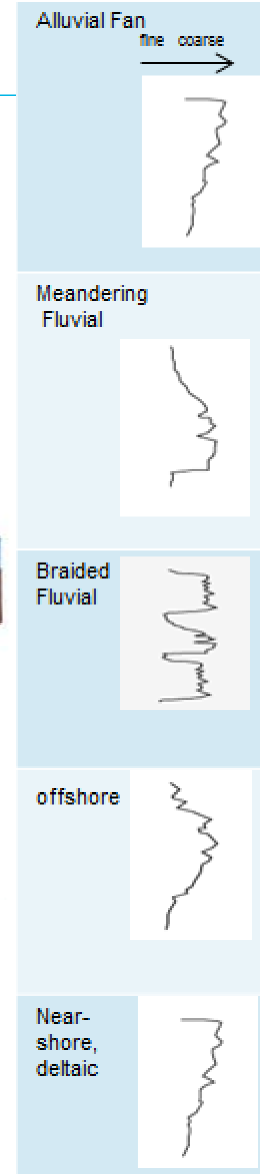
- A CSM that directly addresses subsurface heterogeneity and is based on characteristics of depositional environments
- Prediction of degrees and scales of heterogeneity, selection of appropriate high-resolution characterization methods

OK, but what IS IT already?

ESS is "Pattern Recognition"

- *Patterns in grain size are the language of heterogeneity*
- *Sequence Stratigraphers are the translators*
- *Can correlate/predict heterogeneity at all scales*
- *There are grain size patterns buried within existing boring logs of every site*
- *Experience and background of the practitioner is a prerequisite*





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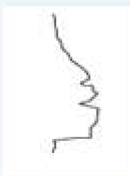
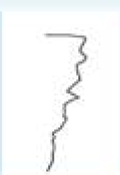
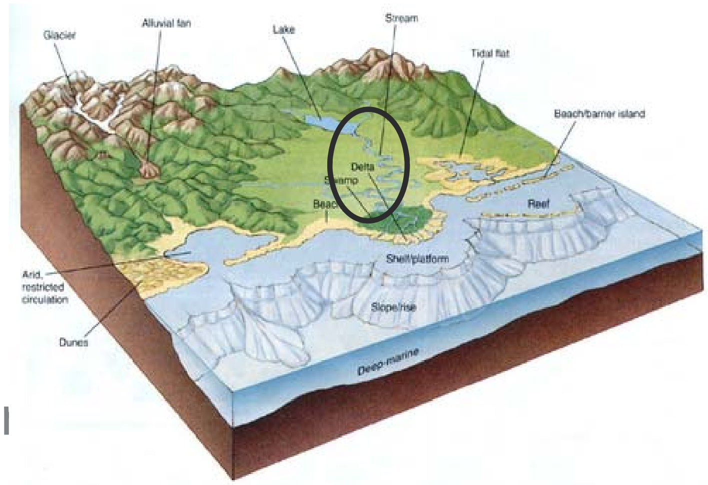
Depositional Environment and typical grain size profile	Major aquifer elements and their common dimensions	Major aquitard elements and their common dimensions	Impact on CSM	Required Data Resolution
Alluvial Fan 	Proximal fan channels, mid-fan sheet sands, distal fringe sands X: 10^2 m – 10^4 m Y: 10^1 m – 10^3 m Z: 10^{-1} m – 10's m	Playa lake deposits or paleosol formations commonly vertically separate fans. Debris-flow deposits also commonly clay-rich X: 10^2 m – 10^3 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10's m	Laterally extensive playa lake deposits can missed by traditional sampling methods due to their thin nature, but can vertically compartmentalize aquifers. Fans have a primary stratigraphic dip basinward at 1-6 degrees, and are laterally offset stacked ("shingled").	High in vertical sense, medium to low in horizontal sense
Meandering Fluvial 	Channel axial fill, point bar, crevasse splays X: 1 m – 10's m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Floodplain deposits, levee deposits, clay drapes on lateral accretion surfaces, plugs filling abandoned channels X: 10^2 m – 10^3 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10's m	Due to well-sorted sand and gravel at bases of channels, permeability can be orders of magnitude higher in this zone. High risk of off site contaminant transport due to groundwater flow controlled by channel orientation and not groundwater gradient. Local groundwater flow up to 270 degrees from regional gradient. Channel-fills highly asymmetric with cutbank characterized by sharp erosional edge and point bar characterized by interfingering with floodplain fines impacting potential for contaminant mass storage. Lateral accretion drapes can separate point bar deposits that would appear to be connected laterally. Clay plugs filling abandoned oxbow lakes common.	High both laterally and vertically if site size is greater than channel widths
Braided Fluvial 	Channel axial fill, bar forms X: 1 m – 10's m Y: 10 m – 10^2 m Z: 10^{-1} m – 1's m	Floodplain deposits, silt and clay plugs filling abandoned channels X: 10^2 m – 10^3 m Y: 10^3 m – 10^2 m Z: 10^{-1} m – 1's m	"Streaky" groundwater flow with isolated high-permeability zones. Overall high permeability and porosity with amalgamated channel deposits. Local groundwater flow up to 90 degrees from gradient, but typically within 45 degrees of gradient	High, but dependent on degree of amalgamation of channels determined by fines content (greater fines content results in less channel connectivity)
offshore 	Offshore bar, transgressive sand X: 10's m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	High-frequency transgressive flooding shales X: 10's m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Laterally extensive, sand-rich deposits. Interbedded storm deposits (coarser grained) with fair-weather deposits l(finer-grained) lead to high degrees of vertical heterogeneity, and low to very low Kv/Kh ratio.	Low in lateral sense, high in vertical
Near-shore, deltaic 	Shoreface (beach), or bayhead delta in upper part, shelf in lower parts X: 10's m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	High-frequency transgressive flooding shales X: 10's m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Laterally extensive, sand-rich near-shore units in upper parts of sequences. High degree of interbedding of coarse and fine-grained units in lower parts. Silt and clay beds capping sequences dip basinward, may lead to erroneous correlations at distances of hundreds of meters to kilometers.	Low in lateral sense, high in vertical

The Problem of Aquifer Heterogeneity

- Outcrop analog of meandering fluvial deposits
- At aquifer remediation site scale
- Ability to explicitly map sand body architecture in 3 dimensions
- Facies Models provide predictive tool for characterization based on depositional environments

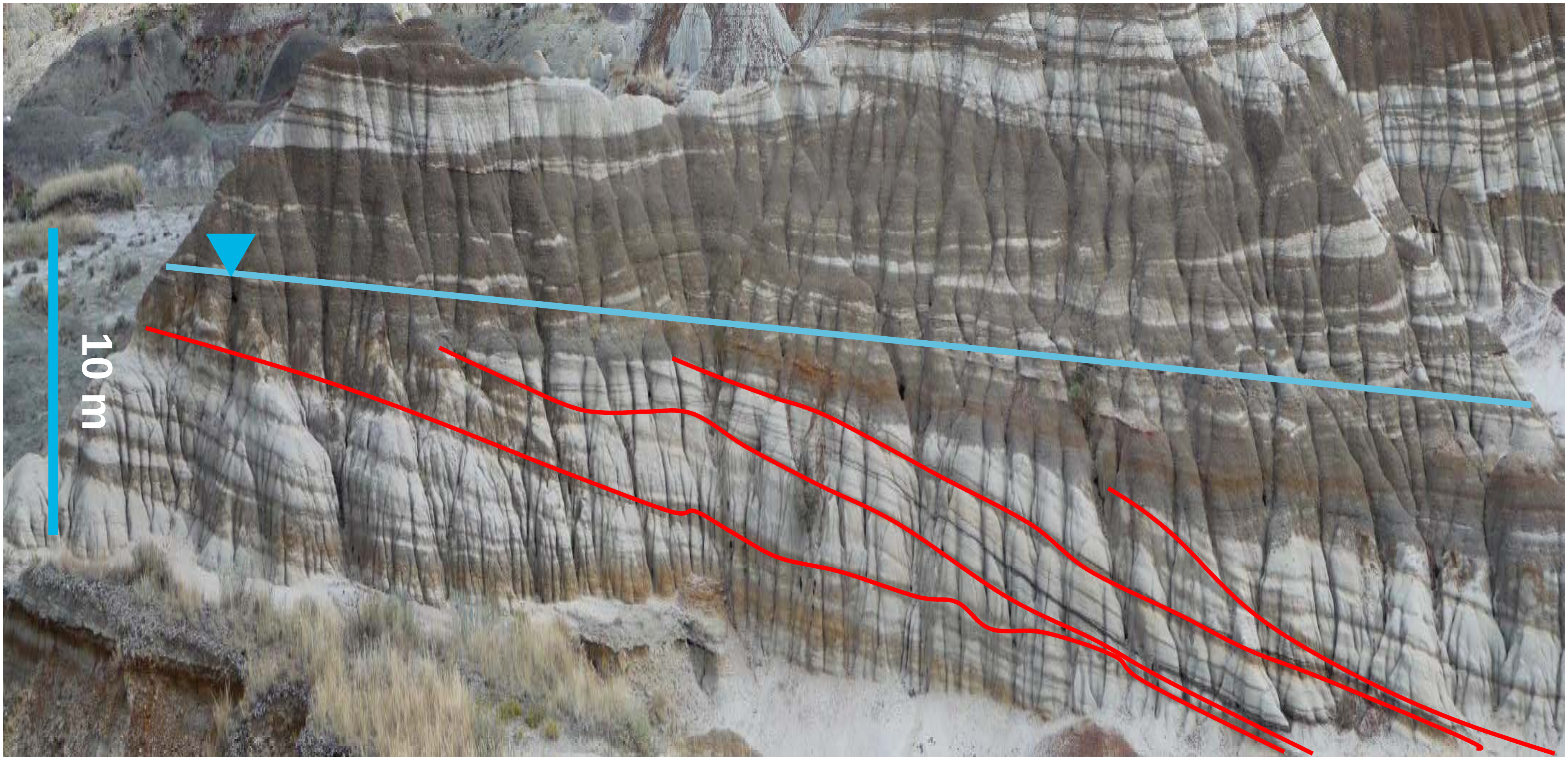


The Problem of Aquifer Heterogeneity

The Problem of Aquifer Heterogeneity

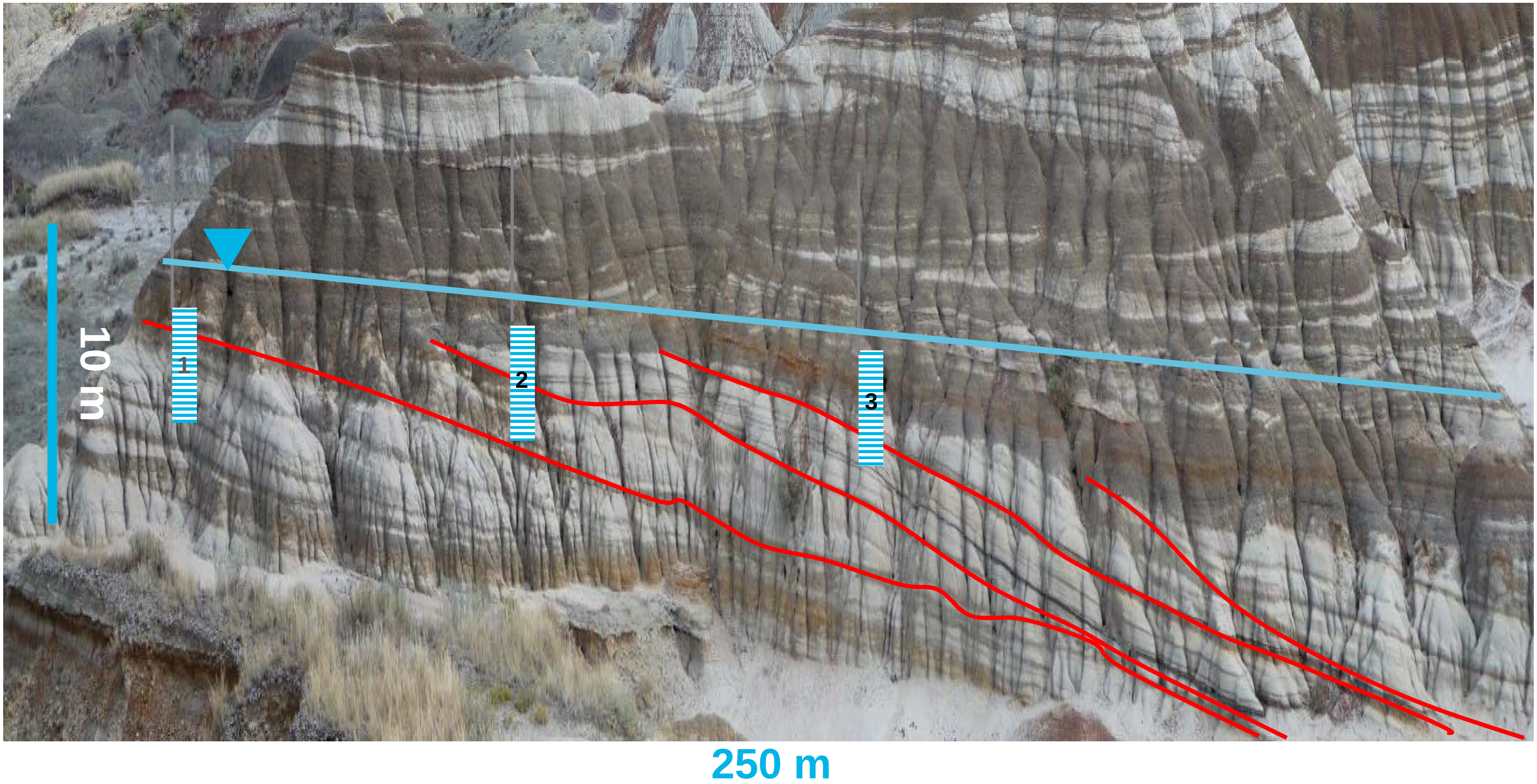
250 m

The Problem of Aquifer Heterogeneity



250 m

The Problem of Aquifer Heterogeneity



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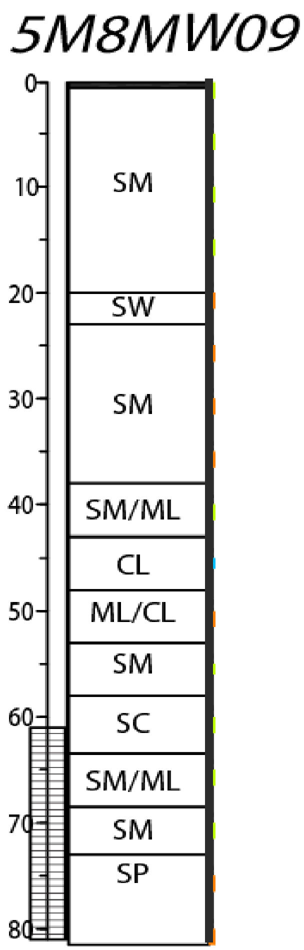
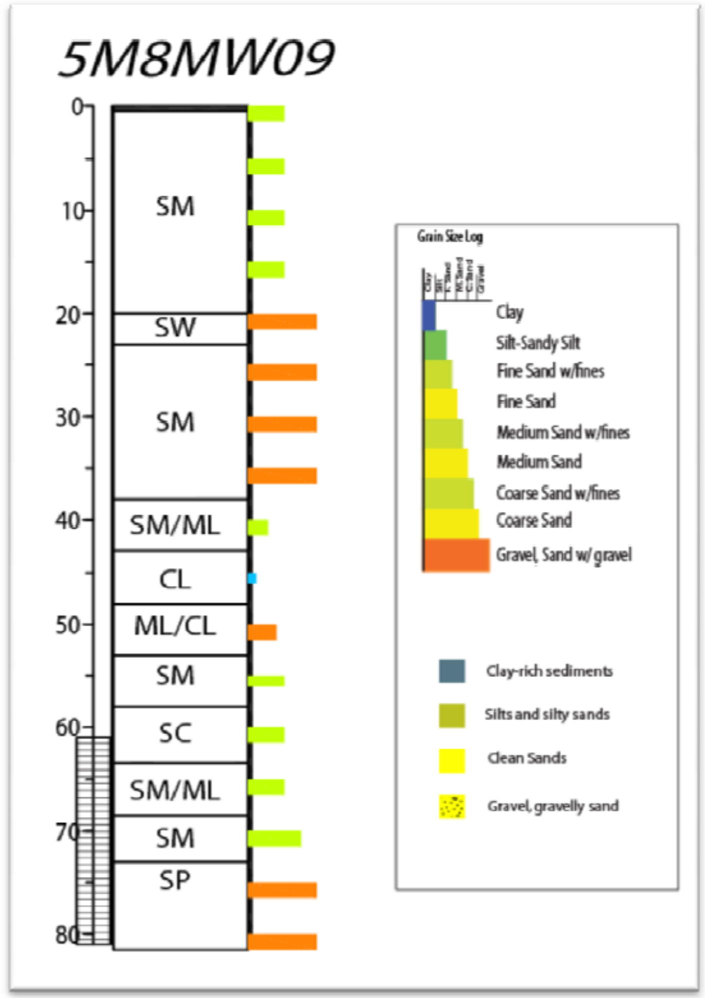
"Hidden" Stratigraphic Data



- "All we have are these lousy USCS boring logs"
- USCS is not a geologic description of the lithology
- Different geologists
- Different drilling methods
- Different sampling intervals
- Etc…

"Hidden" Stratigraphic Data

- Existing data is formatted for stratigraphic interpretation
- Reveals the "hidden" stratigraphic information that is available with existing lithology data



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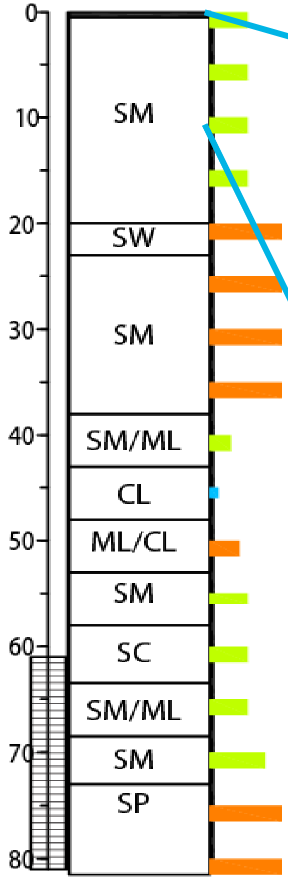
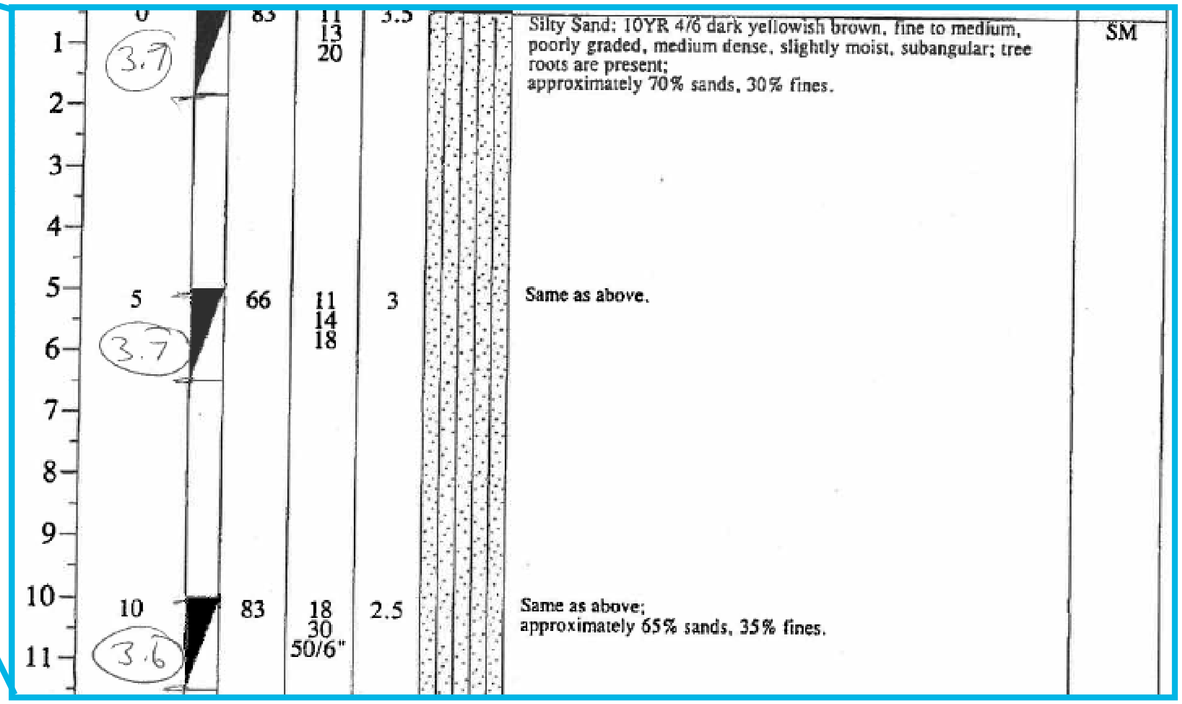
"Hidden" Stratigraphic Data

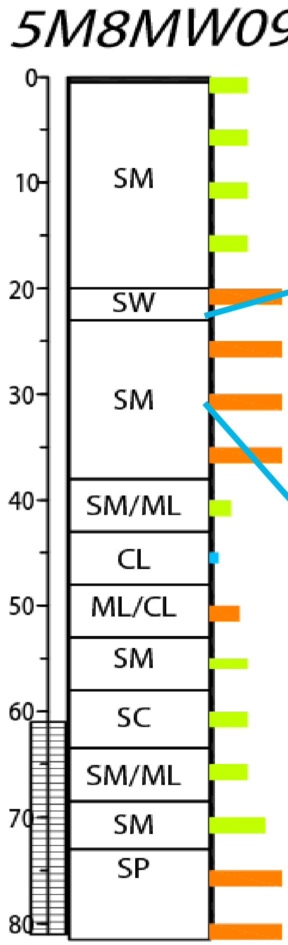
5M8MW09

This SM interval is a <u>fine to medium grained</u> Silty Sand

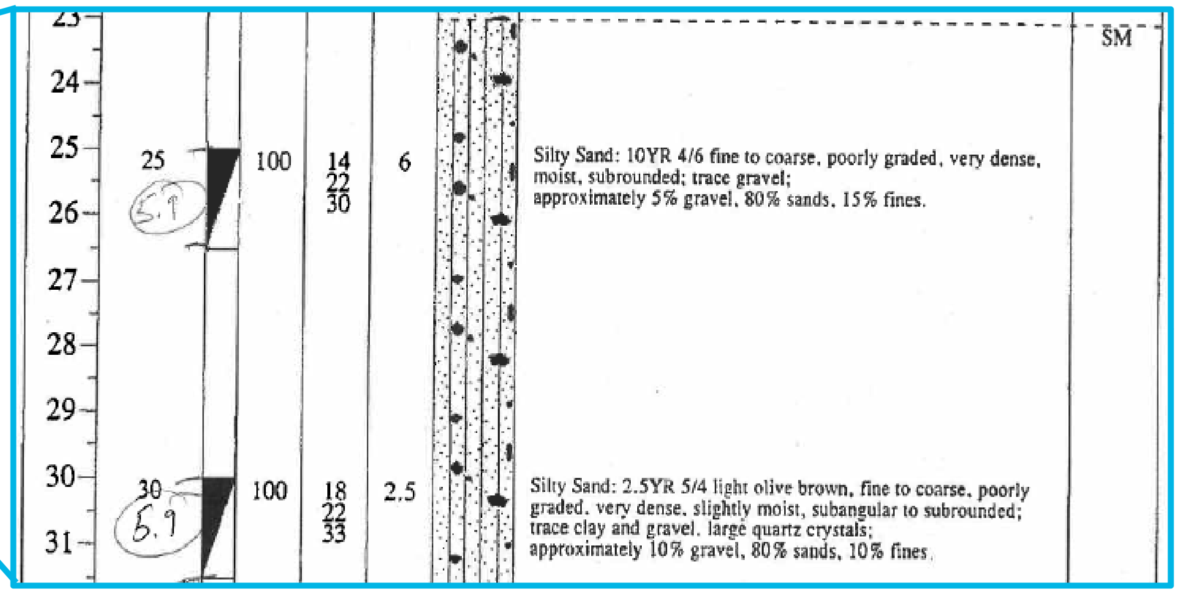




“Hidden” Stratigraphic Data



This SM interval is a fine to coarse grained Silty Sand with gravel, representative of a channel deposit.



Both were logged as SM, but the details show that they have significantly different depositional characteristics.

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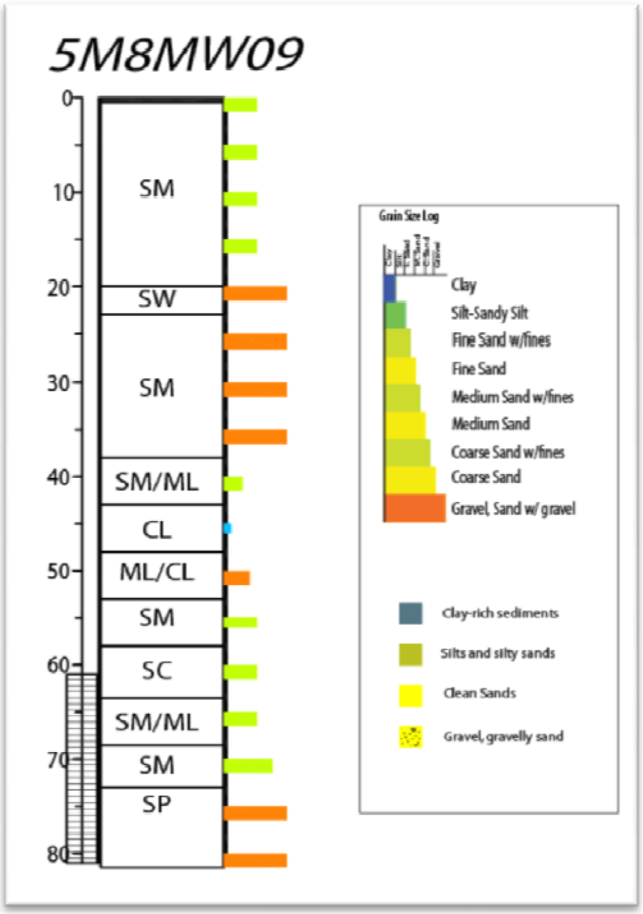
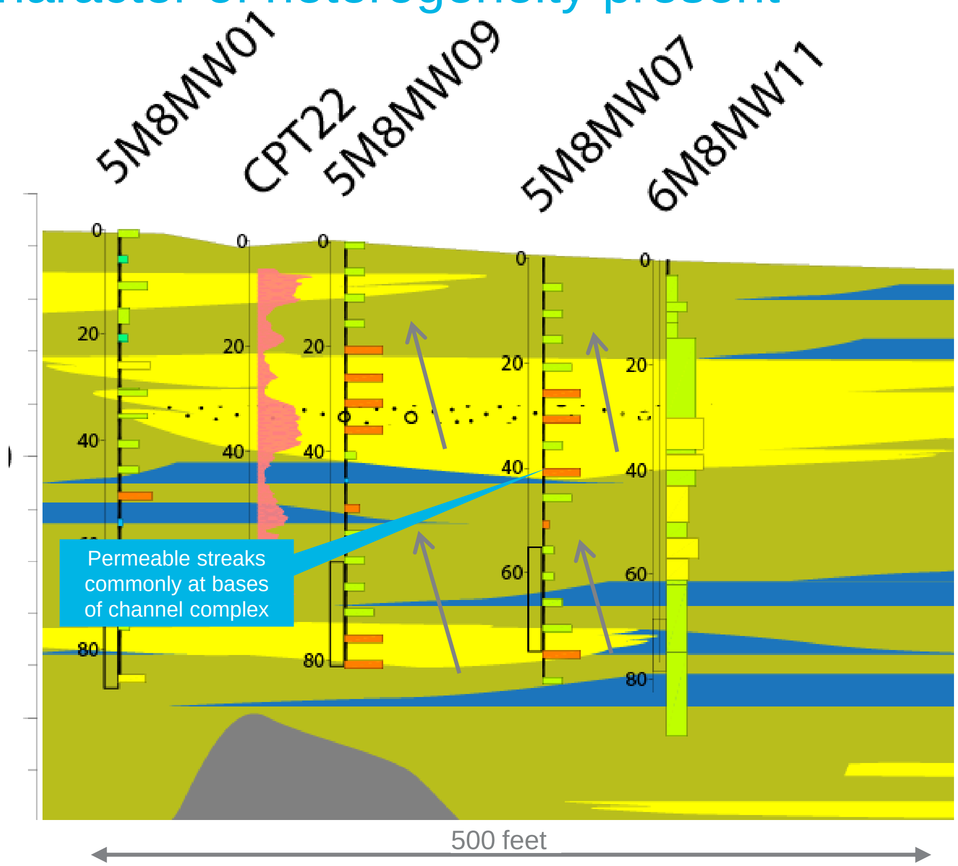
The ESS Workflow in a Nutshell:

1. Reformatting existing data to identify sequences, and
2. Applying facies models, stratigraphic "rules of thumb" to correlate and map the subsurface, predict character of heterogeneity present





Example from GW site in S. CA, USA

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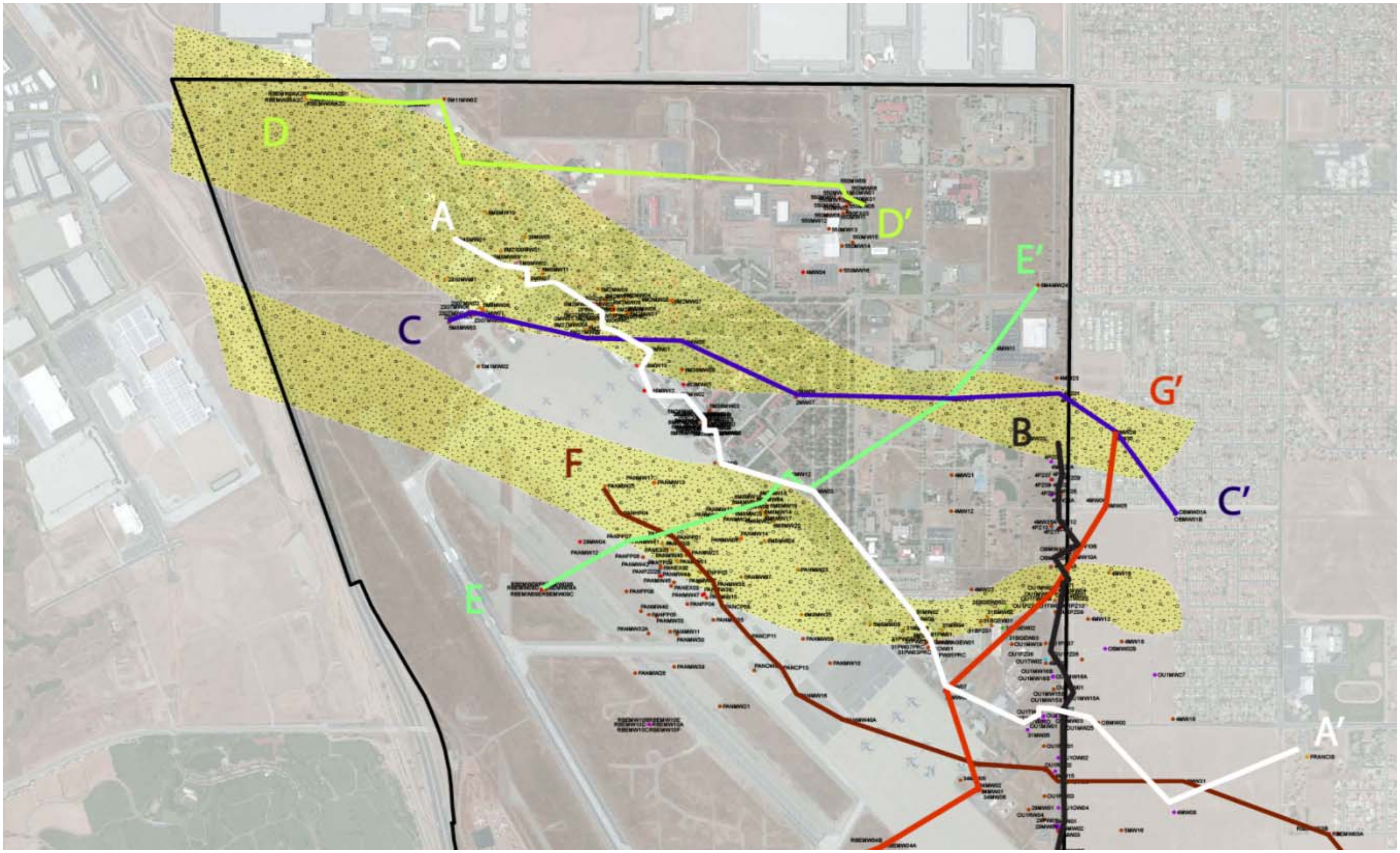
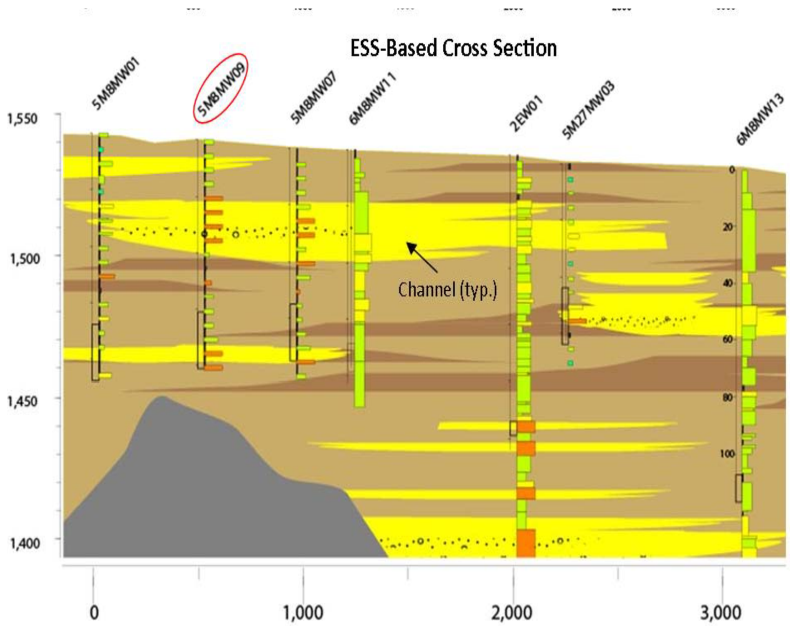
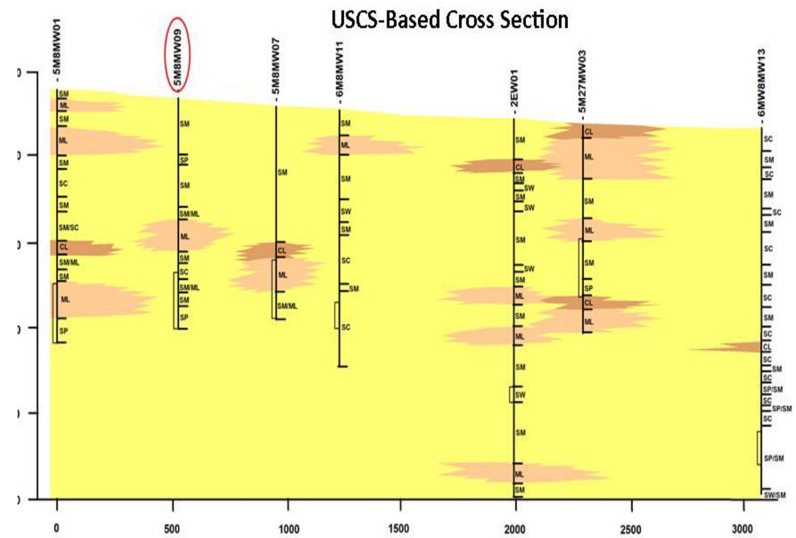
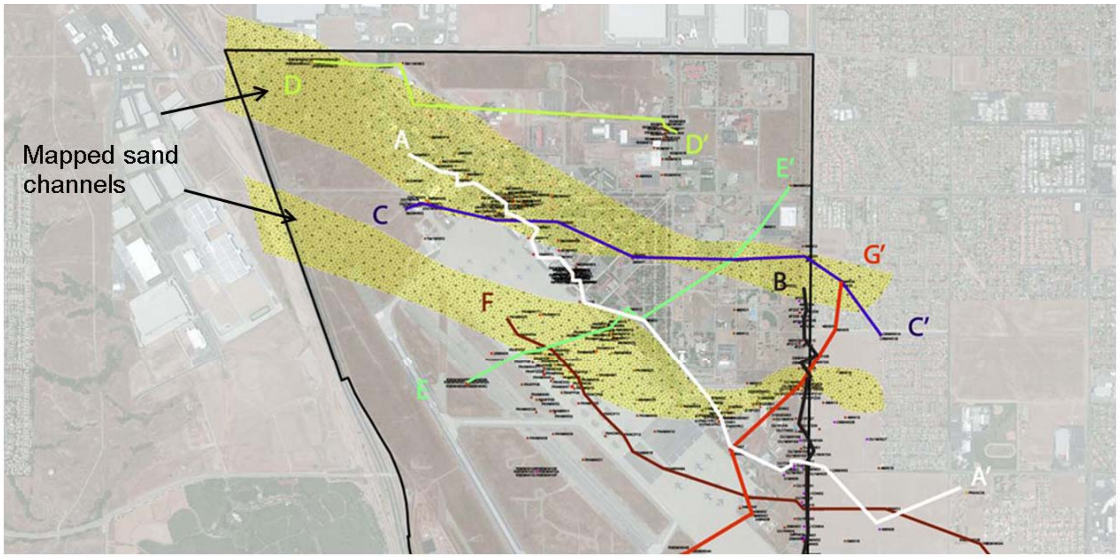
Mapped Sand Channels



Mapped Sand Channels







Case Study #1: *In situ* Bioremediation

Industrial Facility: Ethanol injection to reduce hexavalent chromium plume

Scale: Hundred acres, ~60' depth of investigation

Lithology Data: CPT logs, borehole logs

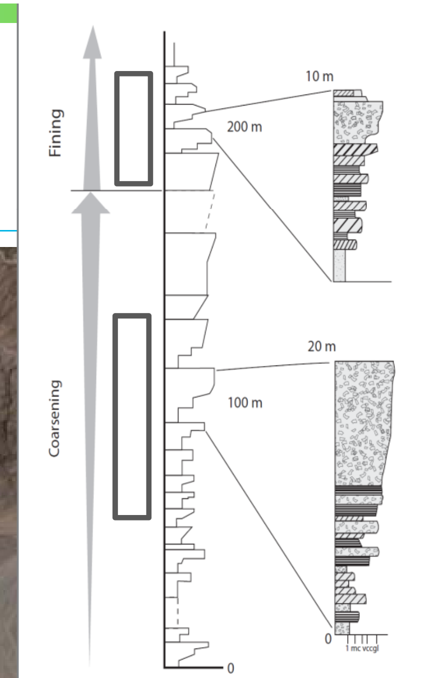
Approach: Apply ESS to explain Mn by-product

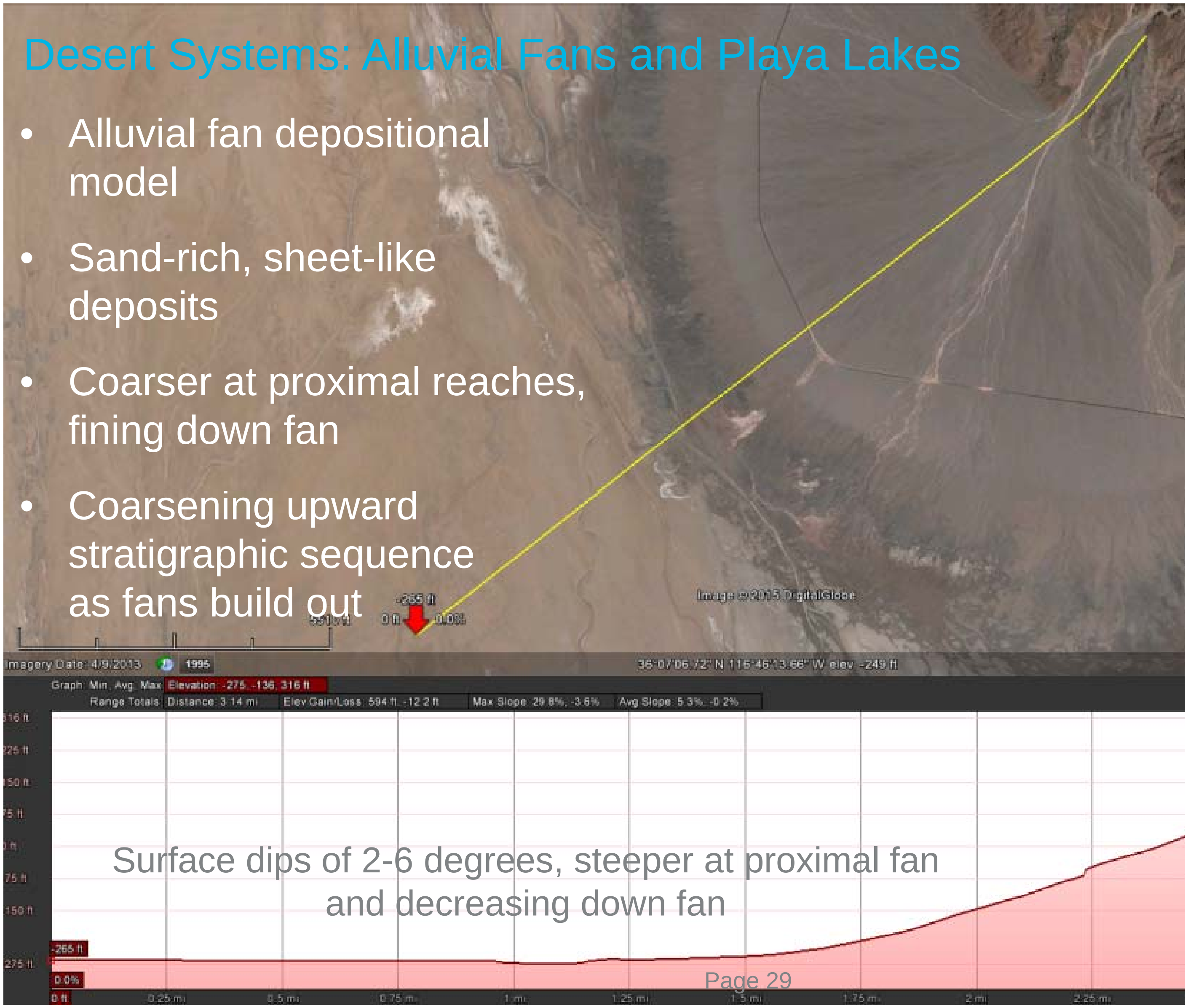
Takeaway: Even with "high-resolution" lithology data, a depositional model is needed for successful remediation

Case Study #1: *In situ* Bioremediation

Desert Systems: Alluvial Fans and Playa Lakes

- Alluvial fan depositional model
- Sand-rich, sheet-like deposits
- Coarser at proximal reaches, fining down fan
- Coarsening upward stratigraphic sequence as fans build out



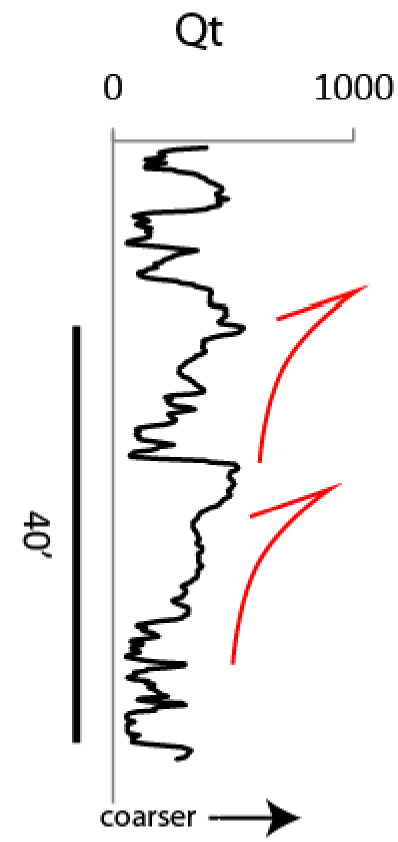


Surface dips of 2-6 degrees, steeper at proximal fan and decreasing down fan

Case Study #1: *In situ* Bioremediation

Grain Size Trends in CPT Data

- Site CPT data
- Coarsening upward vertical grain-size pattern
- Stacked alluvial fan deposits bounded by clays



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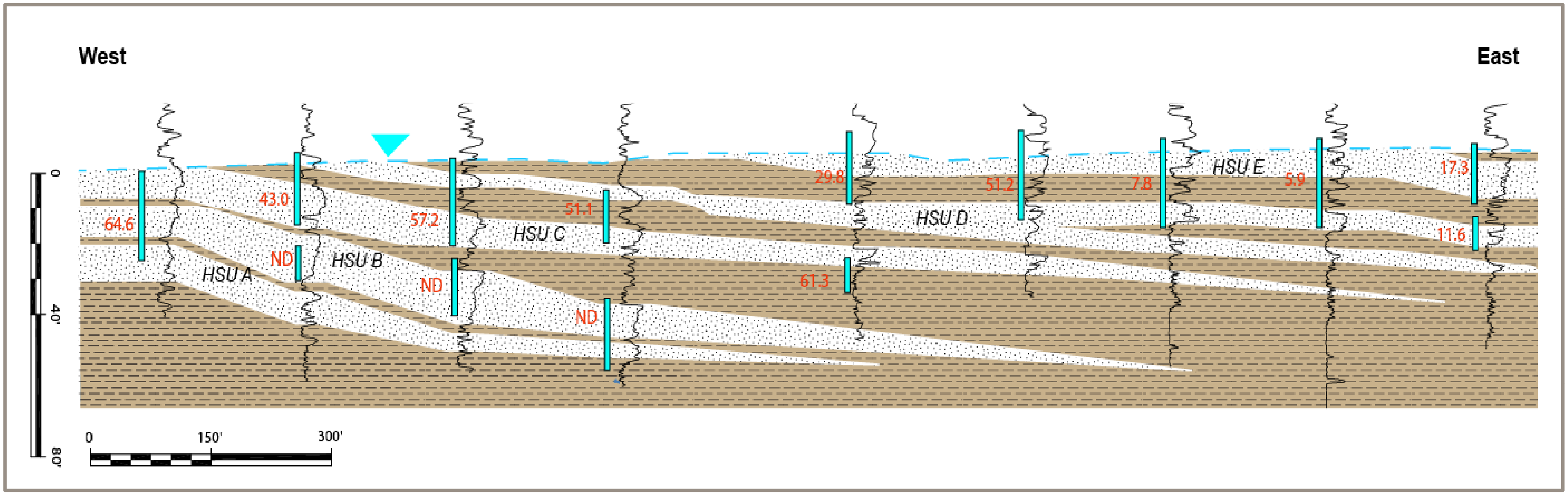
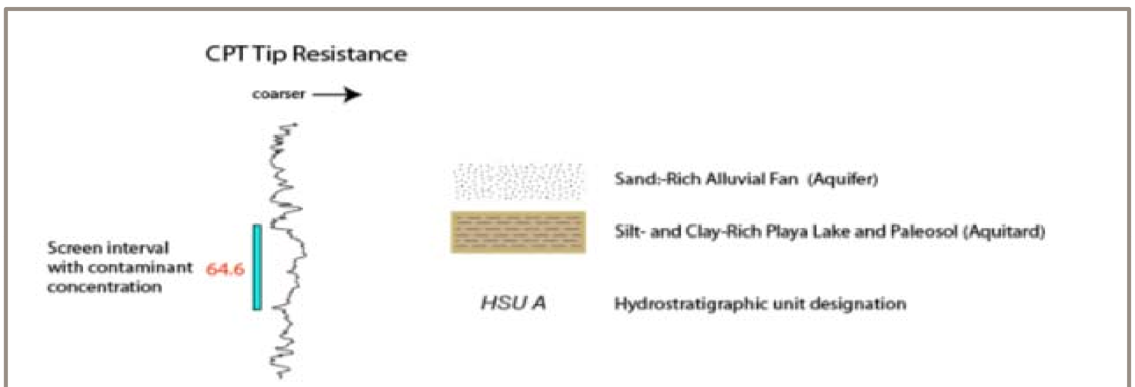
Case Study #1: *In situ* Bioremediation

Cross Section of Hydrostratigraphic Units (HSUs)





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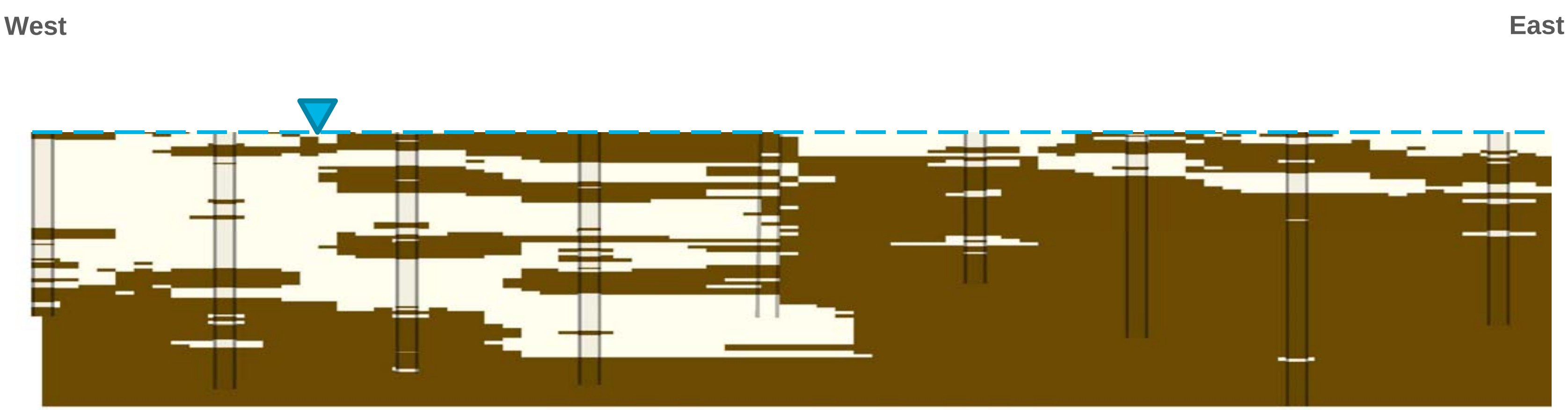
Case Study #1: *In situ* Bioremediation

Kriging of CPT Data to Correlate Lithology

(Same cross section) Miscorrelates thin clay beds giving appearance of randomness in stratigraphic architecture



Brown = silt/clay
White = sand/gravel

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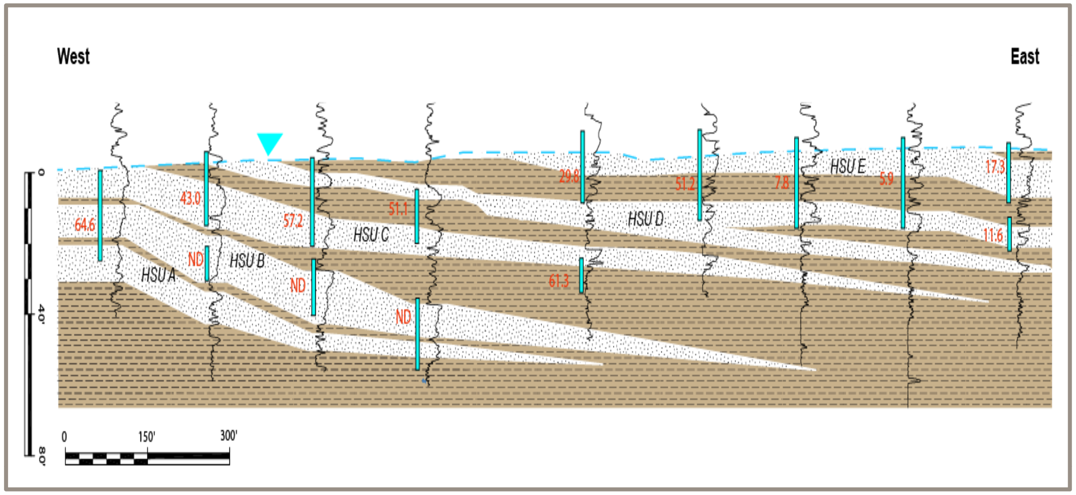
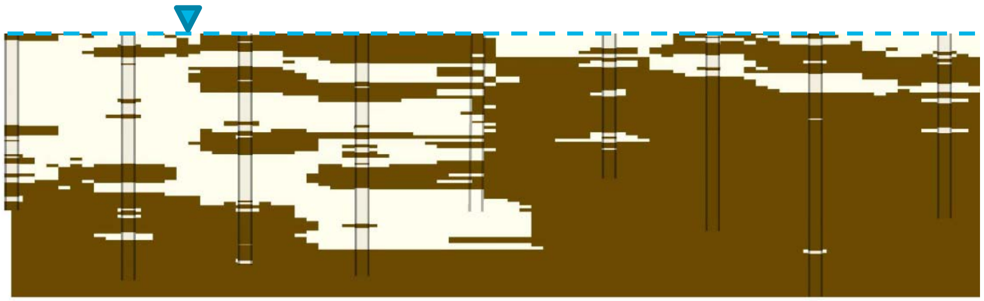
Case Study #1: *In situ* Bioremediation

Conclusions

- Saturated zone consists of discrete HSUs (sand-rich alluvial fans)
- Stratigraphic dip of alluvial fan units is responsible for preferential pathways, channelization is not the primary mechanism
- Kriging correlations are not representative of the stratigraphy
- Not all fan units impacted; injection into clean zones responsible for Mn byproducts





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Case Study #2: Plume Containment Strategy

Munitions Manufacturing Site: Perchlorate plume impacting municipal wells

Scale: Thousand acres, ~700’ depth of investigation

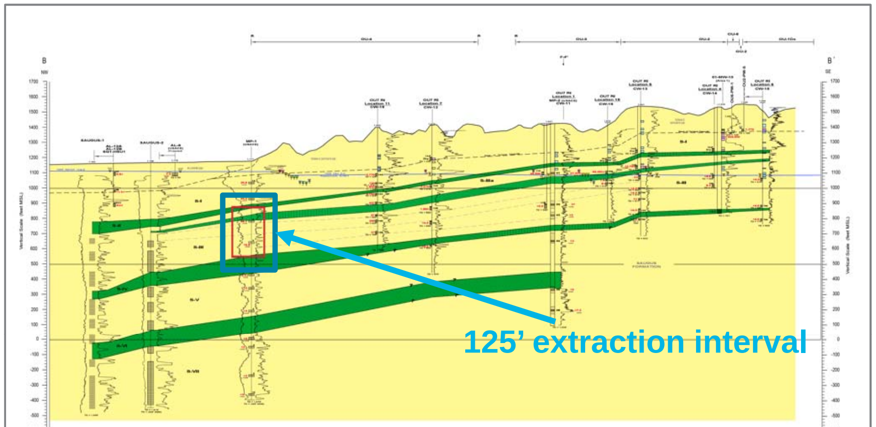
Lithology Data: Geophysical logs, borehole logs

Approach: Apply ESS on existing data to improve CSM and Design Plume Management Program

Takeaway: Detailed stratigraphy has significant impact on remediation design, project cost.

Case Study #2: Plume Containment Strategy

Site Overview



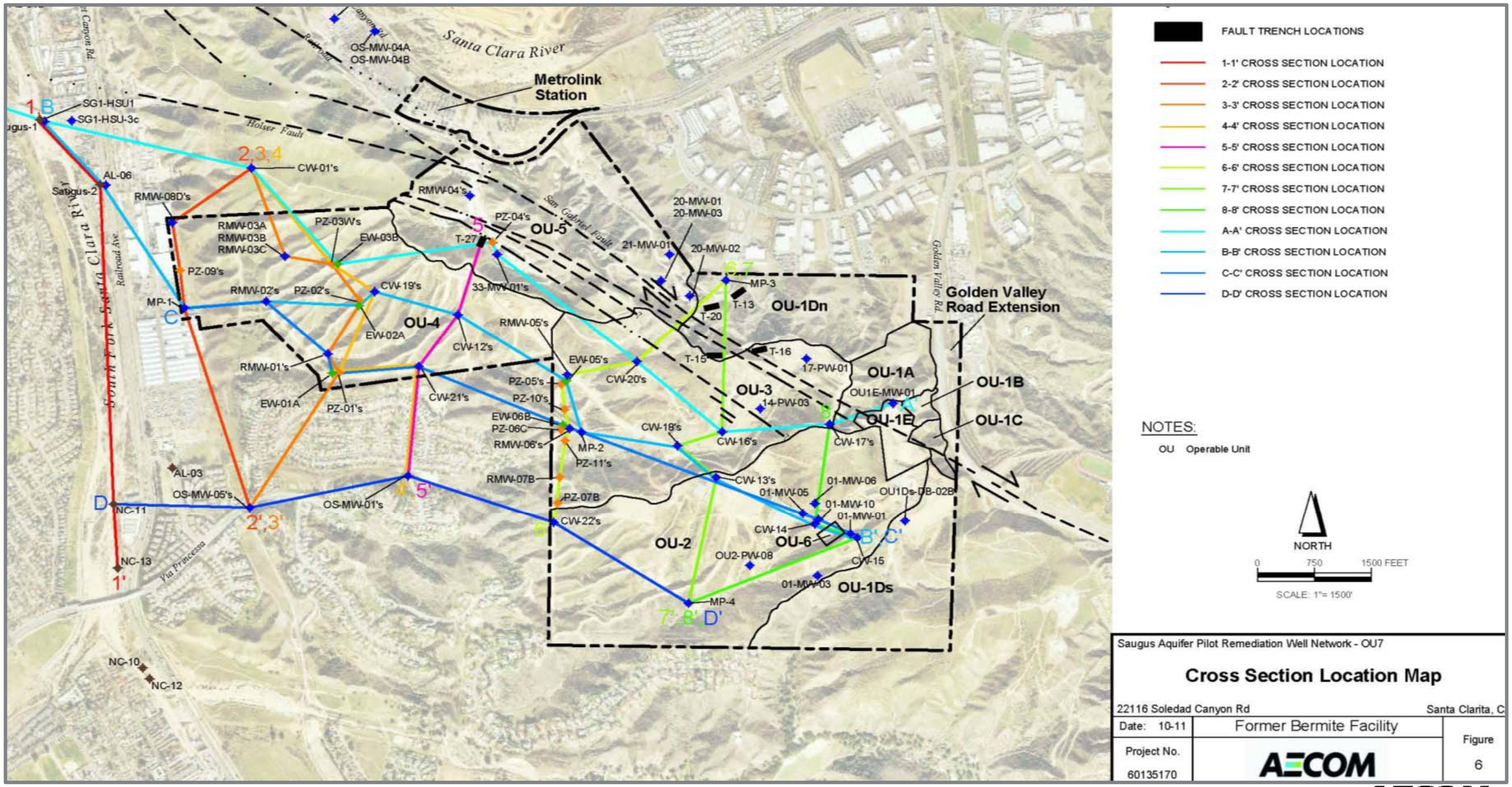
Pre-Existing 3-Layer CSM

- 996-acre (403-hectare) site Santa Clarita, CA
- Complex geology, over 600' of stratigraphy, dipping beds
- Impacted mainly with perchlorate ($ClO4^-$), but locally CVOCs, including TCE
- AECOM awarded contract to implement containment pilot study
- Geologic setting, AECOM expertise prompted CSM review

Case Study #2: Plume Containment Strategy

3-D ESS Cross Section Network

Site-wide analysis for design of containment system



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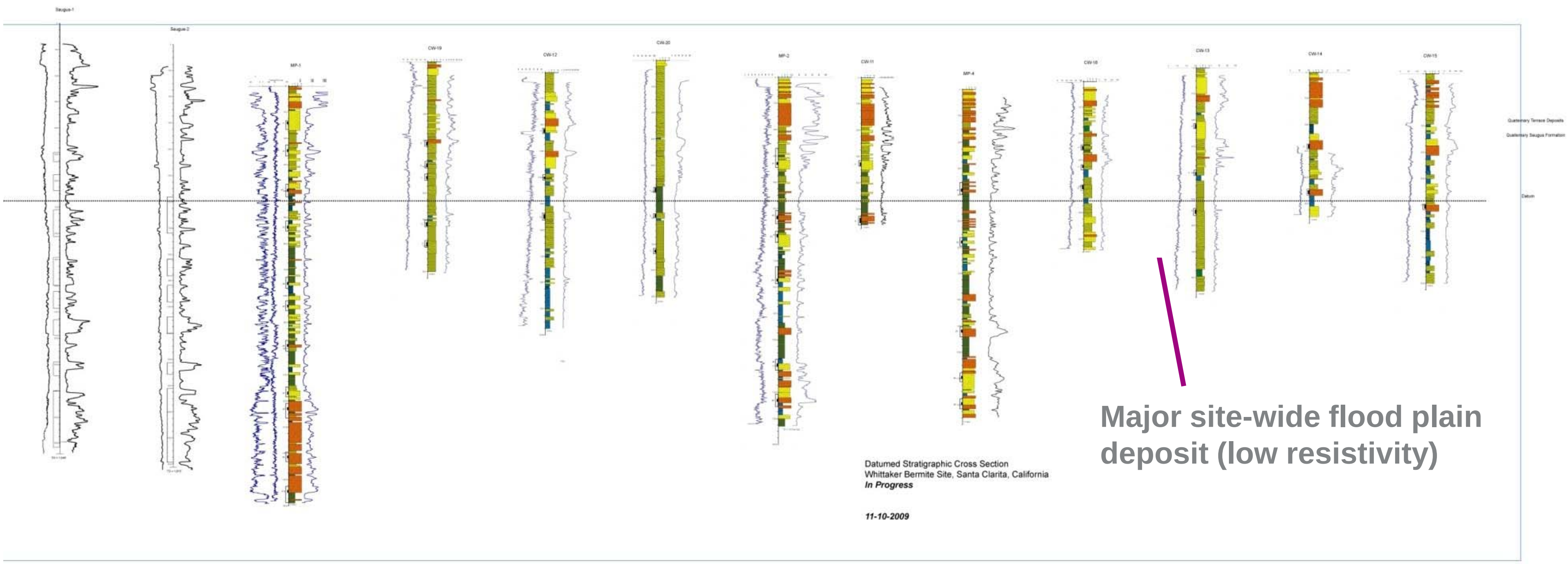
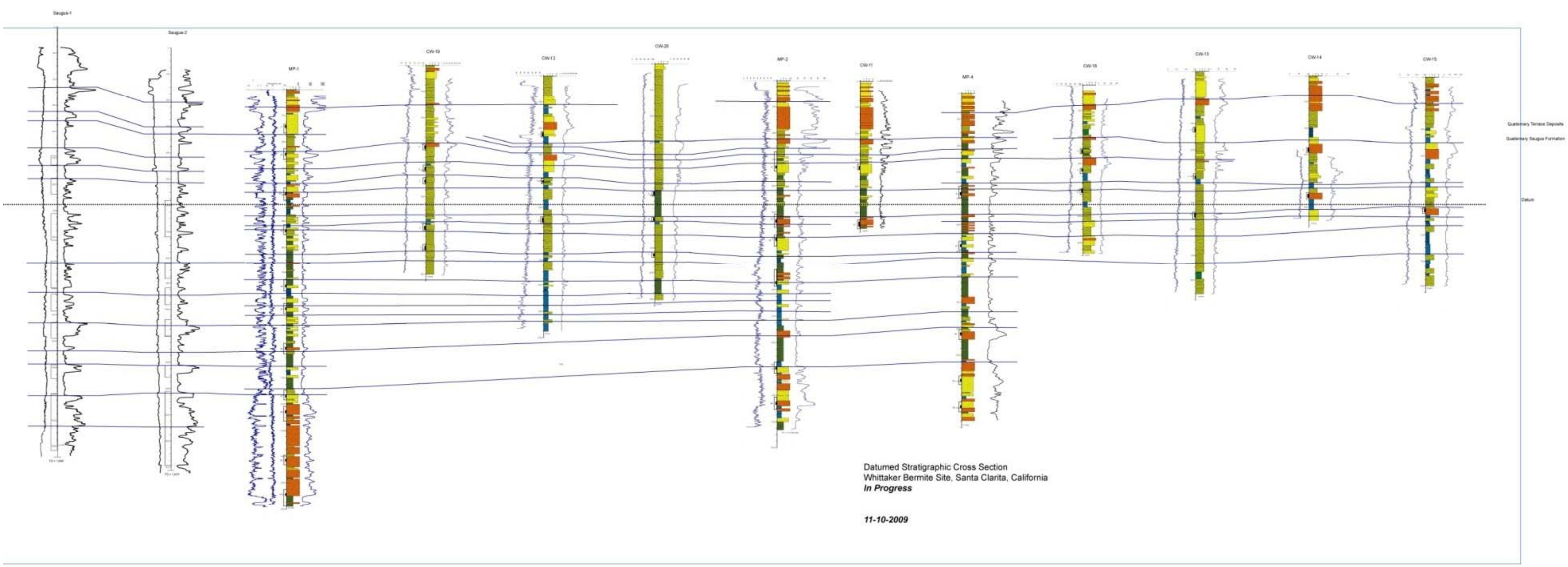
Case Study #2: Plume Containment Strategy

ESS Process: Datum (flatten) Logs on Well-Defined Floodplain Unit



Case Study #2: Plume Containment Strategy

ESS Process: Correlate Floodplain Surfaces



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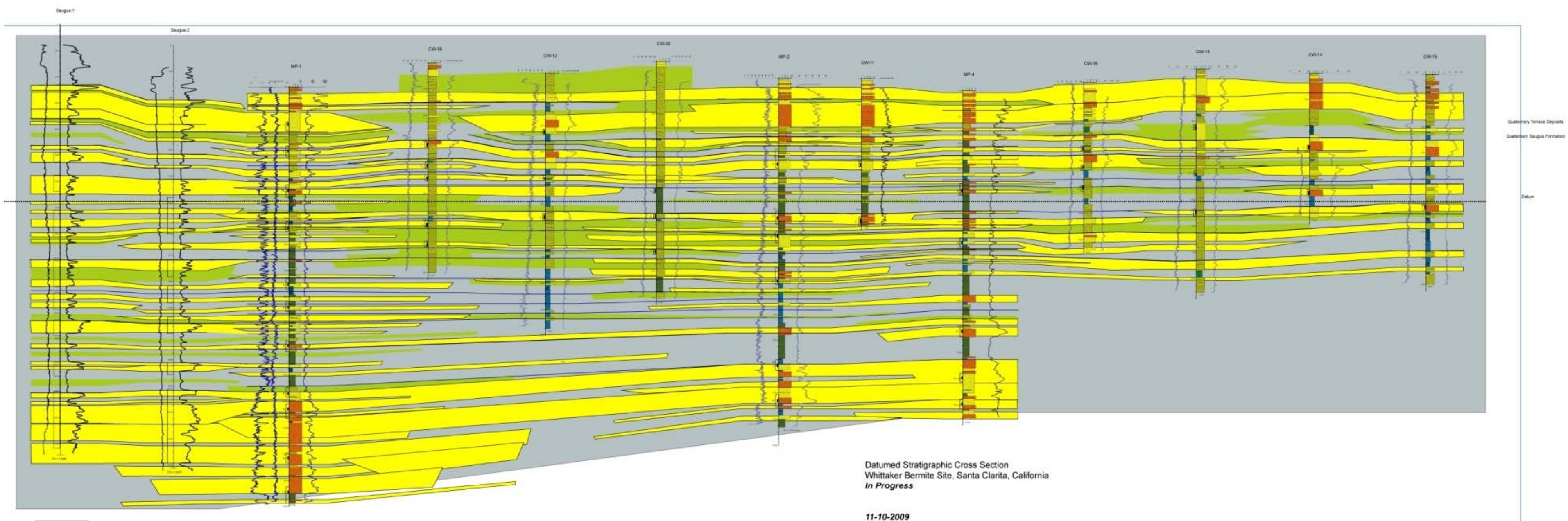
Case Study #2: Plume Containment Strategy

ESS Process: Define Aquifer/Permeability Architecture Based on Stratigraphic Rules



Aquifer (Sands and Gravels)

Aquitard (Clays and Silts)

Transitional (Silty Sands, Sandy Silts)

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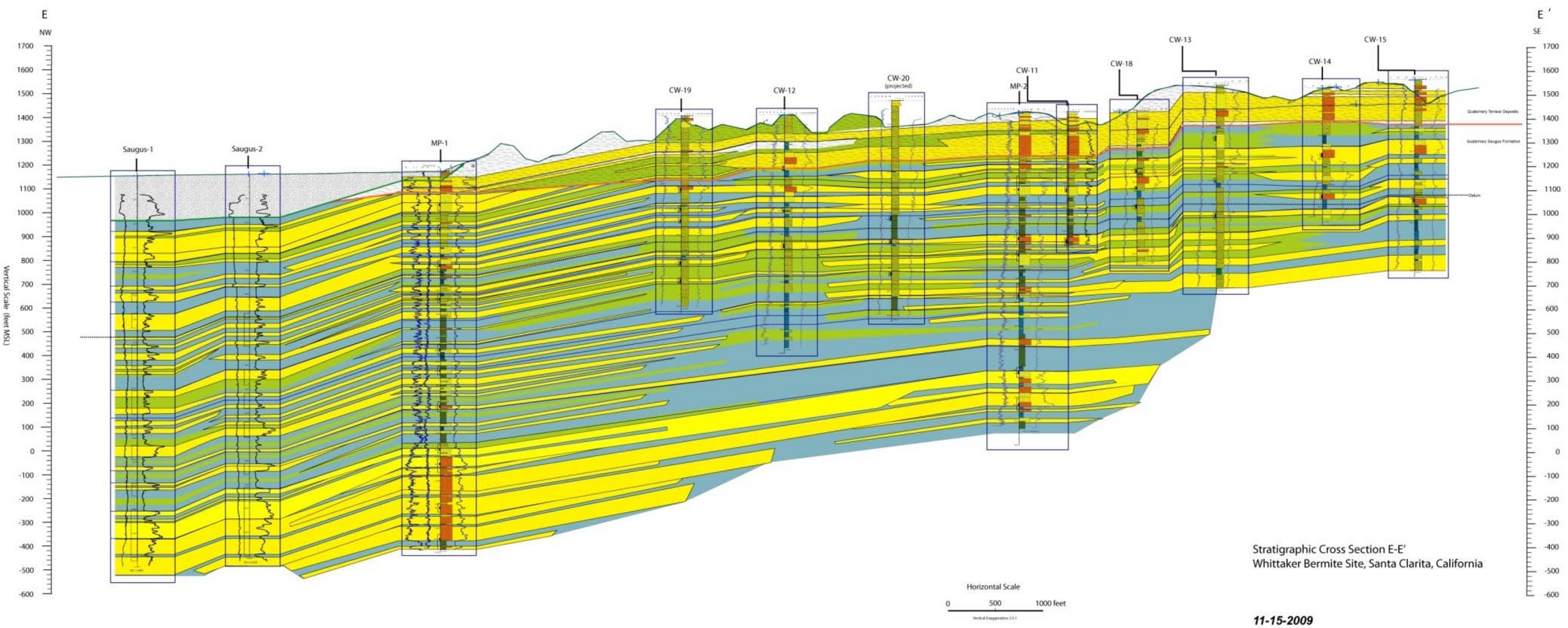
Case Study #2: Plume Containment Strategy

ESS Process: Aquifer Architecture in Structural and Groundwater Flow Context



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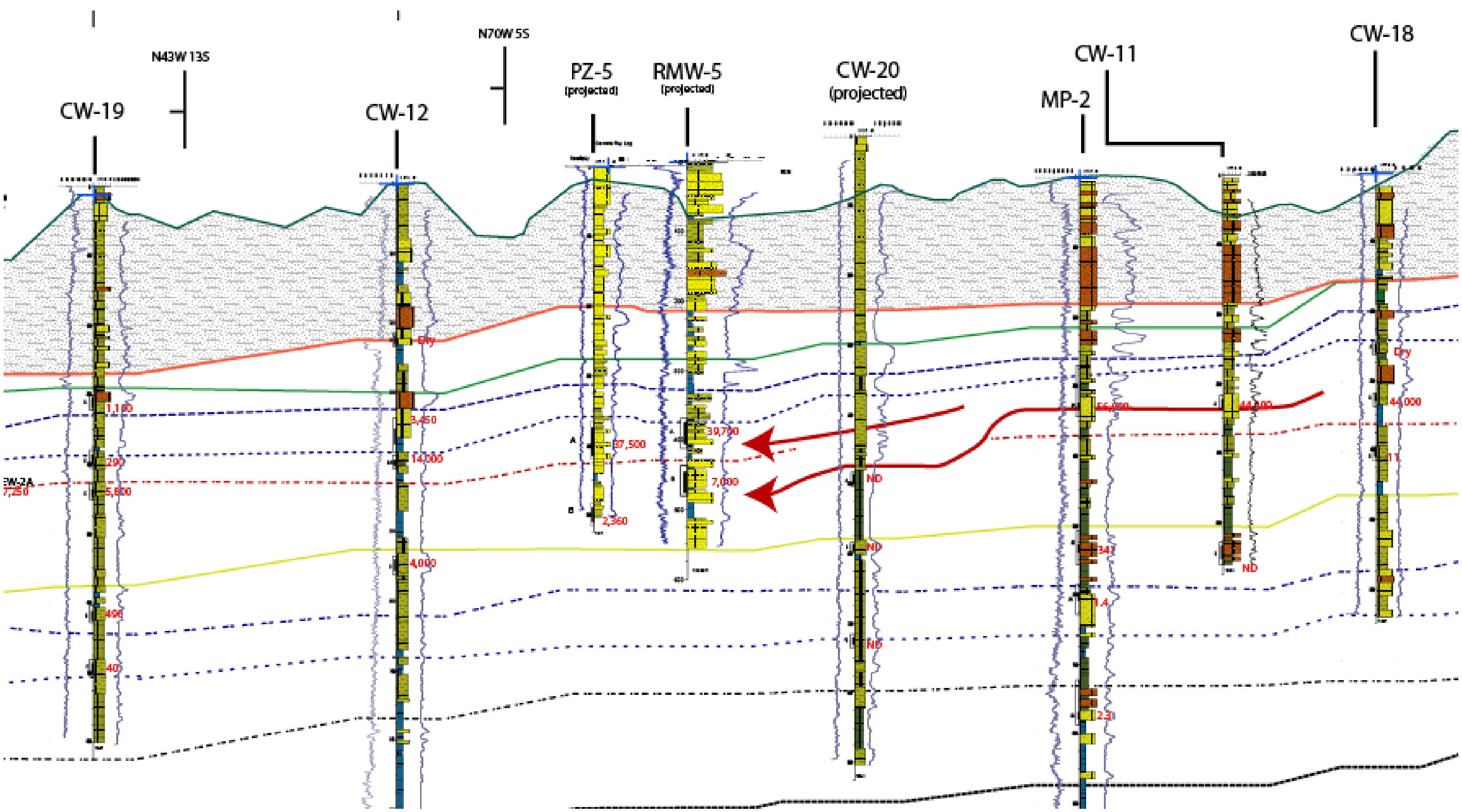
Case Study #2: Plume Containment Strategy

ESS Process: Identification of Breach of Floodplain Aquitard, Map Likely "Hot Zones"



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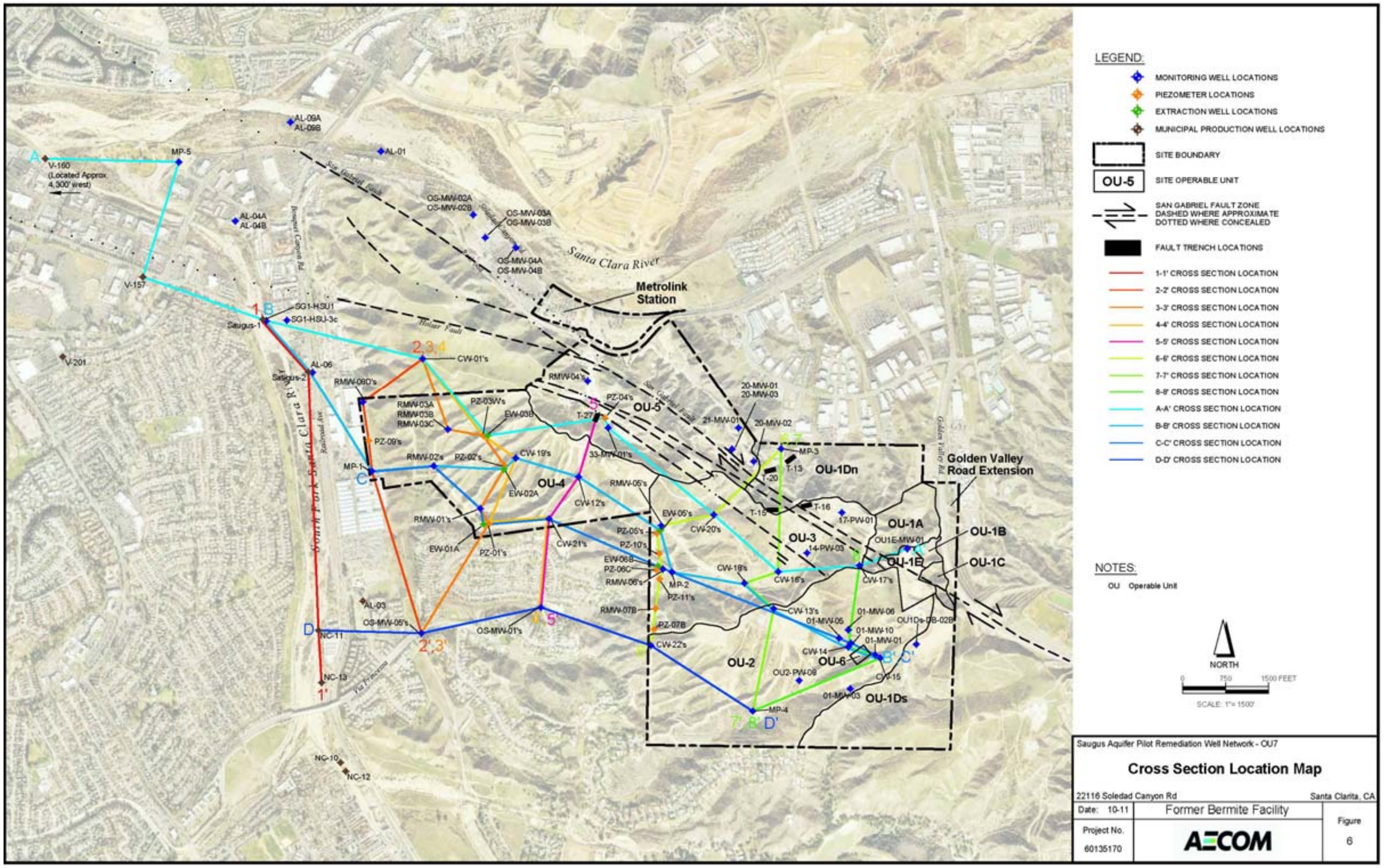
Case Study #2: Plume Containment Strategy

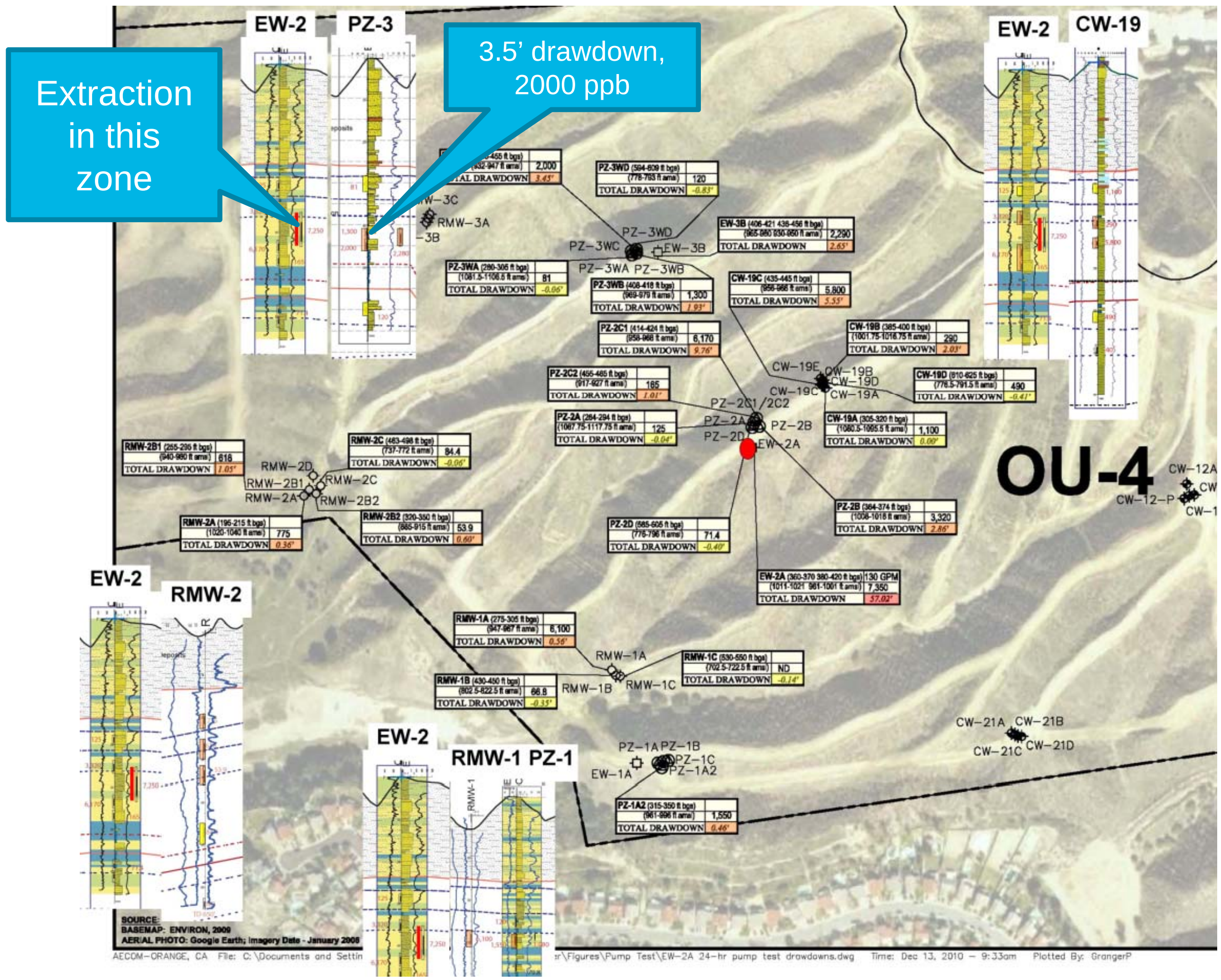
ESS Process: Create 3-D ESS Stratigraphic Framework



Case Study #2: Plume Containment Strategy

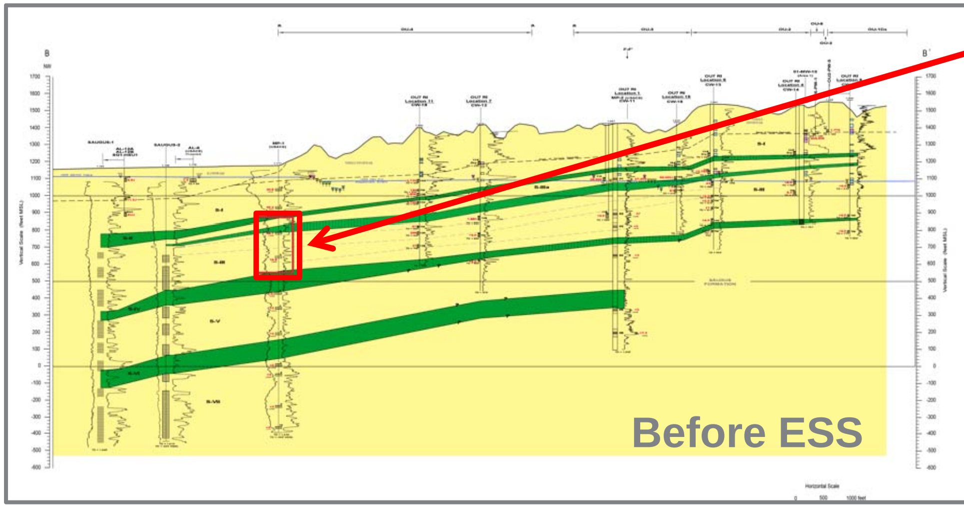
ESS Process: Testing and Validating the CSM – Pathways and Communication

- Aquifer tests were performed sequentially, instead of concurrently, to avoid interference from different pumping wells
- HSU designations, groundwater flow paths verified



Case Study #2: Plume Containment Strategy

ESS Outcome: Overhauled CSM, verified CSM, gained regulatory and stakeholder approval for wholesale modification of containment system design = $55MM savings

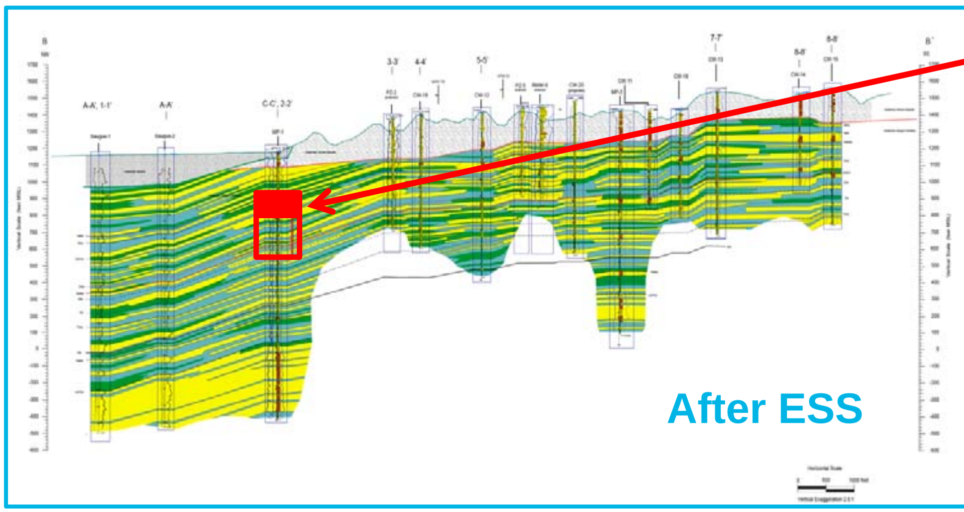


125’ extraction interval; includes non-impacted strata

Remediation System Cost (Before ESS)

- 12 extraction wells
- ~200 gpm per well
- 1,261 million gal per year

Capital cost = $7 MM
Treatment cost = $2.5MM/yr; 30 yr = $75 MM
Total cost = $82 MM



35’ extraction interval; impacted strata only

Remediation System Cost (After ESS)

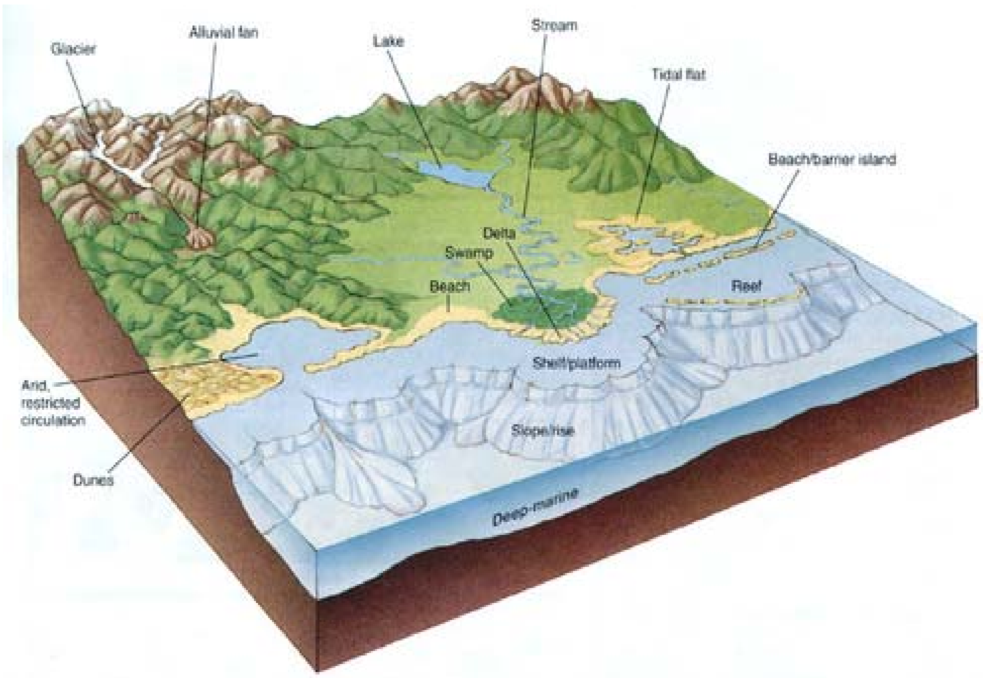
- 13 extraction wells
- 46 gpm per well
- 314 million gal per year

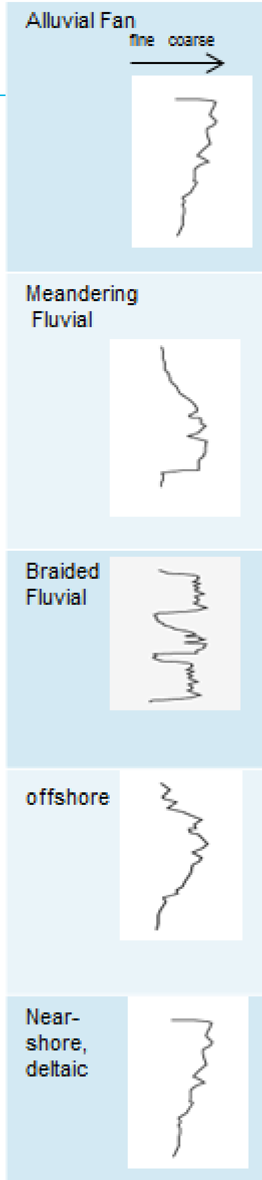
Capital cost = $2.5MM
Treatment cost = $800K/yr; 30 yr = $24MM
Total cost = $26.5 MM

Takeaways Regarding ESS

Addresses Aquifer Heterogeneity with Existing Data

- *Existing data contain important information and recognizable patterns*
- *Low cost, very high Return on Investment*





Questions & Answers

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