Focus on Geology to Define Subsurface Migration Pathways

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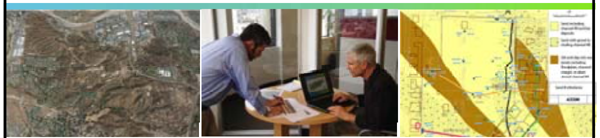

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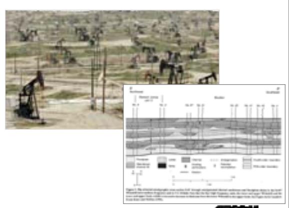
Outline

Technology Established in the Oil Industry

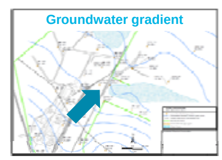
In the early days of exploration and production, once oil reservoir was discovered, production was limited by facilities capacity (engineering focus).

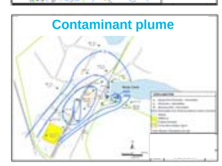
As technology improved and fields matured, the "easy stuff" had been recovered. Problems such as water production became critical. Understanding the geology and predicting reservoir architecture became increasingly critical for economical operations.



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"**

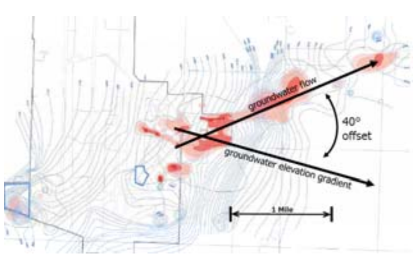




Subsurface Heterogeneity and Groundwater Remediation

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*



Why Geology Matters

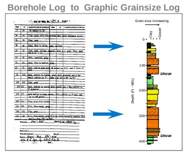
- At least 126,000 sites across the U.S. have contaminated groundwater that requires remediation
- Over **12,000** of these sites are considered "complex"
- "There is general agreement among practicing remediation professionals, however, that there is a substantial population of sites, where, due to **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

Environmental Sequence Stratigraphy (ESS) Process

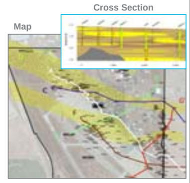
1

Determine depositional environment which is the foundation to the ESS evaluation



2

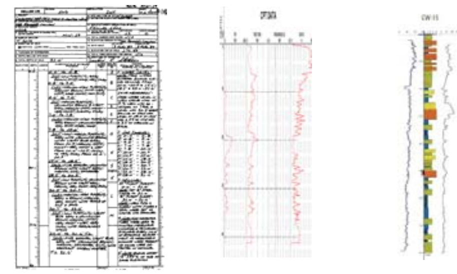
Leverage existing lithology data to identify vertical grain size trends and correlate between boreholes



3

Map the permeability architecture to predict contaminant migration

All sites currently have high resolution data…



…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.

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

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

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*

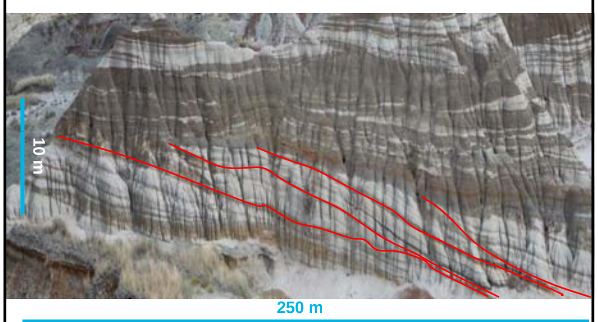
Depositional Environment and typical grain size profile	Major aquifer elements and their common dimensions	Major aquitard elements and their common dimensions	Impact on CSM	Required Data Resolution
Alluvial Fan	Proximal fan channels, mid-fan sheet sands, distal fringe sands X: 10^2 m – 10^4 m Y: 10^1 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: 10^1 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 – 10^3 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 (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

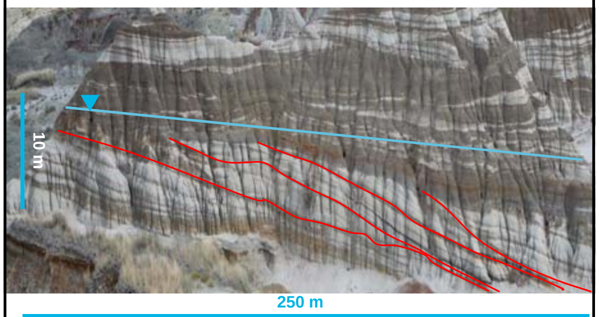
- Outcrop analog of meandering fluvial deposits
- At aquifer remediation site scale
- Ability to explicitly map sand body architecture in 3 dimensions
- Facies Models provide predictive tool for characterization based on depositional environments

The Problem of Aquifer Heterogeneity

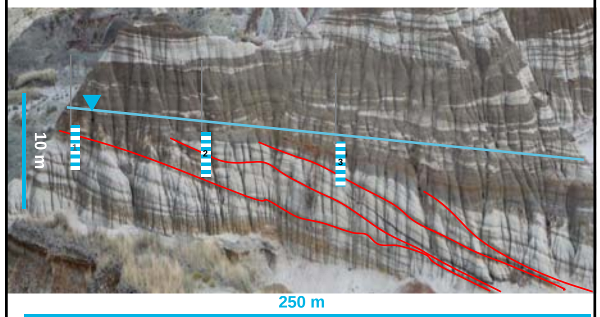
The Problem of Aquifer Heterogeneity



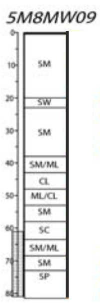
The Problem of Aquifer Heterogeneity



The Problem of Aquifer Heterogeneity



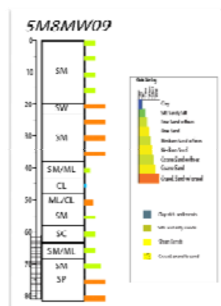
"Hidden" Stratigraphic Data



- "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…

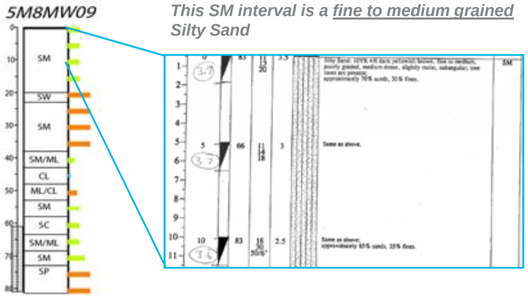
"Hidden" Stratigraphic Data

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



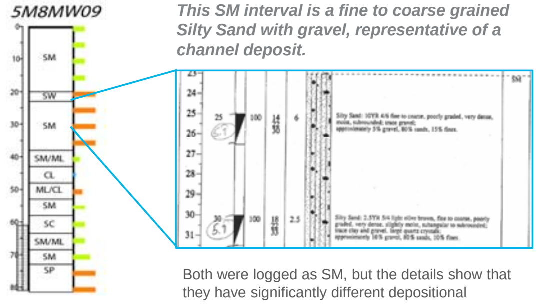
"Hidden" Stratigraphic Data

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



"Hidden" Stratigraphic Data

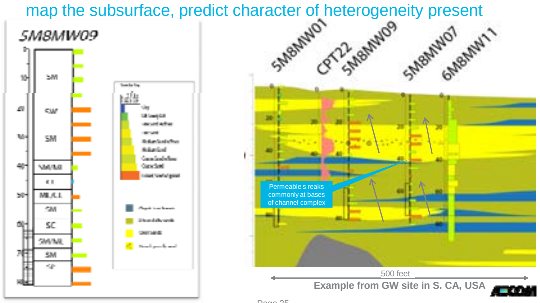
This SM interval is a fine to coarse grained Silty Sand with gravel, representative of a channel deposit.



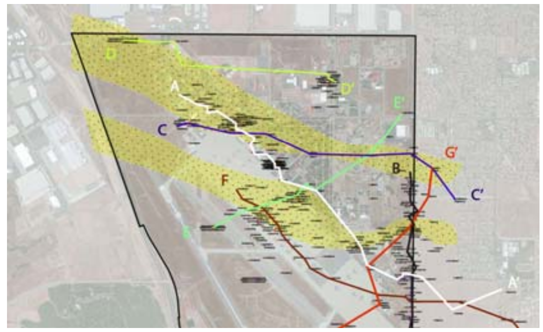
Both were logged as SM, but the details show that they have significantly different depositional characteristics.

The ESS Workflow in a Nutshell:

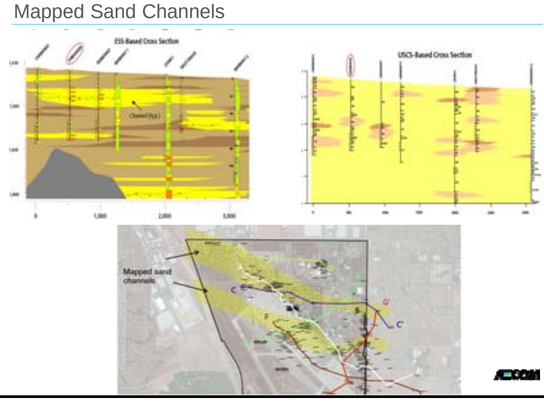
1. Reformatting existing data to identify sequences, and
2. Applying facies models, stratigraphic "rules of thumb" to correlate and map the subsurface, predict character of heterogeneity present



Mapped Sand Channels



Mapped Sand Channels



Case Study #1: *In situ* Bioremediation

Industrial Facility: Ethanol injection to reduce hexavalent chromium plume

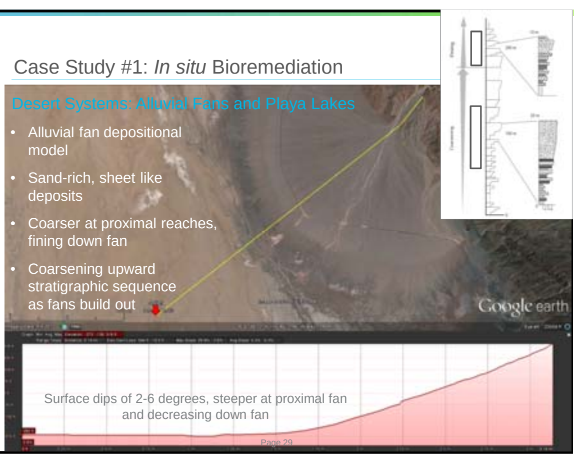
Scale: Hundred acres, ~60' depth of investigation

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

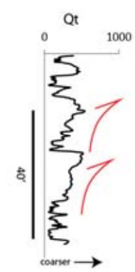


- Alluvial fan depositional model
- Sand-rich, sheet like deposits
- Coarser at proximal reaches, fining down fan
- Coarsening upward stratigraphic sequence as fans build out

Case Study #1: *In situ* Bioremediation

Grain Size Trends in CPT Data

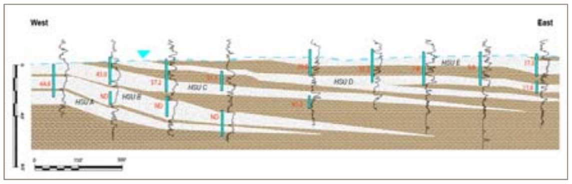
- Site CPT data
- Coarsening upward vertical grain-size pattern
- Stacked alluvial fan deposits bounded by clays



Focus on Geology to Define Subsurface Migration Pathways

Case Study #1: *In situ* Bioremediation

Cross Section of Hydrostratigraphic Units (HSUs)



Case Study #1: *In situ* Bioremediation

Kriging of CPT Data to Correlate Lithology

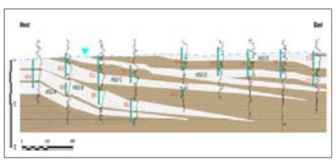
(Same cross section) Miscorrelates thin clay beds giving appearance of randomness in stratigraphic architecture

Brown = silt/clay
White = sand/gravel

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



Case Study #2: Plume Containment Strategy

Munitions Manufacturing Site: Perchlorate plume impacting municipal wells

Scale: Thousand acres, ~700' depth of investigation

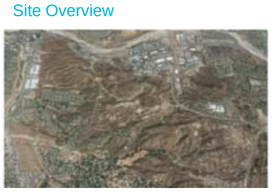
Lithology Data: Geophysical logs, borehole logs

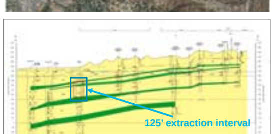
Approach: Apply ESS on existing data to improve CSM and Design Plume Management Program

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

Case Study #2: Plume Containment Strategy

Site Overview





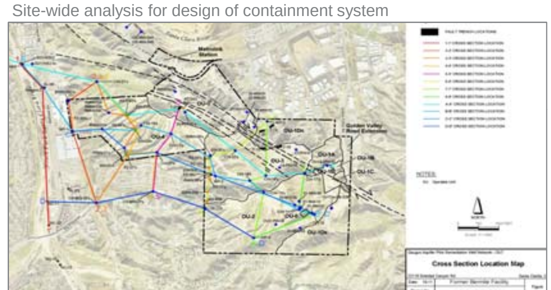
Pre-Existing 3-Layer CSM

- 996-acre (403-hectare) site Santa Clarita, CA
- Complex geology, over 600' of stratigraphy, dipping beds
- Impacted mainly with perchlorate (ClO_4^-), 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

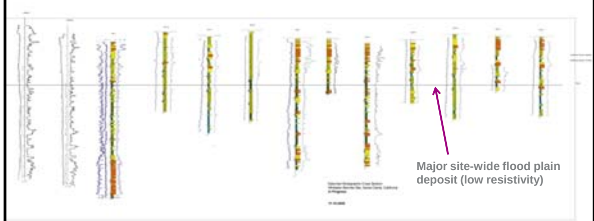
3-D ESS Cross Section Network

Site-wide analysis for design of containment system



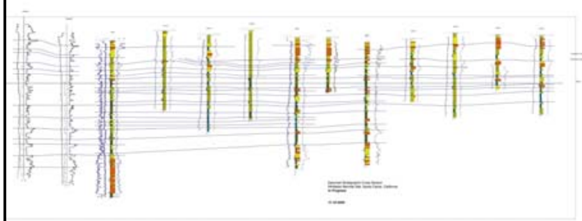
Case Study #2: Plume Containment Strategy

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



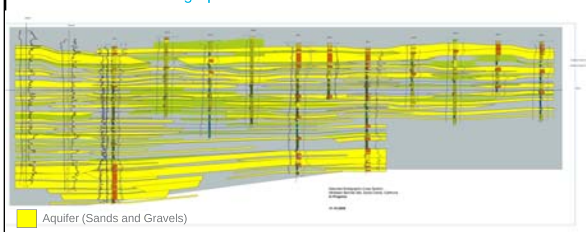
Case Study #2: Plume Containment Strategy

ESS Process: Correlate Floodplain Surfaces



Case Study #2: Plume Containment Strategy

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



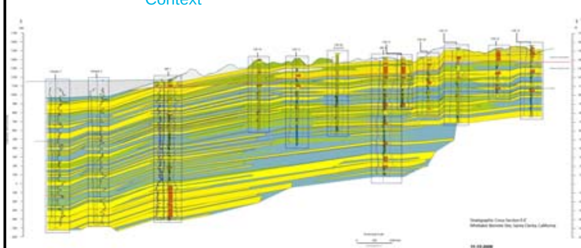
Aquifer (Sands and Gravels)

Aquitard (Clays and Silts)

Transitional (Silty Sands, Sandy Silts)

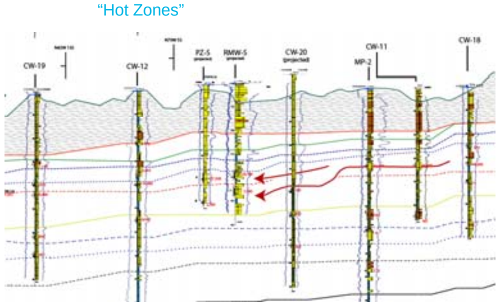
Case Study #2: Plume Containment Strategy

ESS Process: Aquifer Architecture in Structural and Groundwater Flow Context



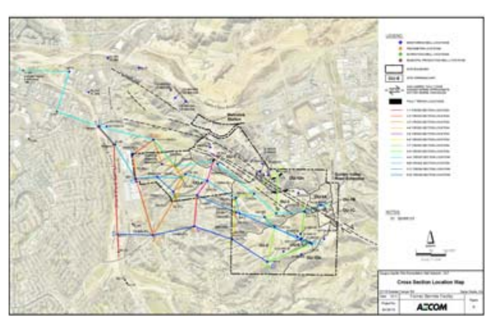
Case Study #2: Plume Containment Strategy

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



Case Study #2: Plume Containment Strategy

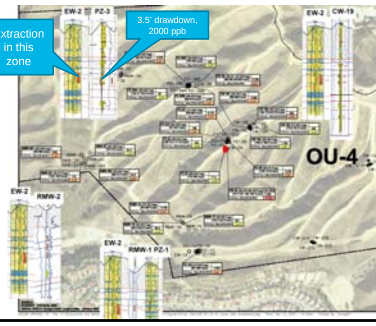
ESS Process: Create 3-D ESS Stratigraphic Framework



Case Study #2: Plume Containment Strategy

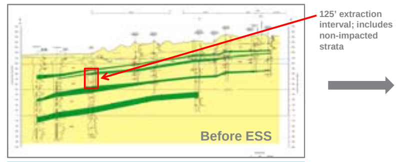
ESS Process: Testing and Validating the CSM – Pathways and Communication

- 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

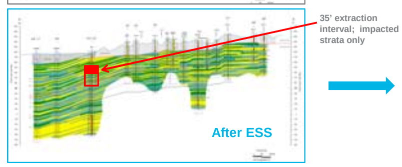
ESS Outcome: Overhauled CSM, verified CSM, gained regulatory and stakeholder approval for wholesale modification of containment system design = $55MM savings



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



Remediation System Cost (After ESS)

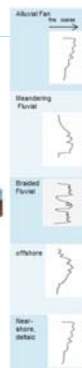
- 13 extraction wells
- 46 gpm per well
- 314 million gal per year

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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