2017 Battelle Panel Discussion: Using Geology to Follow the Groundwater, Follow the Flow to Successful Remediation

- **Moderators:** John Wilson (Scissortail Environmental) and Rick Cramer (Burns & McDonnell)
- **Panelists**: Herb Levine (USEPA), Adria Bodour (AFCEC), Tamzen MacBeth (CDM Smith)

Introduction:

- Problem statement…why is geology important to remediation? (John)
- Cannot oversimply subsurface heterogeneity by assuming homogeneous conditions. There is a process to define the heterogeneity. (Rick)
- As a resource manager, why Air Force (and the industry) needs to do business differently. (Adria)

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2017 Battelle Panel Discussion: Using Geology to Follow the Groundwater, Follow the Flow to Successful Remediation

Panelists providing examples

- **Herb Levine (regulatory):** Defining buried sand channels example of Geologic Best Practice, introduce EPA technical issue paper **= 20 min**
- **Adria Bodour (DOD):** Perspective from large portfolio of Air Force facilities, Kirkland success story tied to the geology **= 20 min**
- **Tamzen MacBeth (remediation engineer):** How to address complex/heterogeneous geology with flexible/proactive remediation strategy based on knowledge of the geology…carrying the geology through the remediation process **= 20 min**

Open Discussion = 25 min

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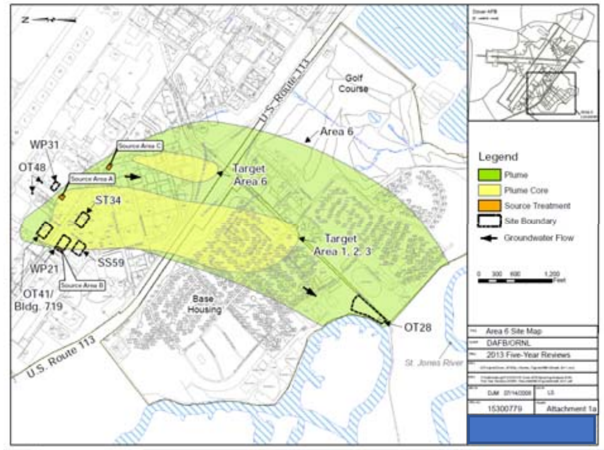
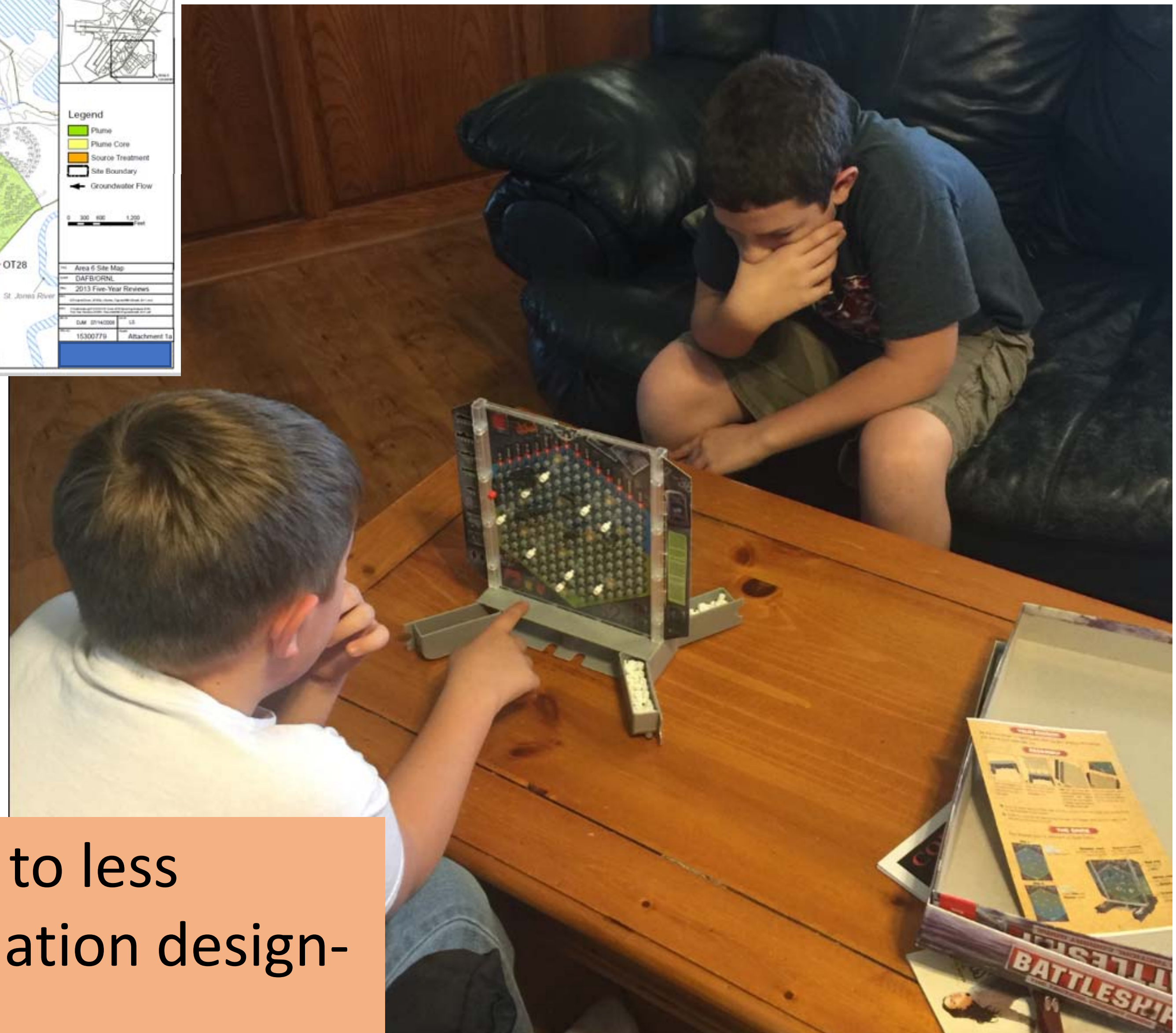




Habits that lead to less effective remediation design-

Thinking in two dimensions

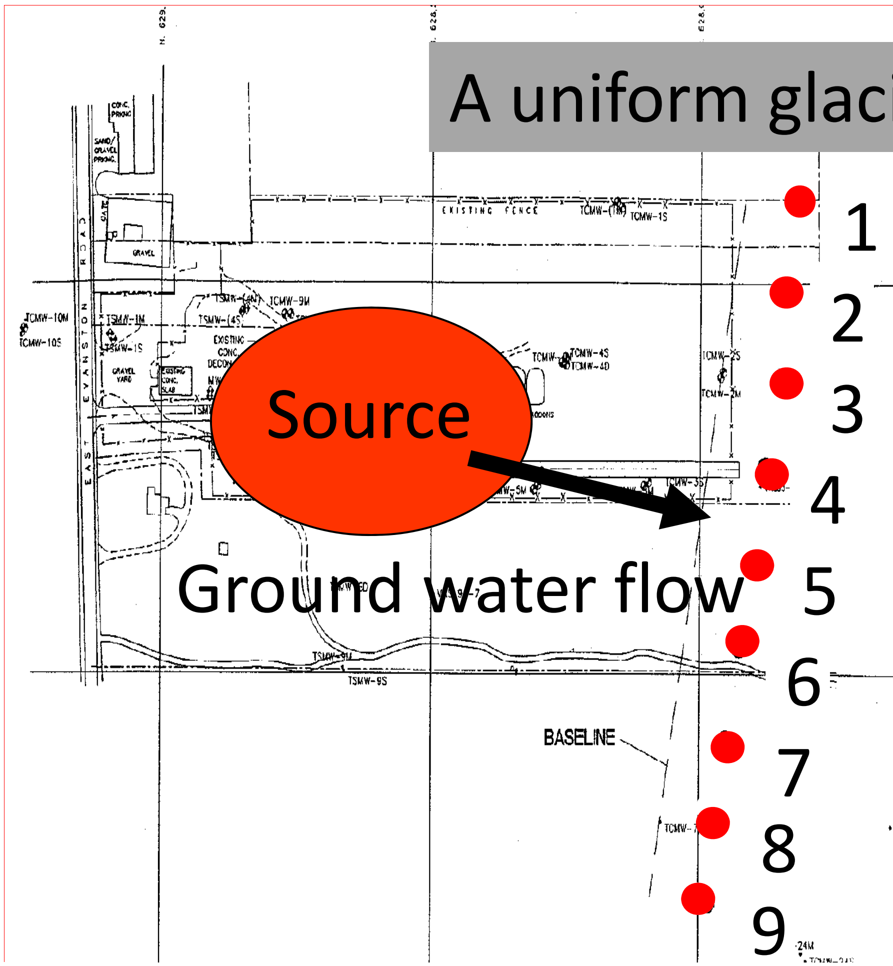
Habits that lead to less effective remediation design-

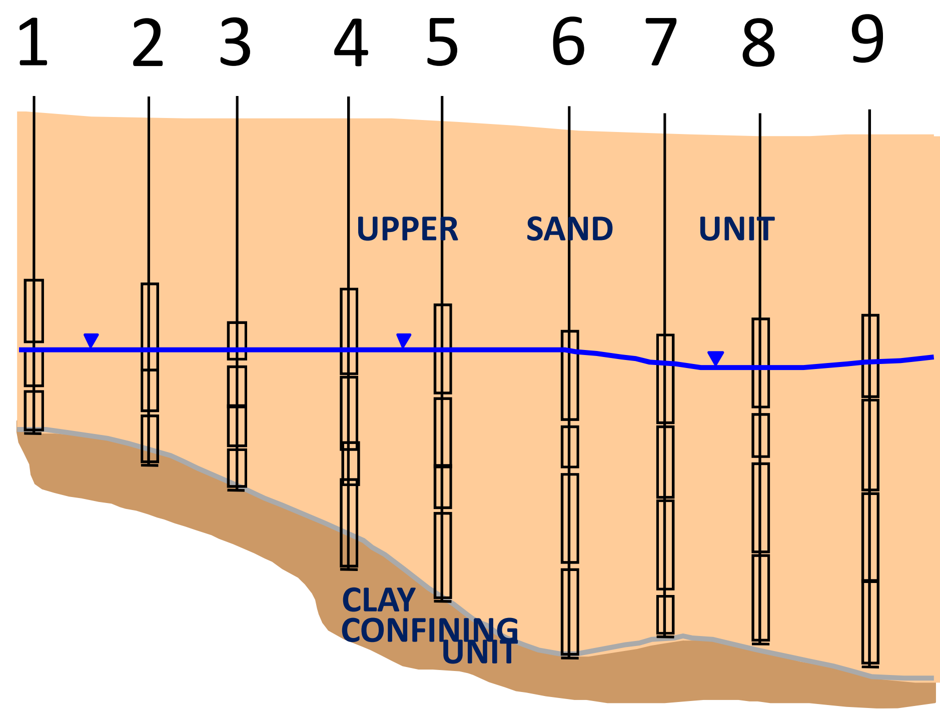
Imagining large continuous layers in plan two dimensions that distribute water.

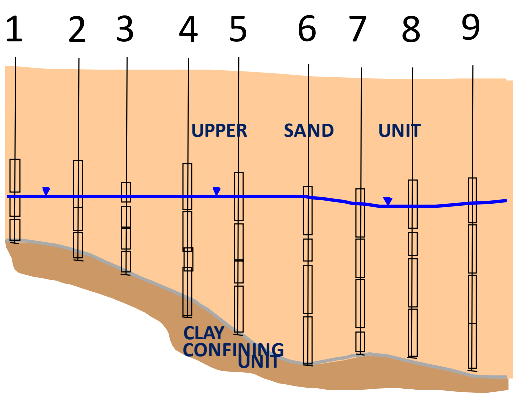
Habits that lead to less effective remediation design-

Imagining large continuous layers in plan two dimensions that distribute water.

A uniform glacial outwash sand.






1
2
3
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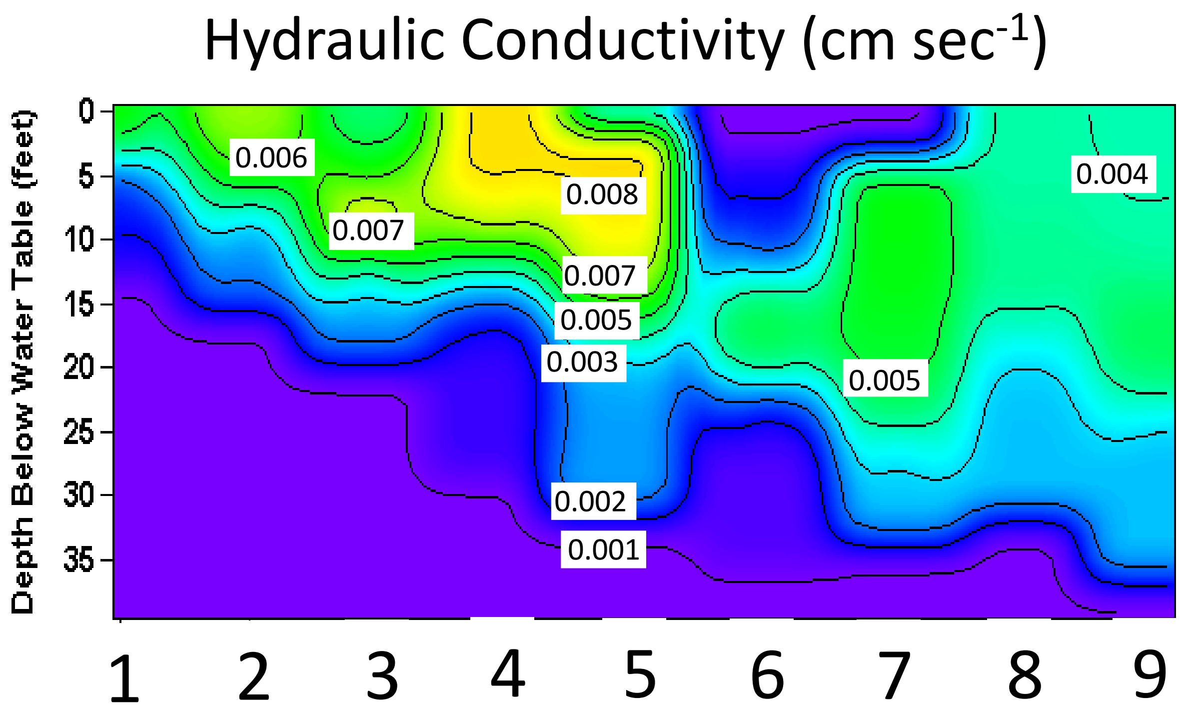
5
6
7
8
9
UPPER
SAND
UNIT
CLAY
CONFINING
UNIT


Hydraulic Conductivity (cm sec-1)
Depth Below Water Table (feet)
0
5
10
15
20
25
30
35
0.006
0.007
0.008
0.007
0.005
0.003
0.002
0.001
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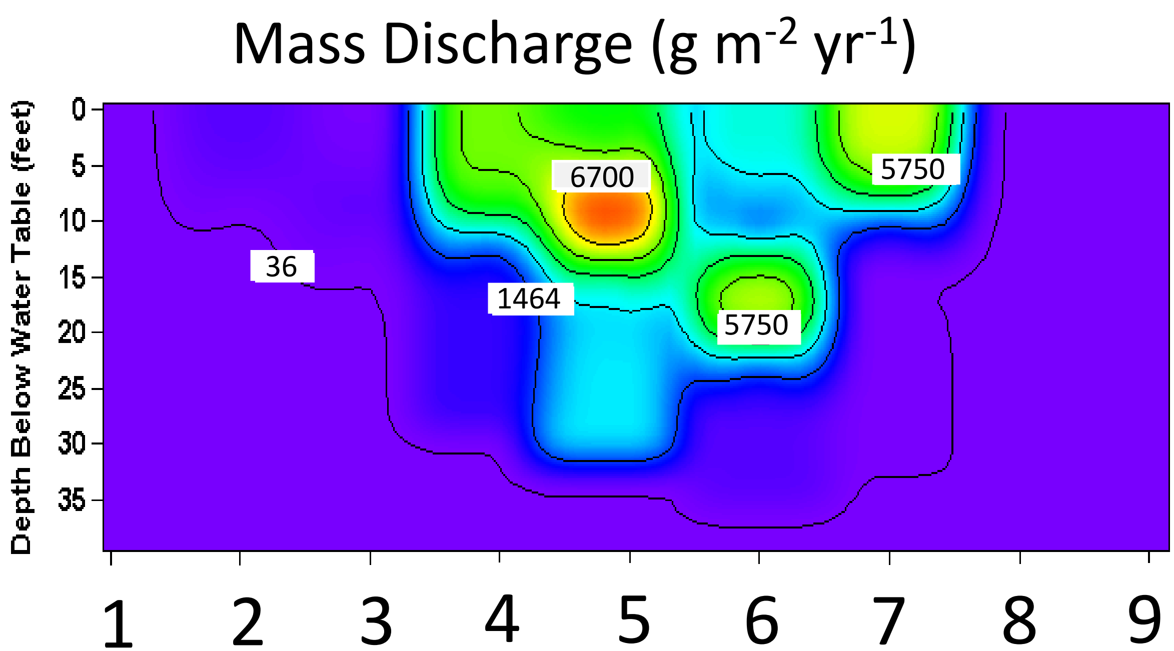
Mass Discharge (g m-2 yr-1)
Depth Below Water Table (feet)
0
5
10
15
20
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6700
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5750
1
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3
4
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6
7
8
9

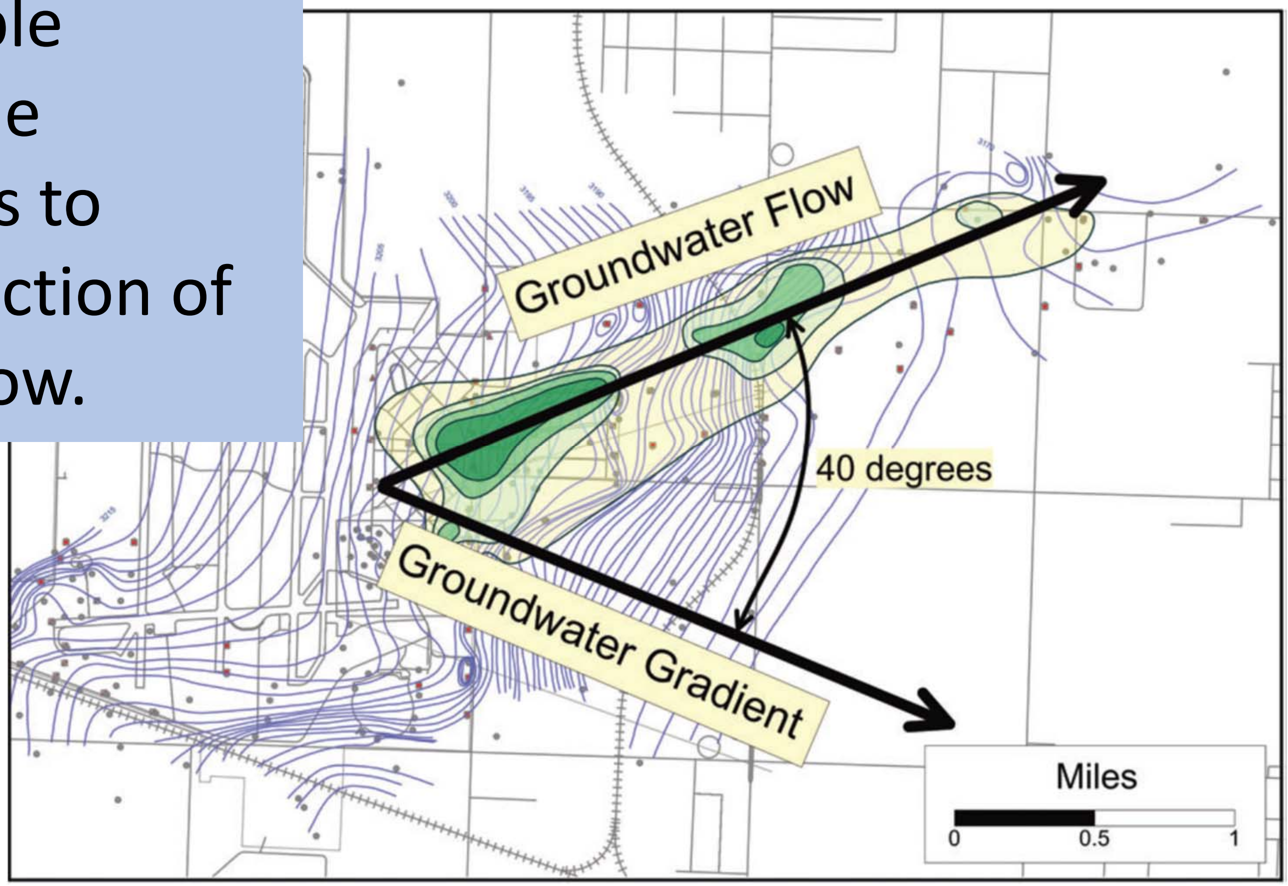
Habits that lead to less effective remediation design-

Using water table elevations as the exclusive means to predict the direction of groundwater flow.

Habits that lead to less effective remediation design-

Using water table elevations as the exclusive means to predict the direction of groundwater flow.

Suthersan et al. 2016. *Groundwater Monitoring & Remediation* 35(4):27-35



Goal: Communicate with Non-Geologists

Problem Statement

- Is groundwater flow, and the contaminant migration, **controlled by geologic features** (e.g., buried sand channels)?
- Does the CSM **adequately define** the geologic features?
- What **tools are available** to define the geologic features?
- How do buried channels and other geologic features **affect source identification**?
- How do they **affect remedial design**?

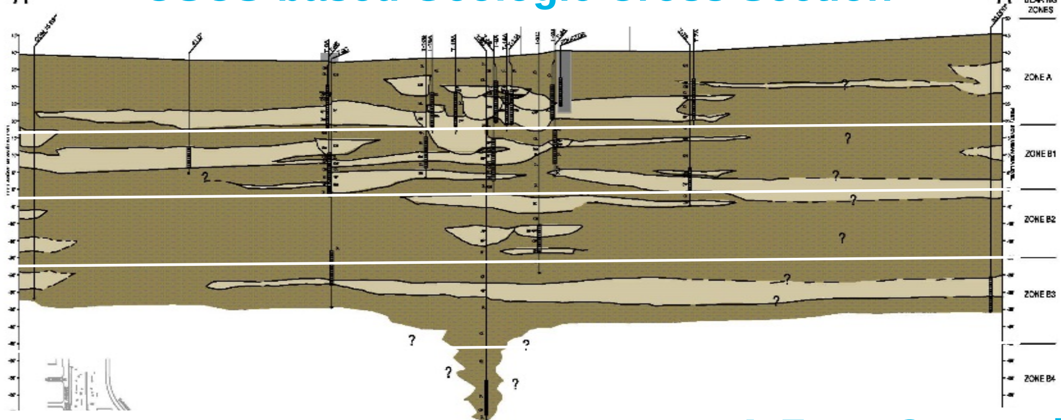
Geology Matters

- 126,000 sites across the U.S. require remediation
- 12,000 considered "complex"
- "…due to **inherent geologic complexities**, restoration within the next 50-100 years is likely not achievable."

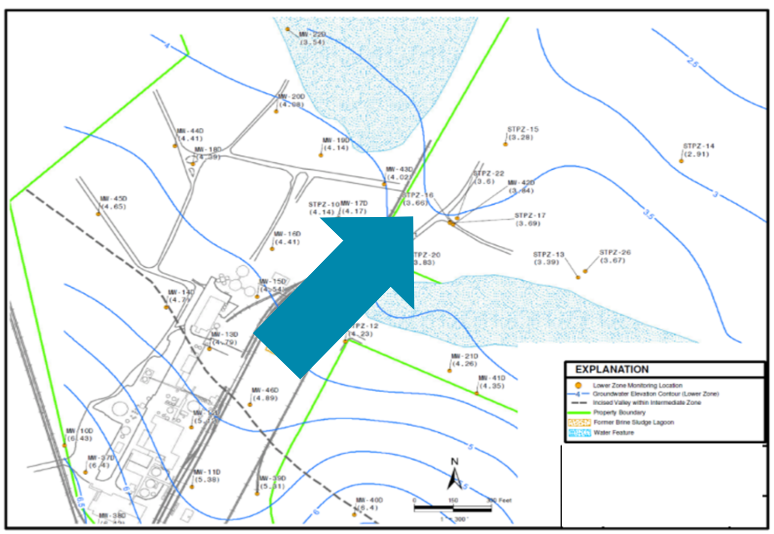
Traditional Approach to the Subsurface

This is what we are doing **now**…state of the practice.
Assumes **homogeneous** isotropic conditions.

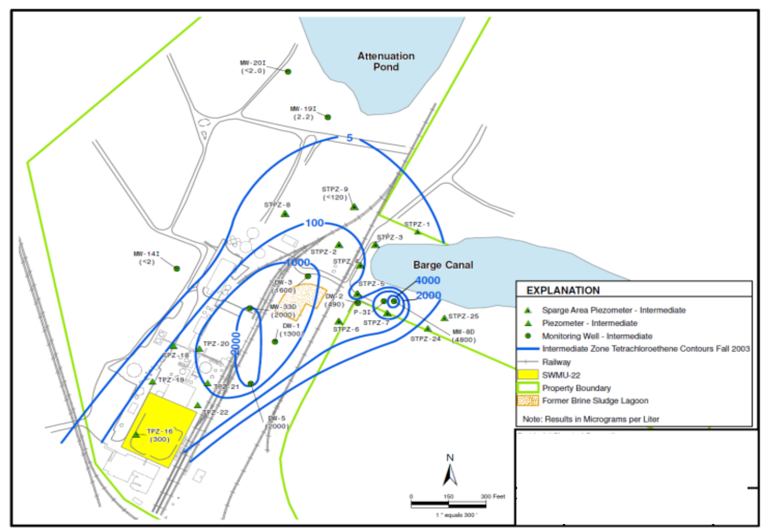
USCS-based Geologic Cross Section



A-Zone Groundwater Gradient

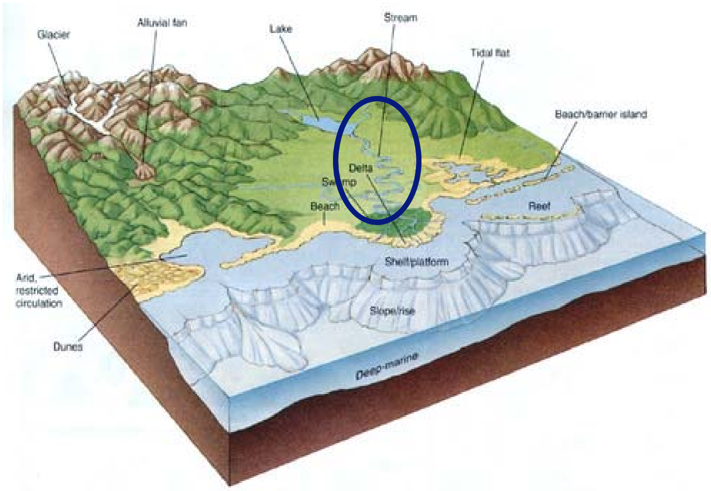


A-Zone Contaminant Plume



The Problem of Aquifer Heterogeneity

- Outcrop analog of buried river channel deposits
- At aquifer remediation site scale
- Ability to map sand channels in 3 dimensions
- Facies Models provide predictive tool for characterization based on depositional environments



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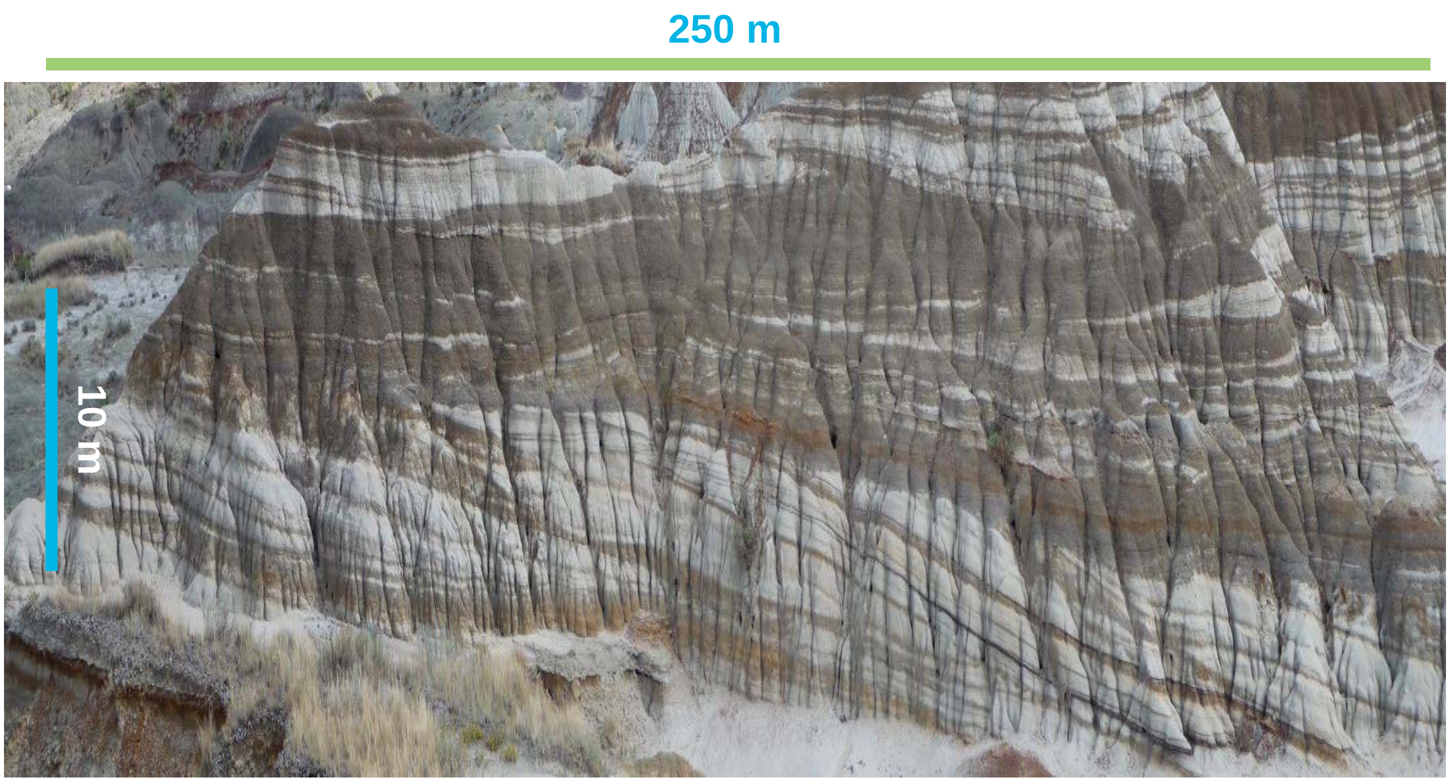

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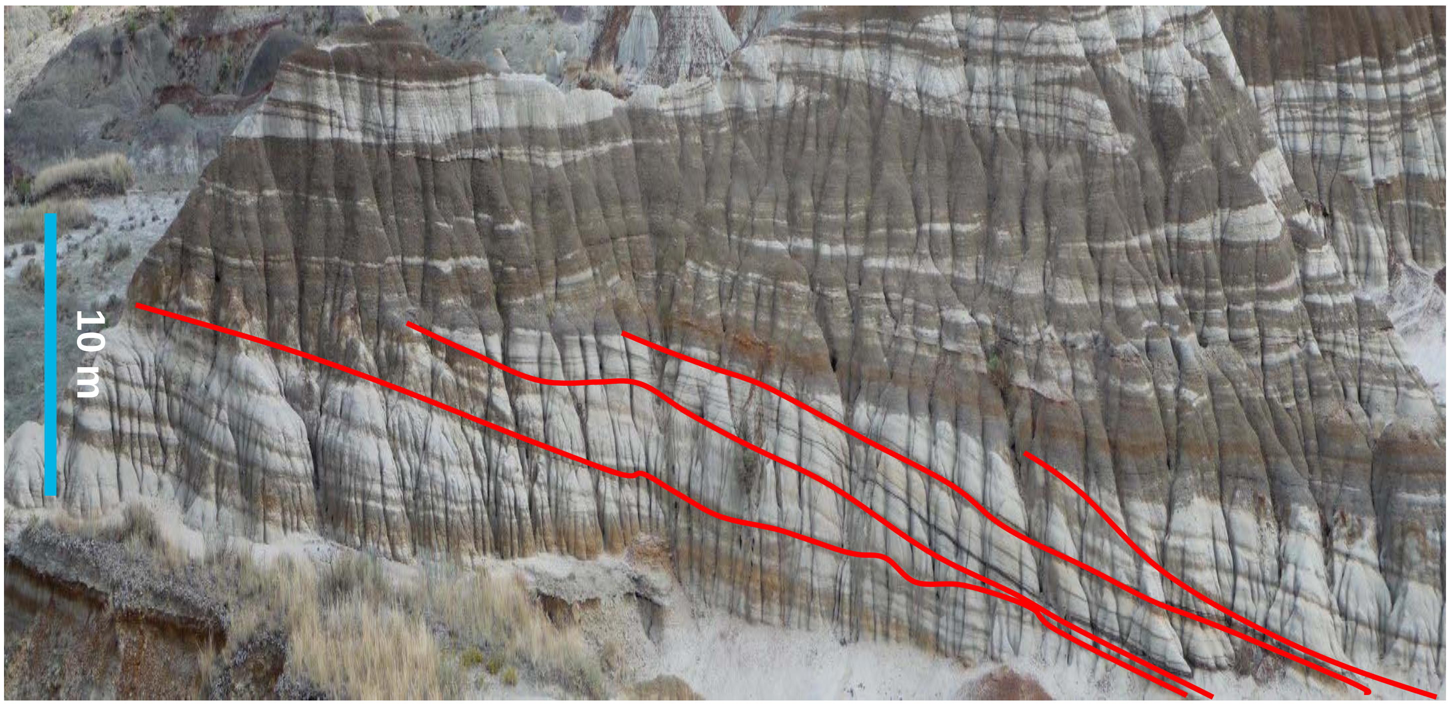

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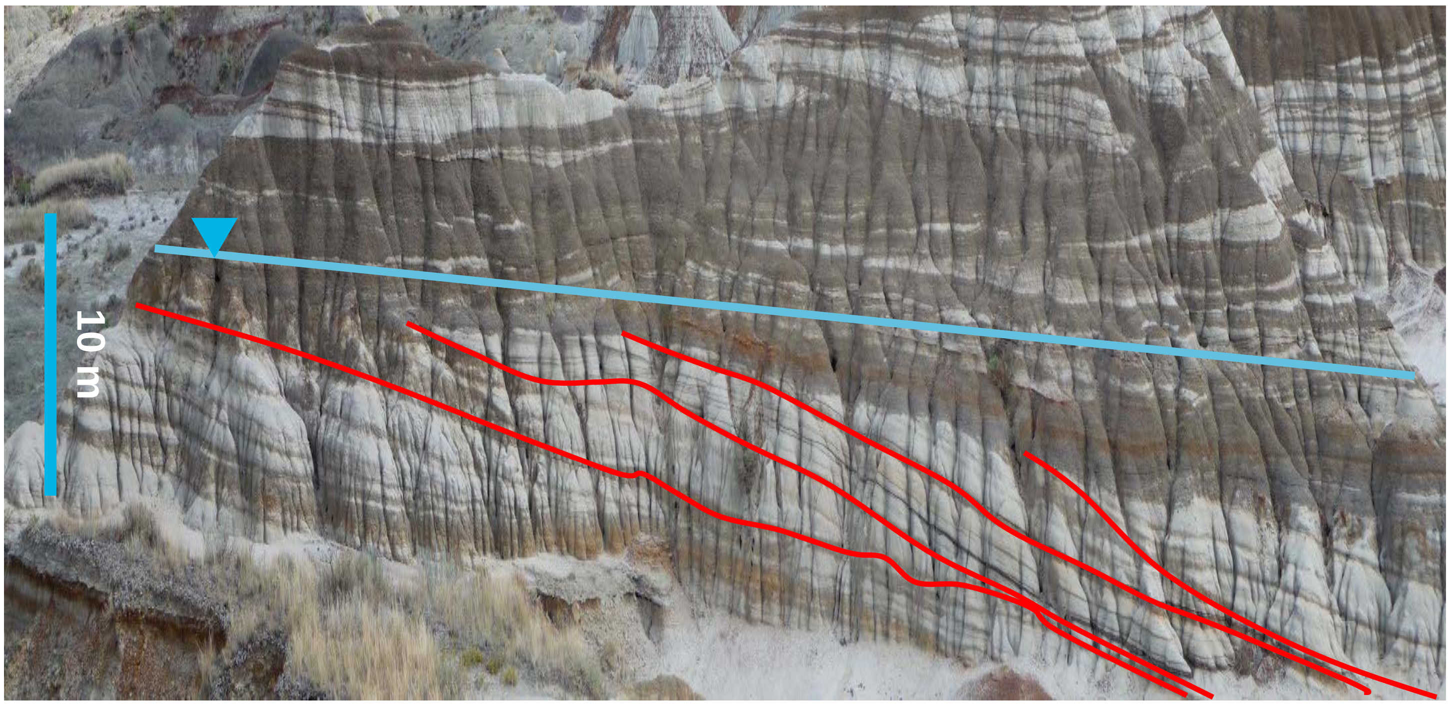

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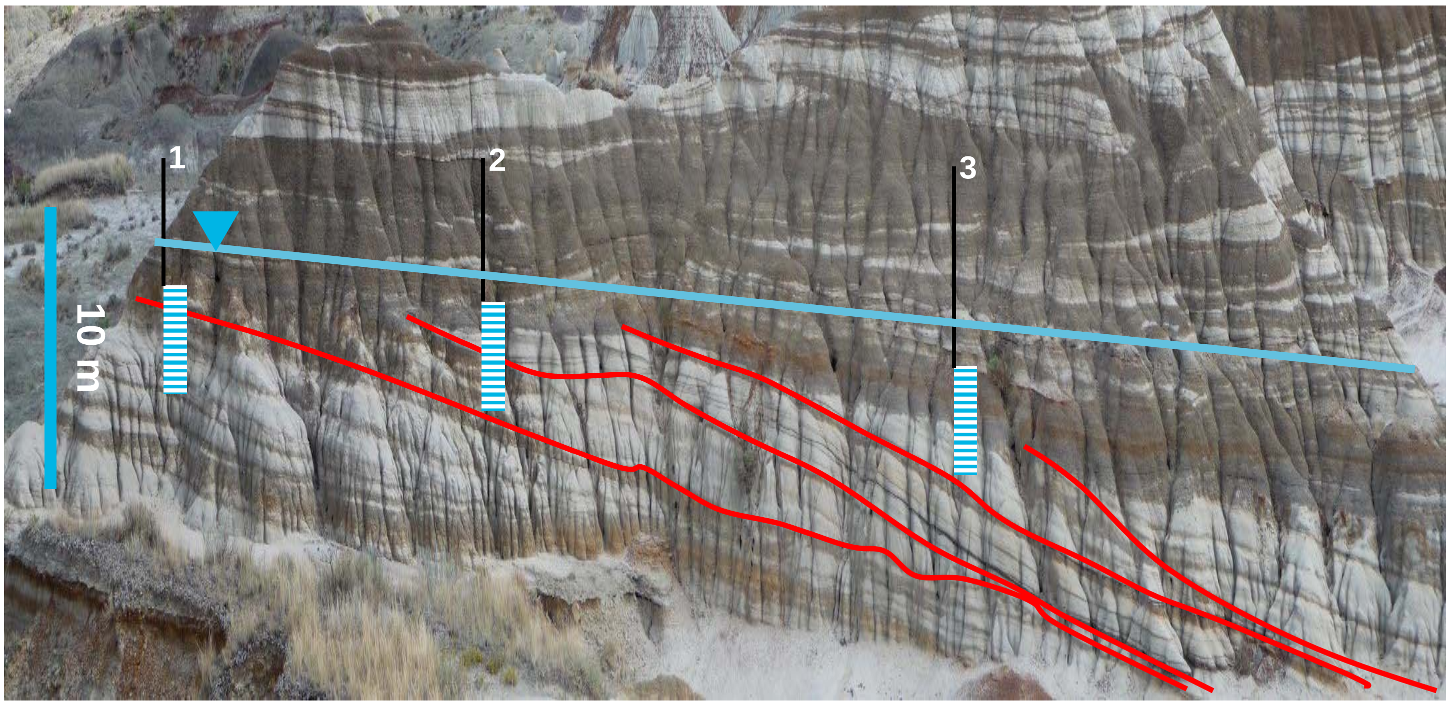
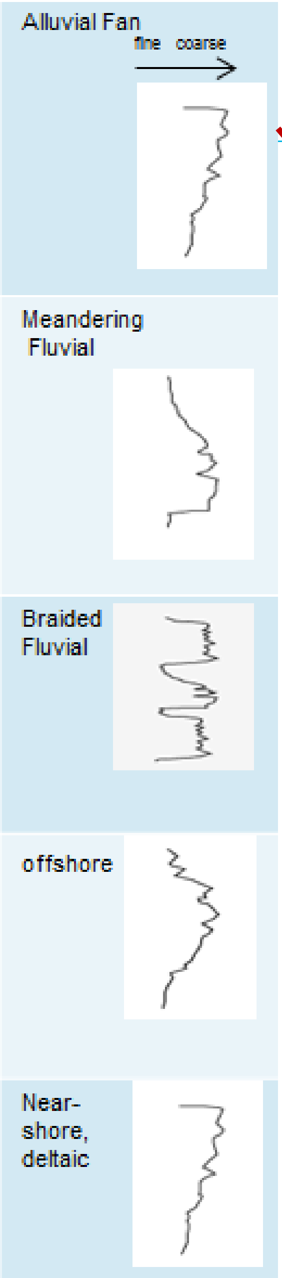
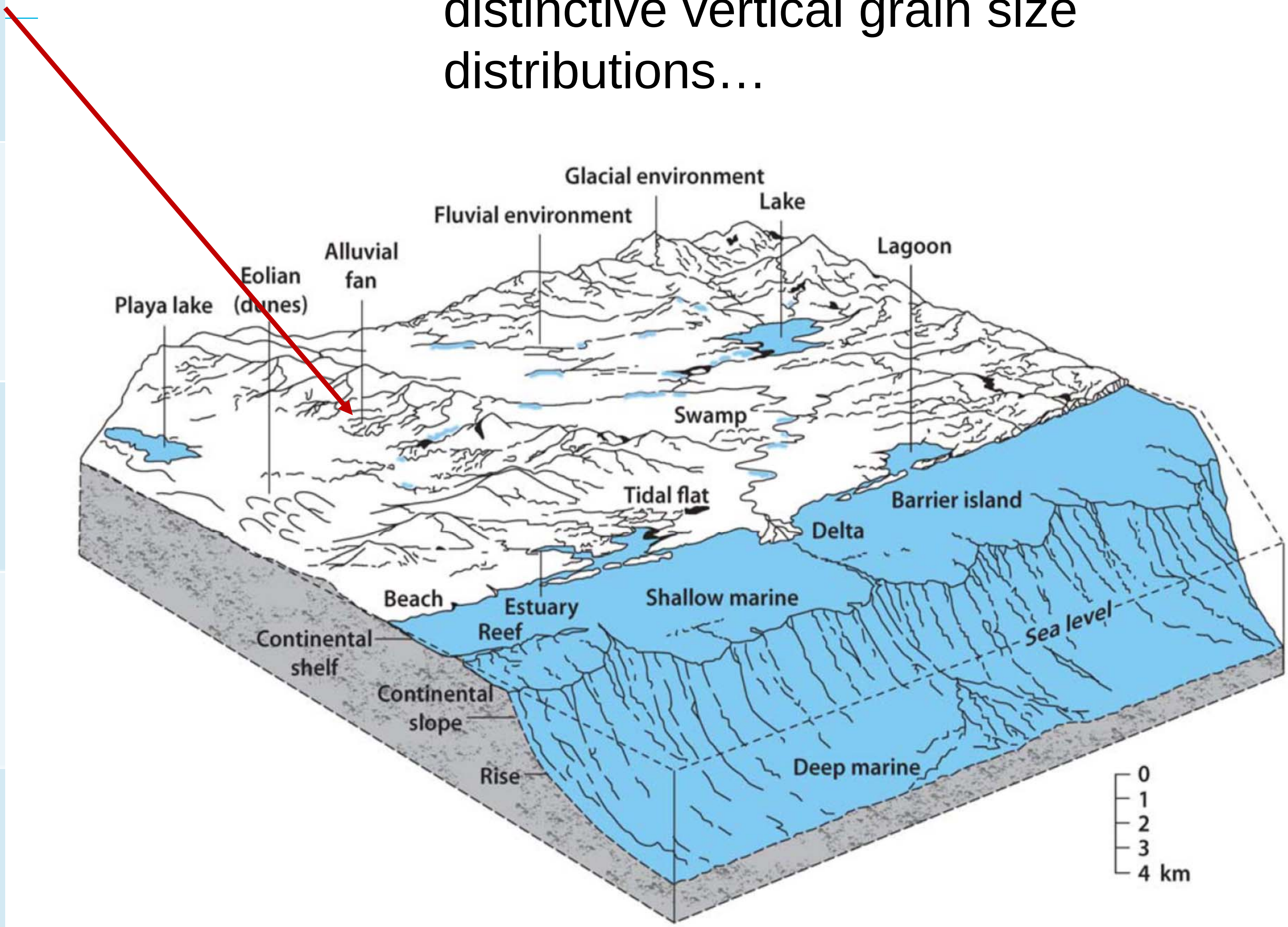


ESS Is Pattern Recognition



Depositional environments have distinctive vertical grain size distributions…



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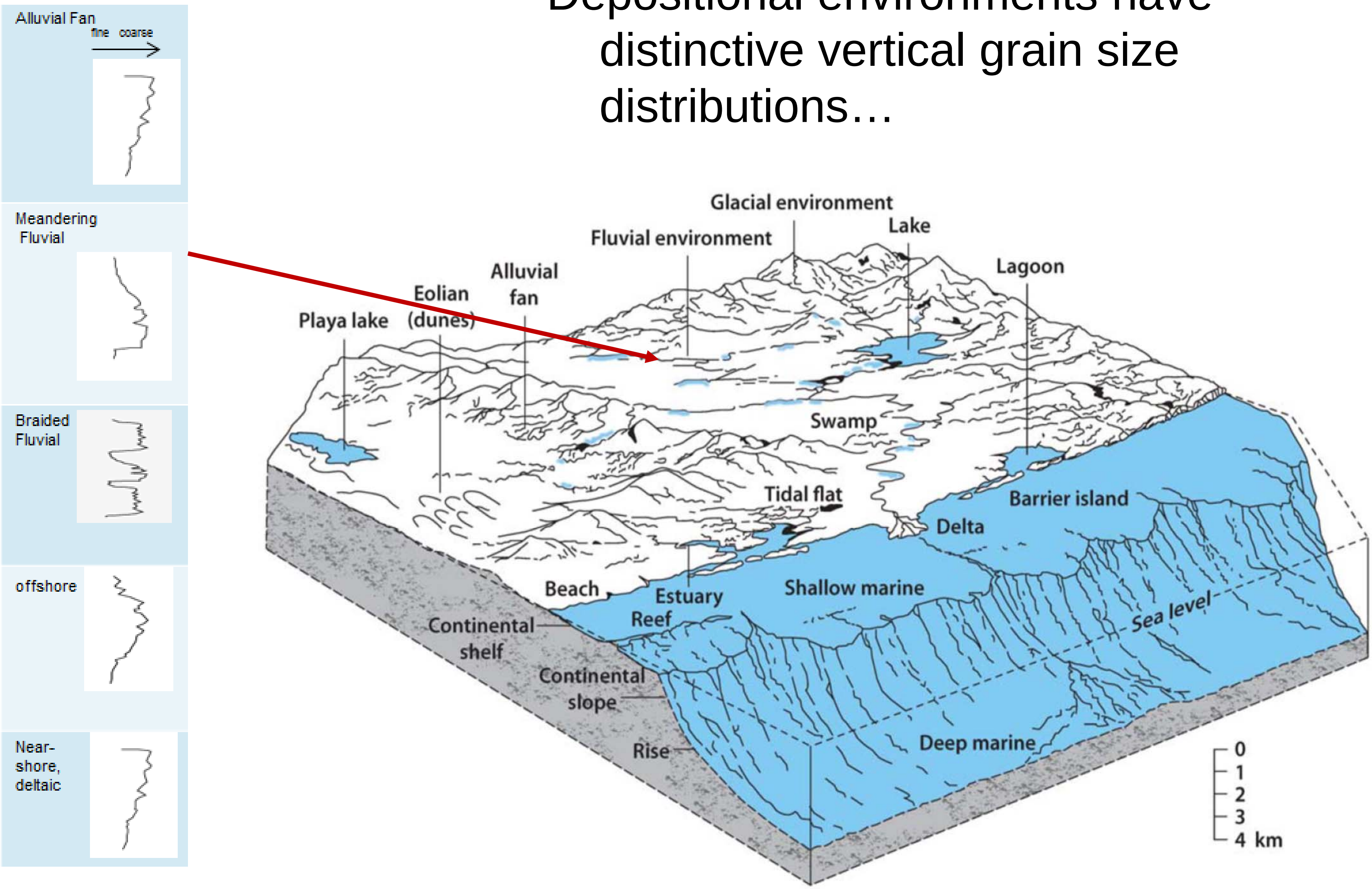

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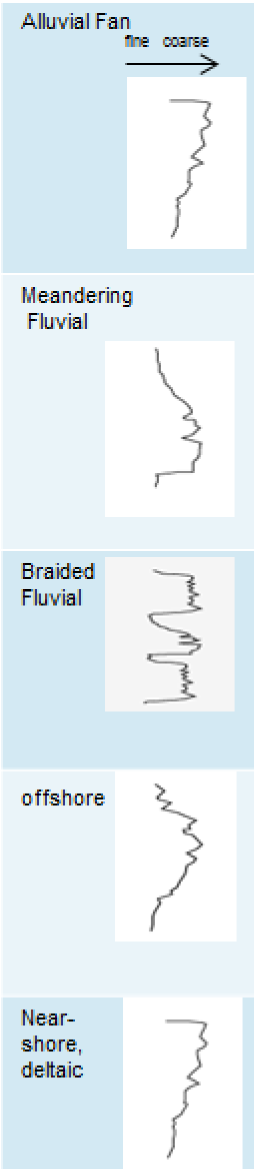

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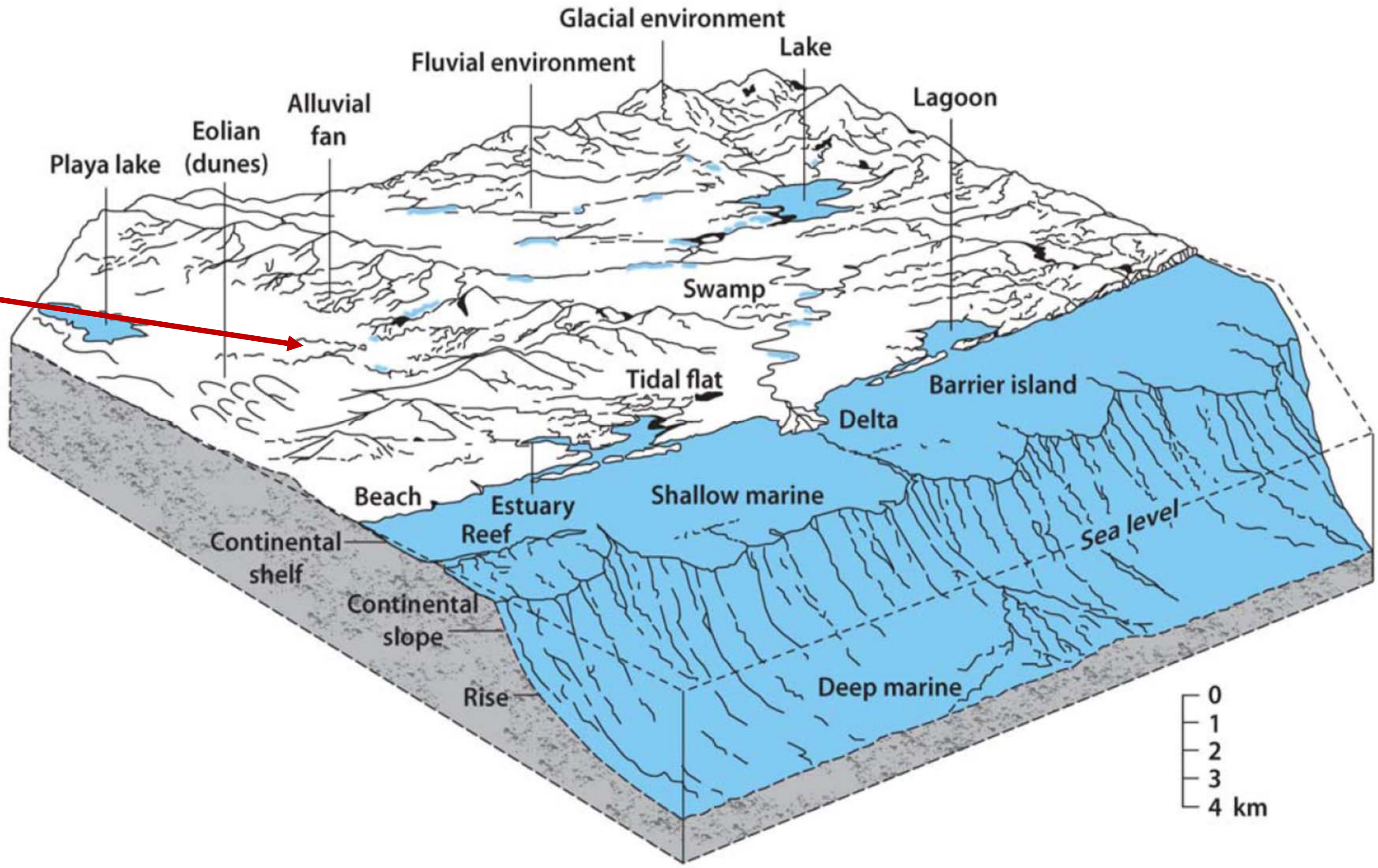

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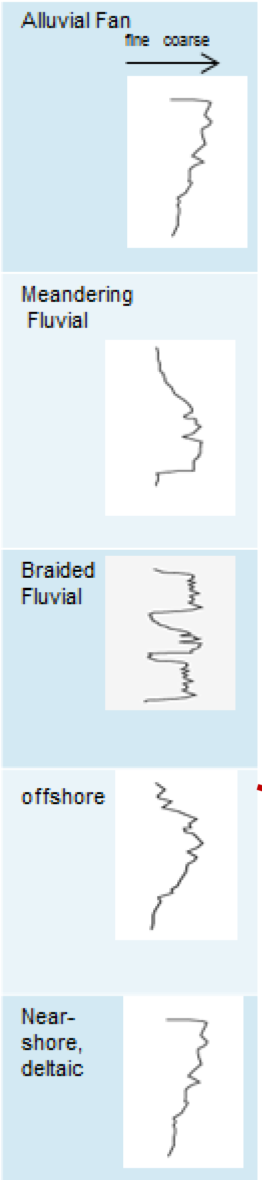

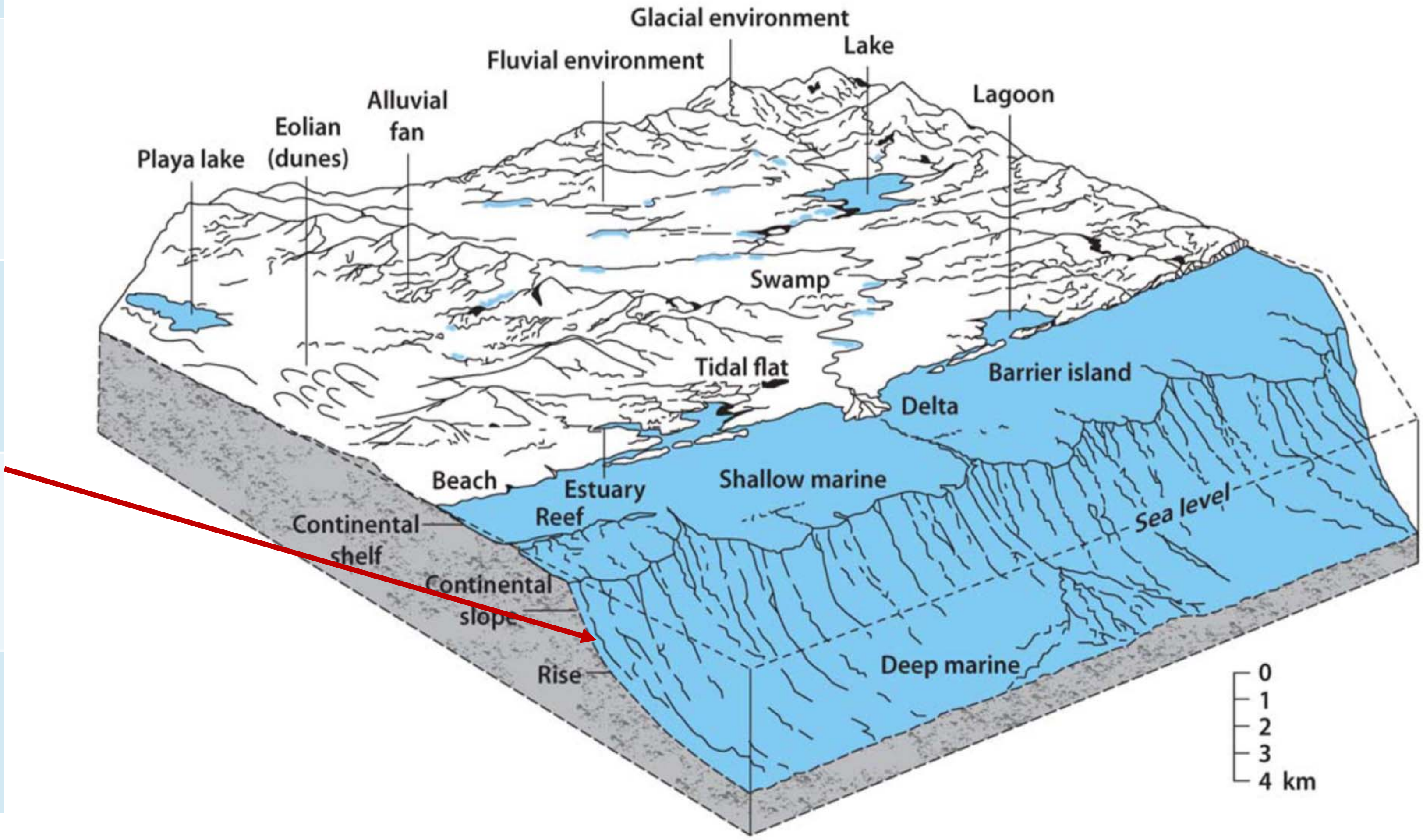

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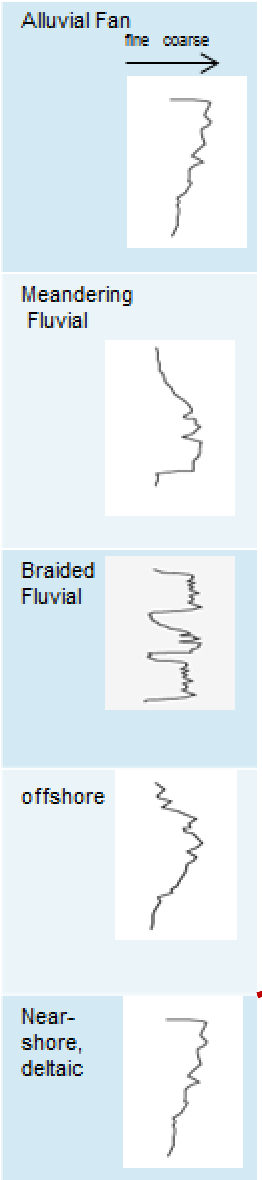
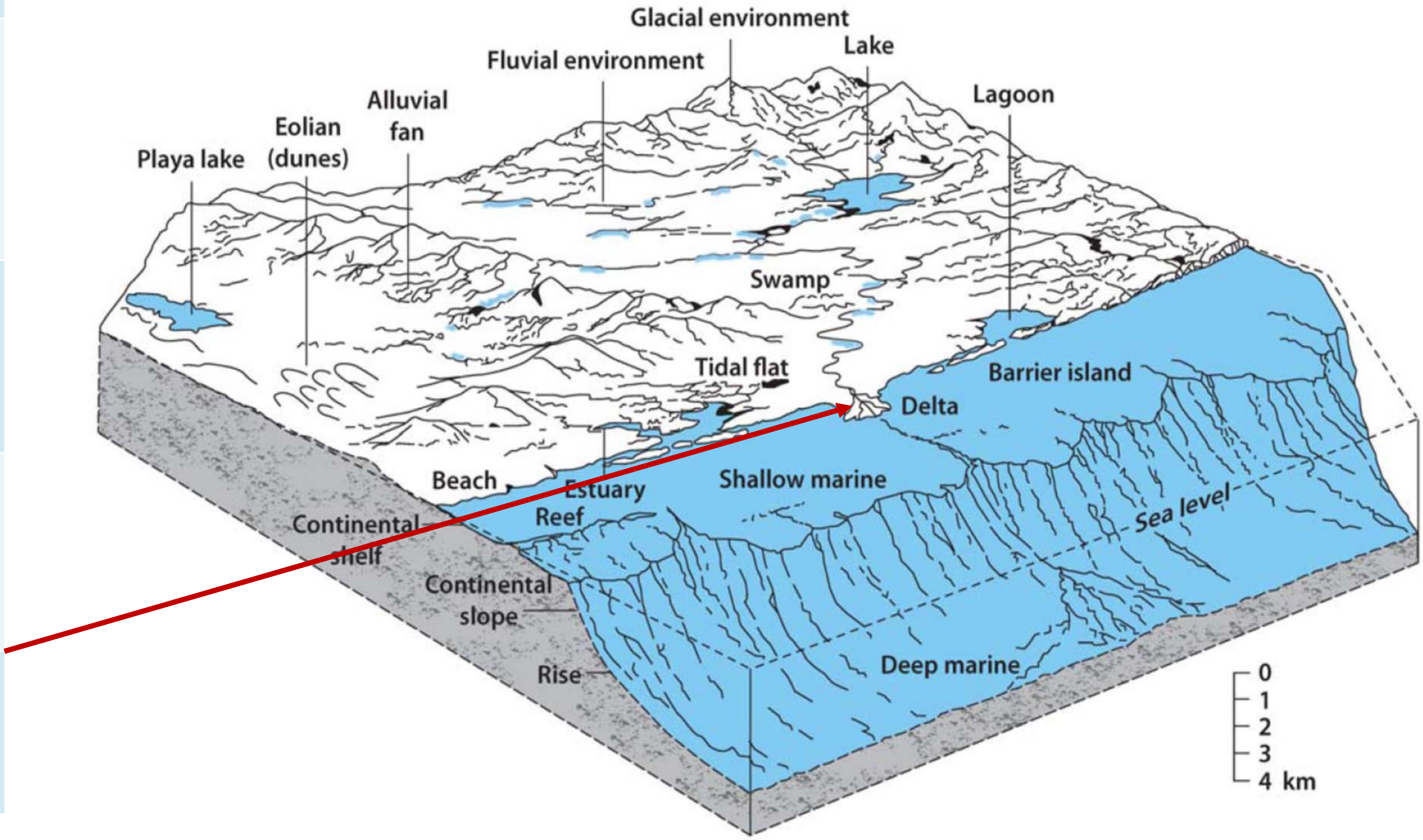
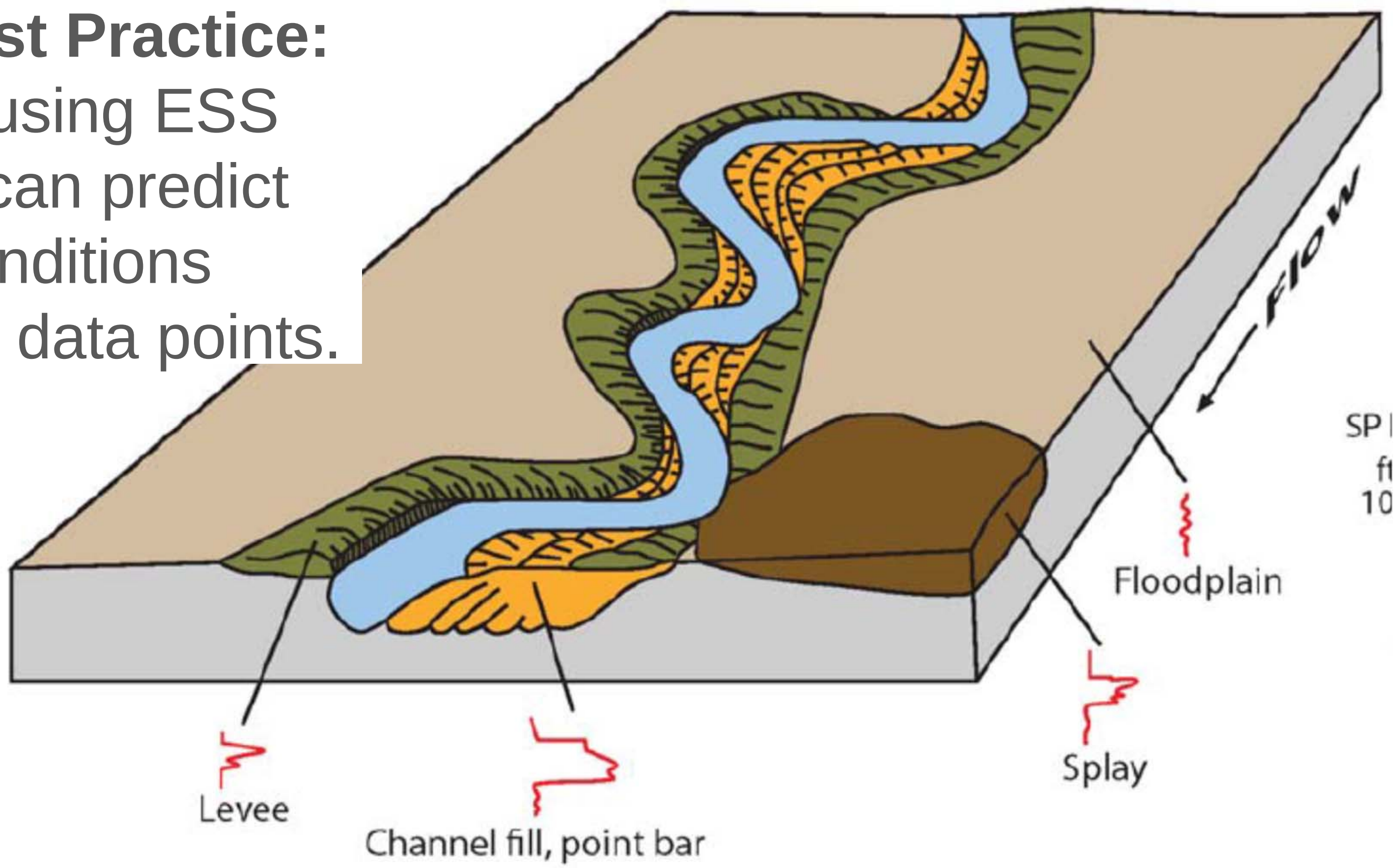




…and the associated sand bodies have characteristic/predictable dimensions and continuity.

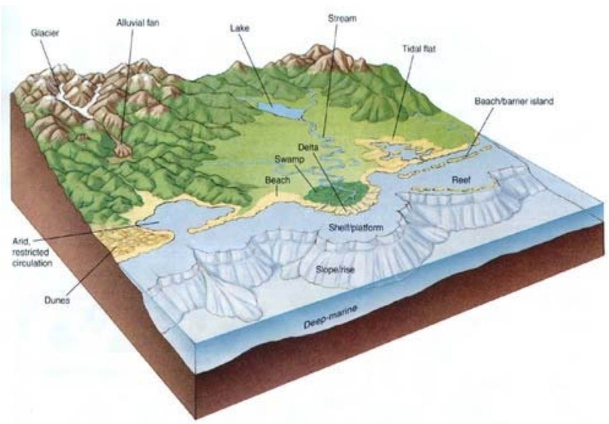
Emerging Best Practice: Stratigrapher using ESS methodology can predict subsurface conditions away from the data points.

Meandering river



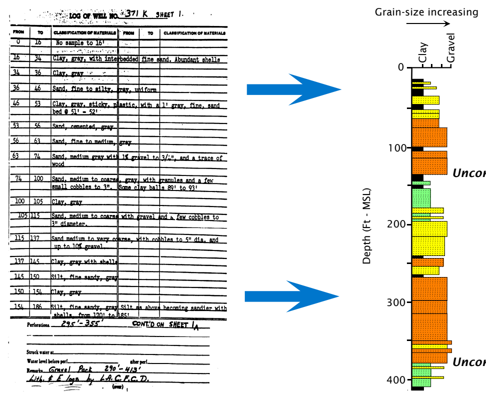
Geology-Based CSM

1



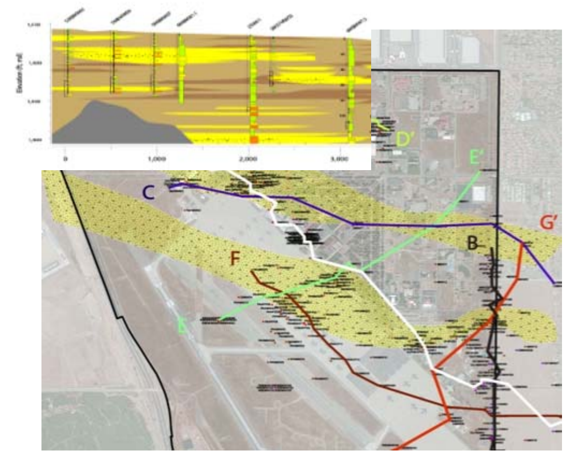
Determine depositional environment which is the foundation to the ESS evaluation

2



Leverage existing lithology data format to emphasize vertical grainsize distribution

3

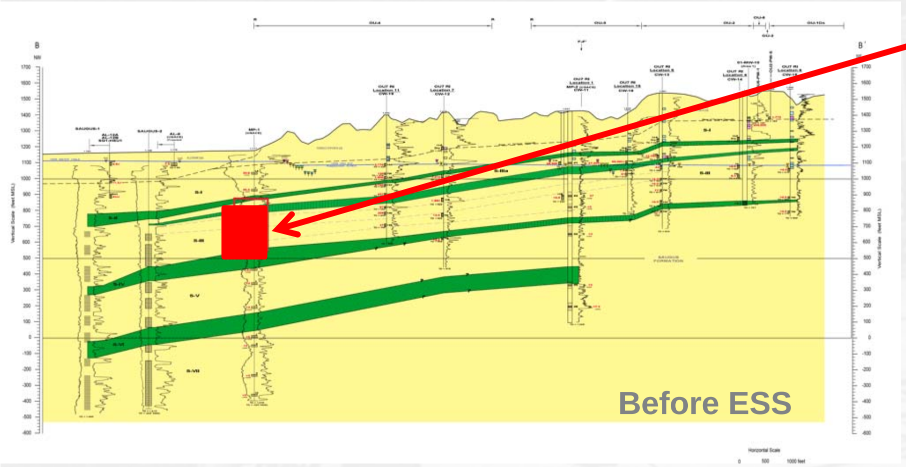


Predict and map in 3D the subsurface conditions away from the data points

Complex Site Remediation Optimization

Critical to Remedy Design

ESS Outcome: Gained regulatory and stakeholder approval for wholesale modification of containment system design = $55MM cost savings

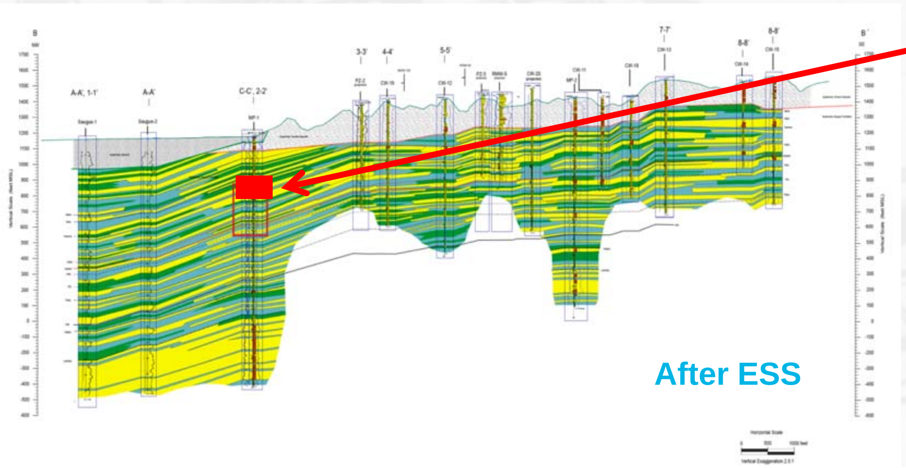


125’ extraction interval; includes non-impacted strata

Estimated 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/year
30 yr = $75 MM
Total cost = $82 MM



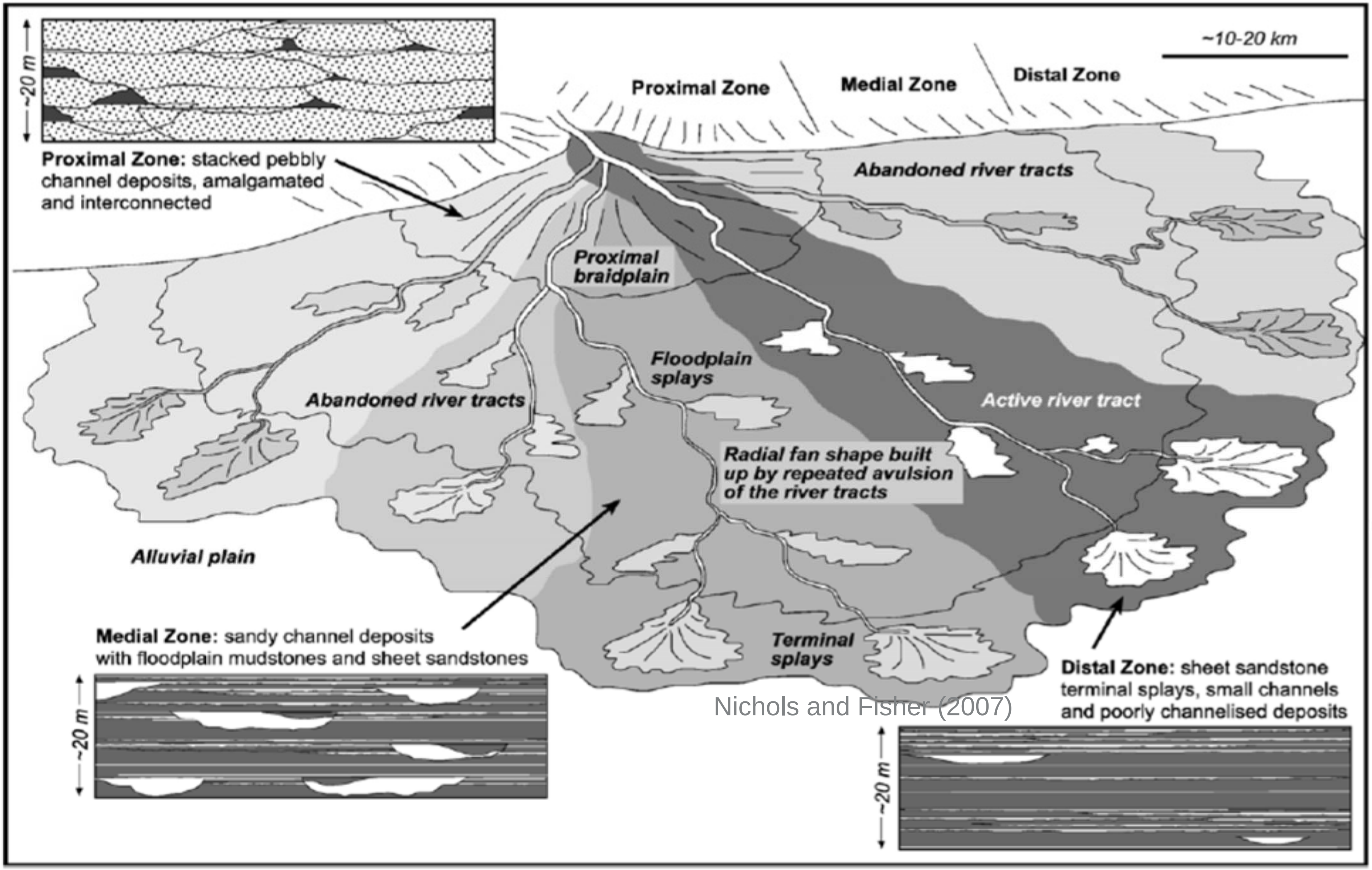
35’ extraction interval; impacted strata only

Estimated Remediation System Cost (After ESS)

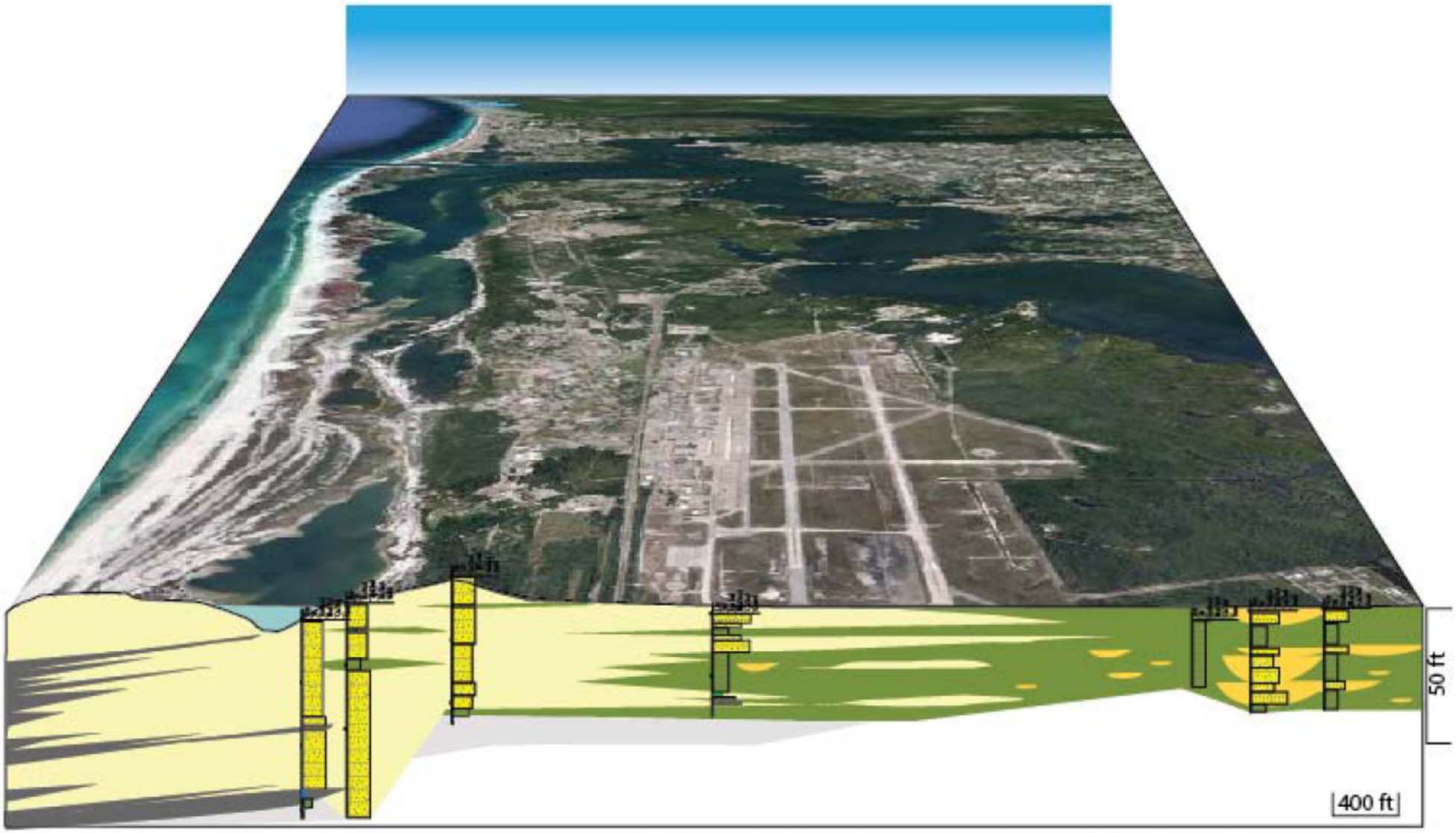
- 13 extraction wells
- 46 gpm per well
- 314 million gal per year

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

Alluvial Fan Facies Model



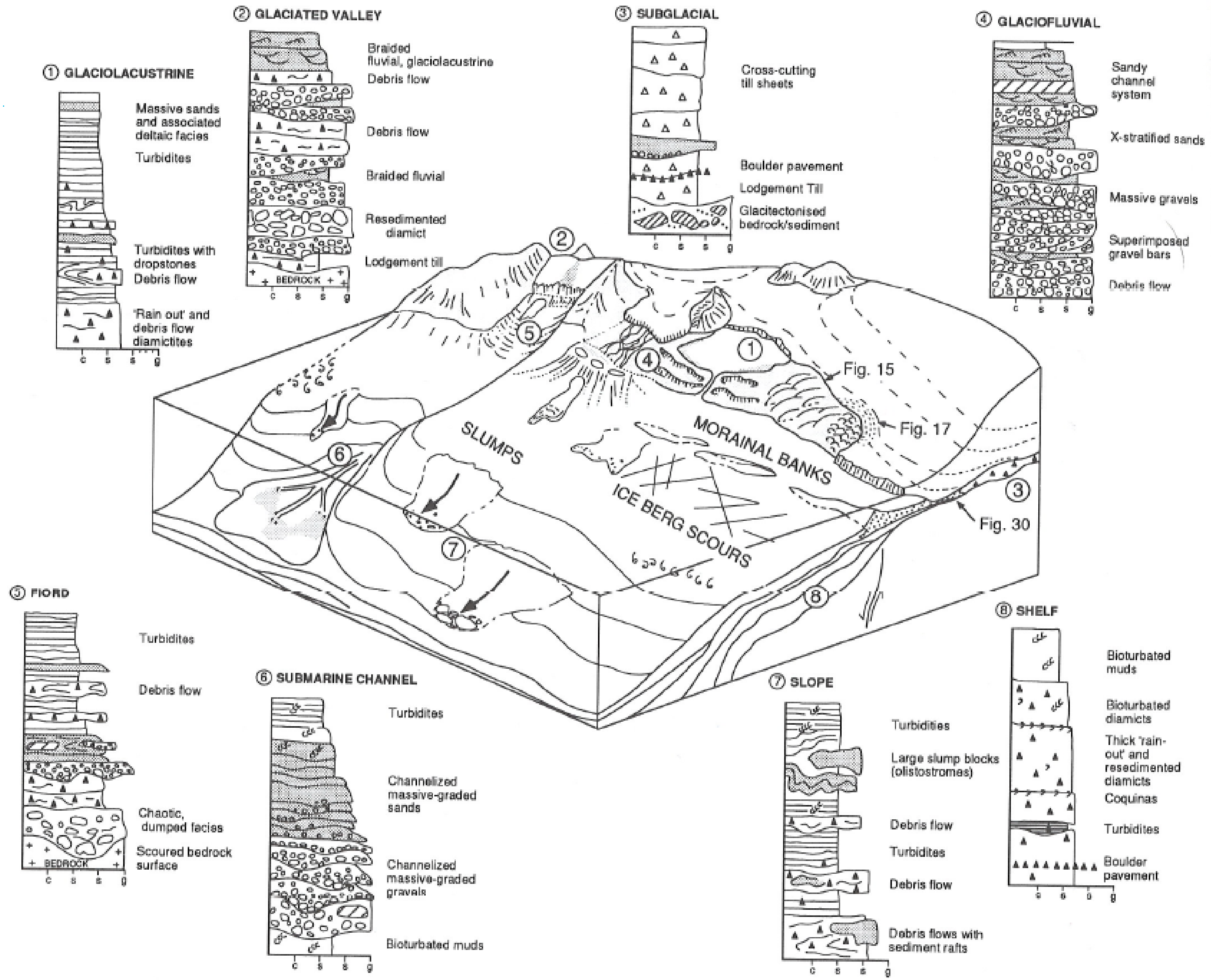
Nichols and Fisher (2007)



Barrier Front Environments:
Offshore /Lower shoreface deposits
Beach Face and Swashbar Sands
Eolian sands
Limited fines in Beach Ridge Runnels

Mid Barrier Environments:
Overwash Fans
Flood Tidal Deltas
Tidal Chanel Fills and Point bars
Marsh/Mangrove Swamp organics

Back Barrier Environments:
Tidal Chanel Fills and Point bars
Marsh/Mangrove Swamp organics
Lagoon and Tidal Flat deposits


① GLACIOLACUSTRINE
Massive sands and associated deltaic facies
Turbidites
Turbidites with dropstones
Debris flow
'Rain out' and debris flow diamictites
② GLACIATED VALLEY
Braided fluvial, glaciolacustrine
Debris flow
Debris flow
Braided fluvial
Resedimented diamict
Lodgement till
BEDROCK
③ SUBGLACIAL
Cross-cutting till sheets
Boulder pavement
Lodgement Till
Glacitectonised bedrock/sediment
④ GLACIOFLUVIAL
Sandy channel system
X-stratified sands
Massive gravels
Superimposed gravel bars
Debris flow
SLUMPS
MORAINAL BANKS
ICE BERG SCOURS
Fig. 15
Fig. 17
Fig. 30
⑤ FIORD
Turbidites
Debris flow
Chaotic, dumped facies
Scoured bedrock surface
BEDROCK
⑥ SUBMARINE CHANNEL
Turbidites
Channelized massive-graded sands
Channelized massive-graded gravels
Bioturbated muds
⑦ SLOPE
Turbidities
Large slump blocks (olistostromes)
Debris flow
Turbidites
Debris flow
Debris flows with sediment rafts
⑧ SHELF
Bioturbated muds
Bioturbated diamicts
Thick 'rain-out' and resedimented diamicts
Coquinas
Turbidites
Boulder pavement
c s s g

Perspective on Complex Sites

- Air Force Environmental Restoration Program is under performance-based contracting (PBC)
- PBCs intended to get our contractors to put their “best brains” to work on our most complex sites
- At ~ ¾ of the way through, low hanging fruit has been picked, complex sites are under an “optimized exit strategy” (OES) performance objective
  - Most OES have focused on monitoring with minimal CSM updating and effective remediation implementation
  - Air Force complex sites will remain and represent the large majority of our liability/cost
- Air Force will incorporate lessons learned into the next round of contracting to ensure sites progress towards completion

What is Limiting Cleanup at Complex Sites?

- Tight budgets
  - Specialized folks are expensive
  - Misperception that data mining and visualization is wasted money
  - Over simplified conceptual site models (CSMs)
- Wrong staff mix
  - Multidisciplinary teams required
  - Experience counts
- Rush to get something in the ground
  - Remedy in place is better than not having one
- Weak performance monitoring
  - Does not produce data necessary to inform data driven decisions
- Regulatory requirements and public affairs are after thoughts
  - Often leads to multiple versions and schedule delays

Success Can Be Had!

- Implementing Air Force complex site initiative (CSI) has proven successful at several complex sites
- Kirtland Air Force Base Bulk Fuel Facility in Albuquerque is one such site

Case Study: Silicon Valley Site

We have this problem, post source zone remediation concentrations of TCE downgradient were increasing!

Direction of groundwater flow and transport from water level maps are misleading.

This doesn't make sense so we took a closer look.

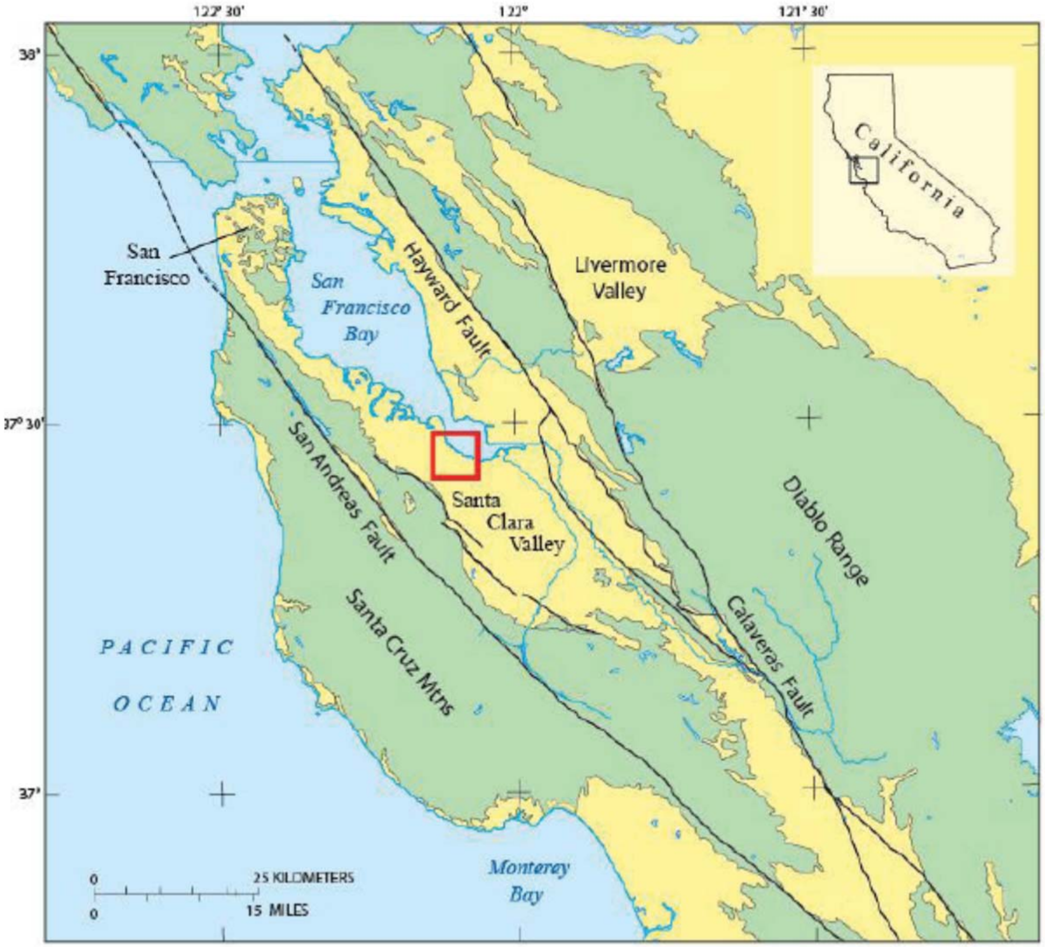
Case Study: Untangling Comingled Contaminants

Former Semiconductor Manufacturing Site: VOC groundwater plume comingled with neighboring plumes

Scale: <10 acres, ~100' depth of investigation

Lithology Data: Borehole logs

Approach: In response to 5-year review, use ESS to define contaminant migration pathways from on-site/off-site sources

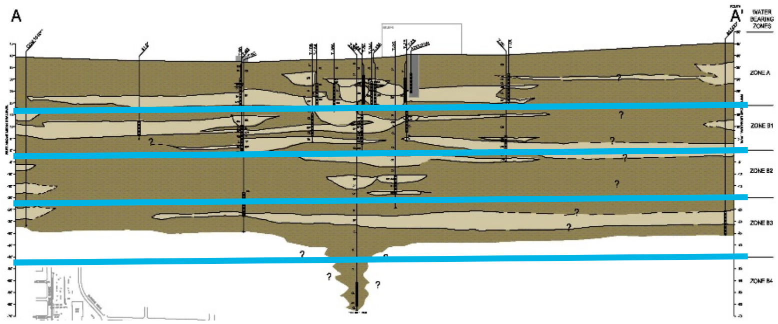


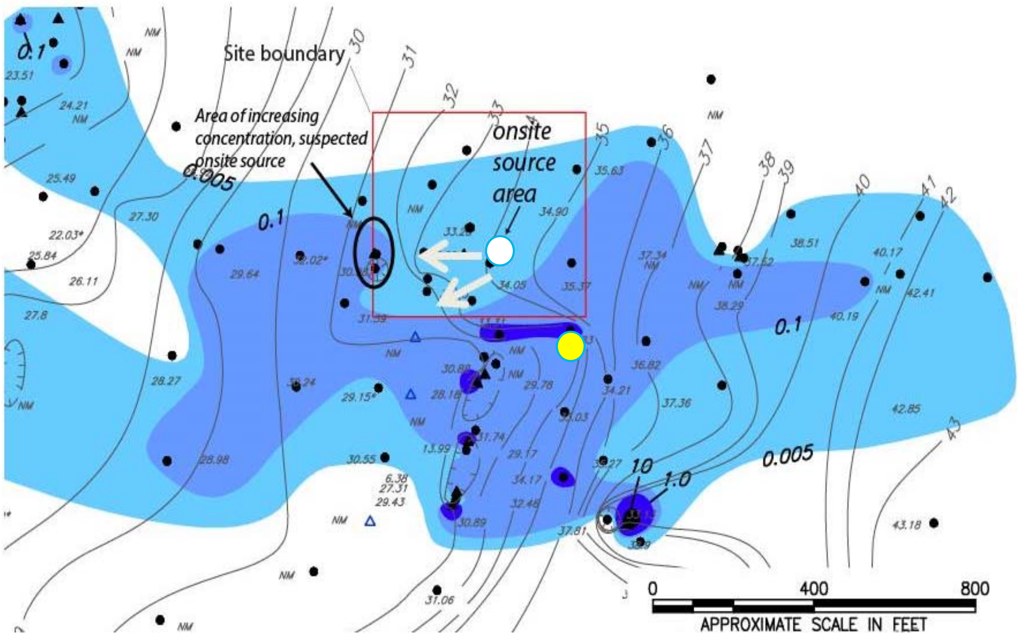
Slide 2

CR5 Need north arrow and scale. Take off company names and make TRW a rectangle like site map.
Cramer, Rick, 9/20/2016

LH2 I think that we can keep the company names, from EPA's perspective this is not enforcement confidential
Levine, Herb, 9/21/2016

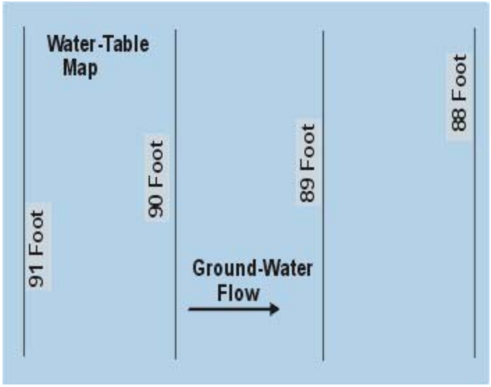
Original CSM – B1 Zone

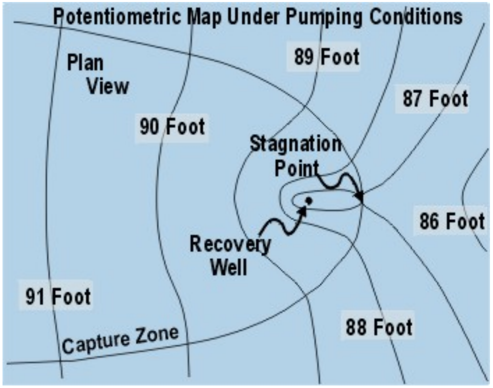




= Off site source area

Heterogeneous conditions





Homogeneous conditions

Geology Based CSM

Based on geology processes

No longer need to assume heterogeneity = homogeneous

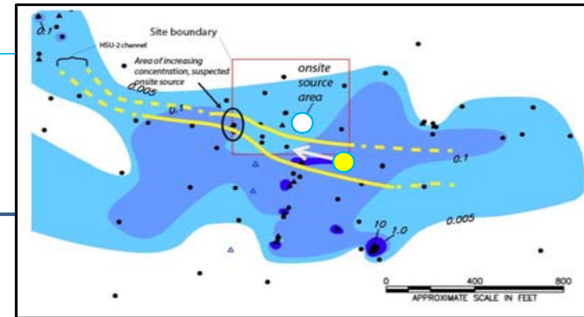
Benefits of a Geology-based CSM

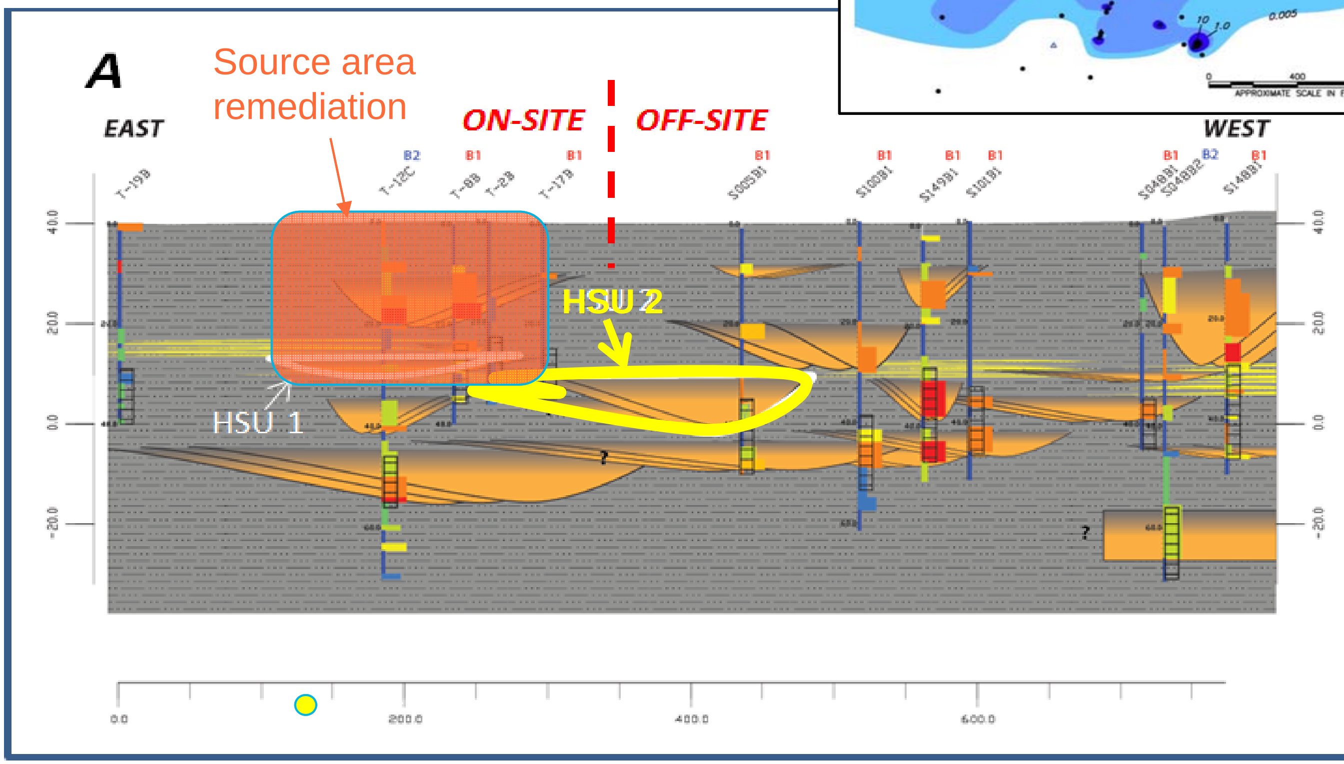
Defines subsurface “plumbing”, contaminant pathways

Critical to successful remedy selection, design, and performance

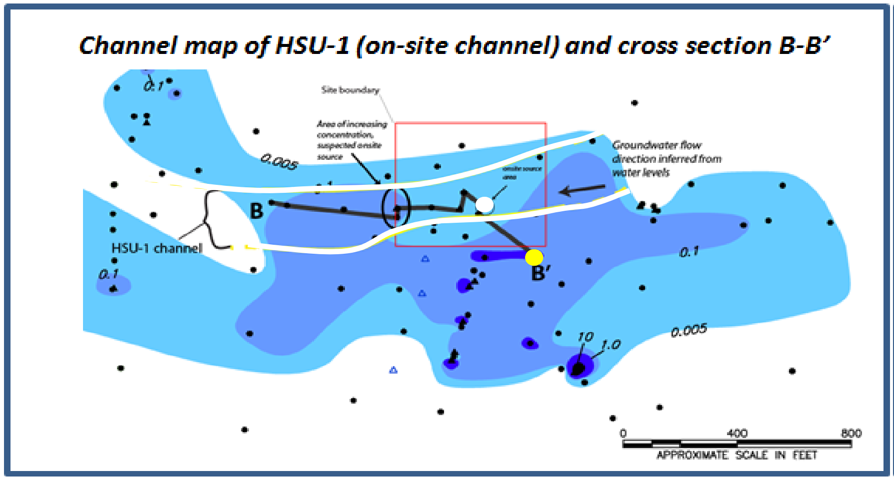
Consequence of not focusing on the geology…

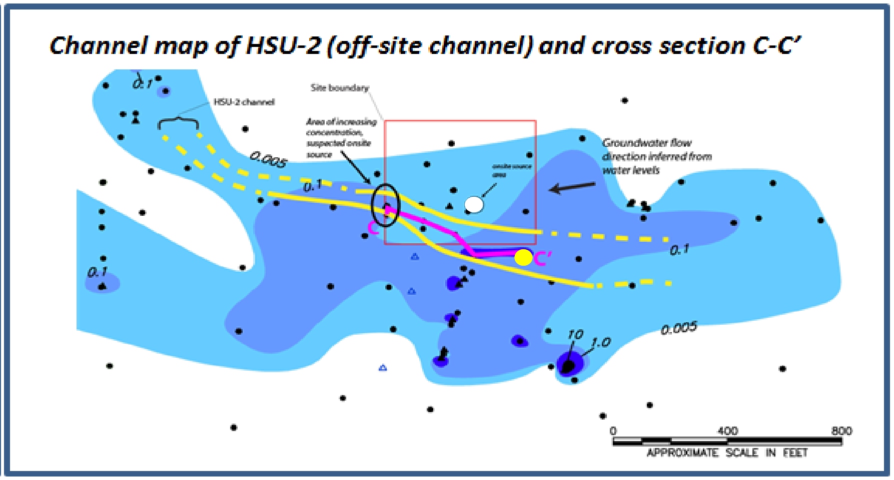
Best Practice, ESS-based CSM: Defines Buried Channels

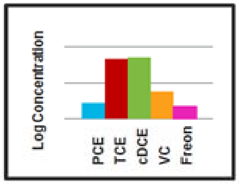


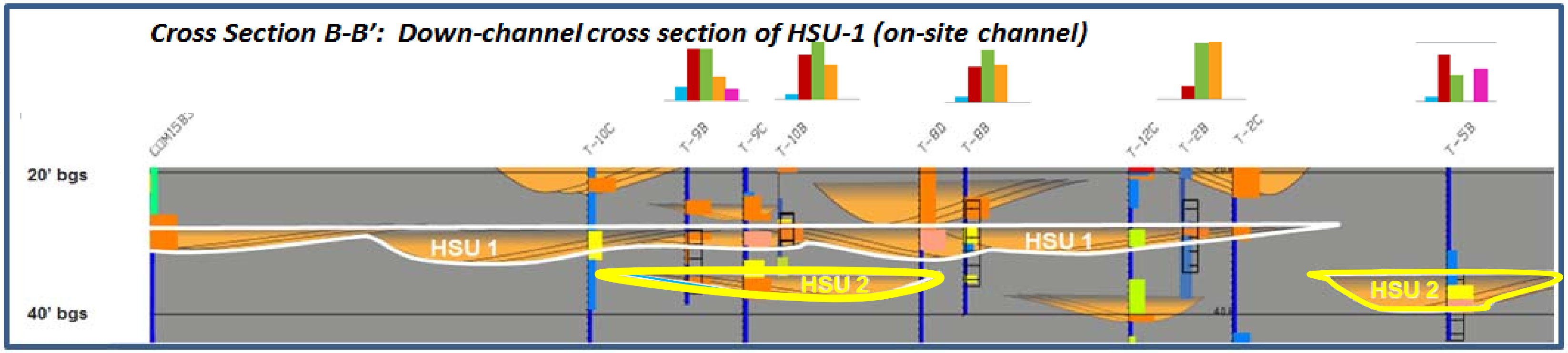


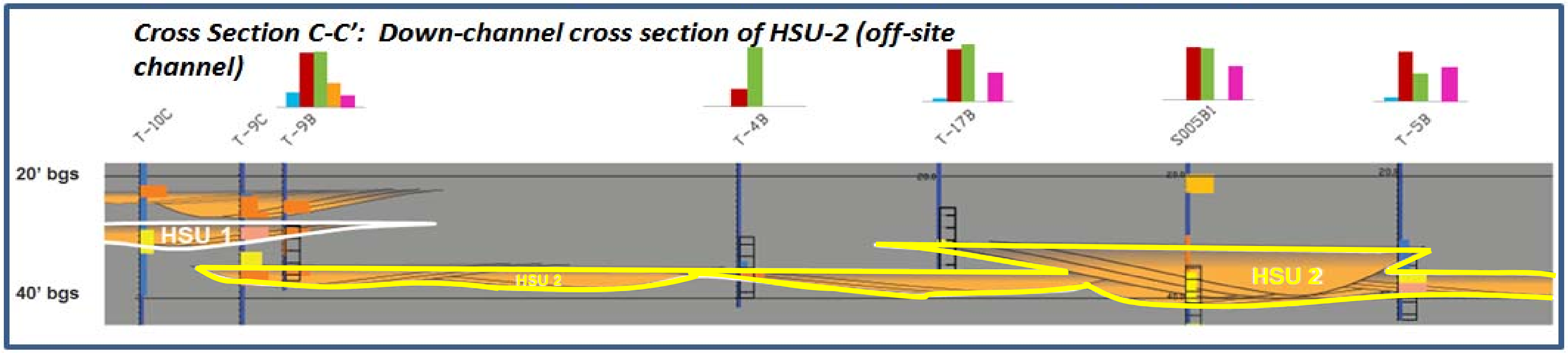
Resolve the mystery of commingled plumes





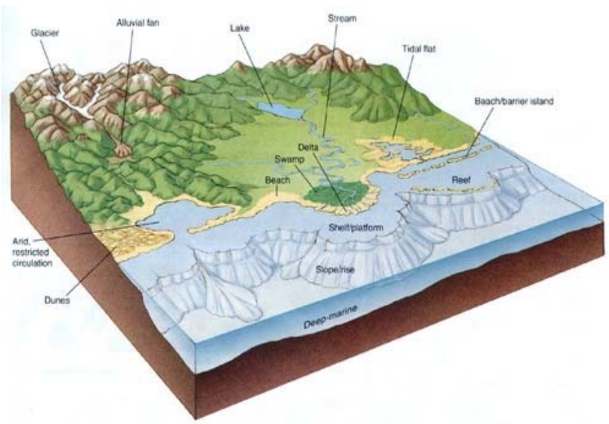






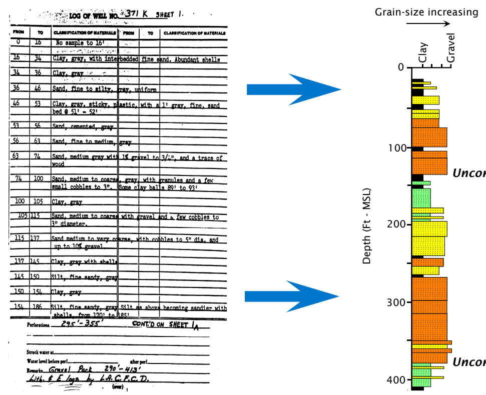
Geology-Based CSM

1



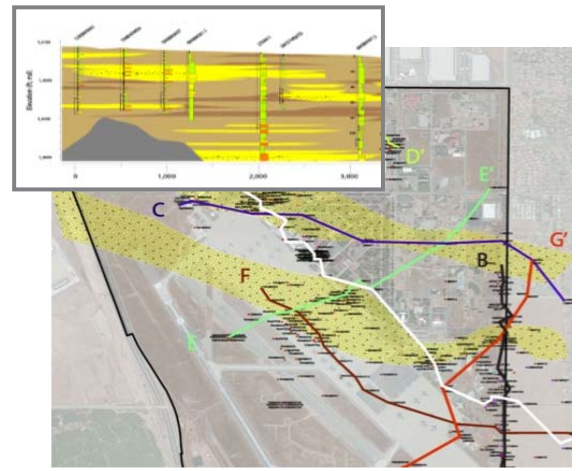
Determine depositional environment which is the foundation to the ESS evaluation

2



Leverage existing lithology data format to emphasize vertical grainsize distribution

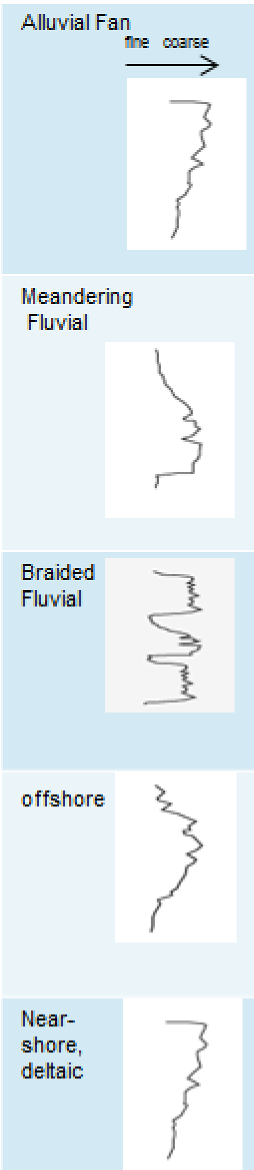
3

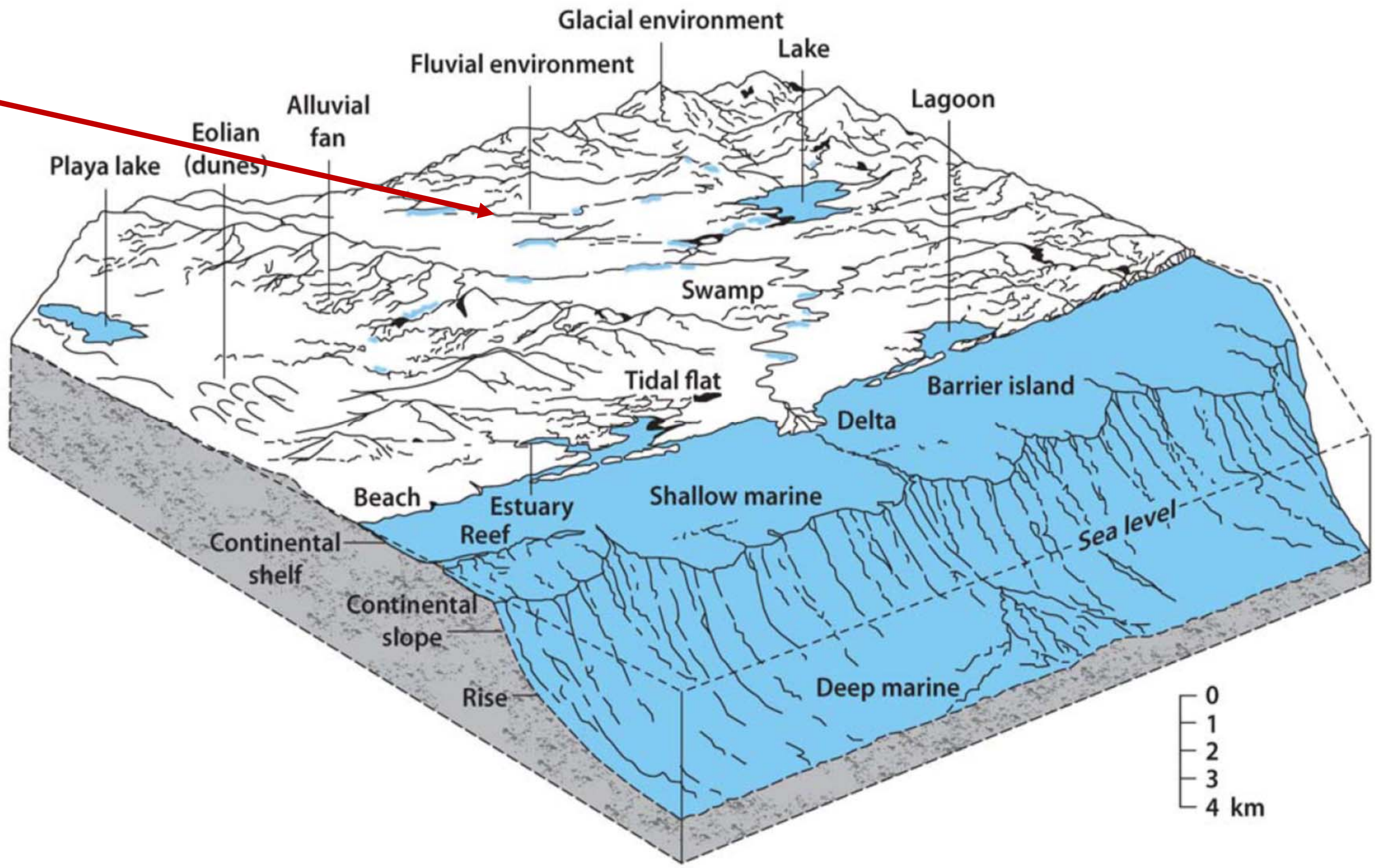


Predict and map in 3D the subsurface conditions away from the data points

ESS Is Pattern Recognition

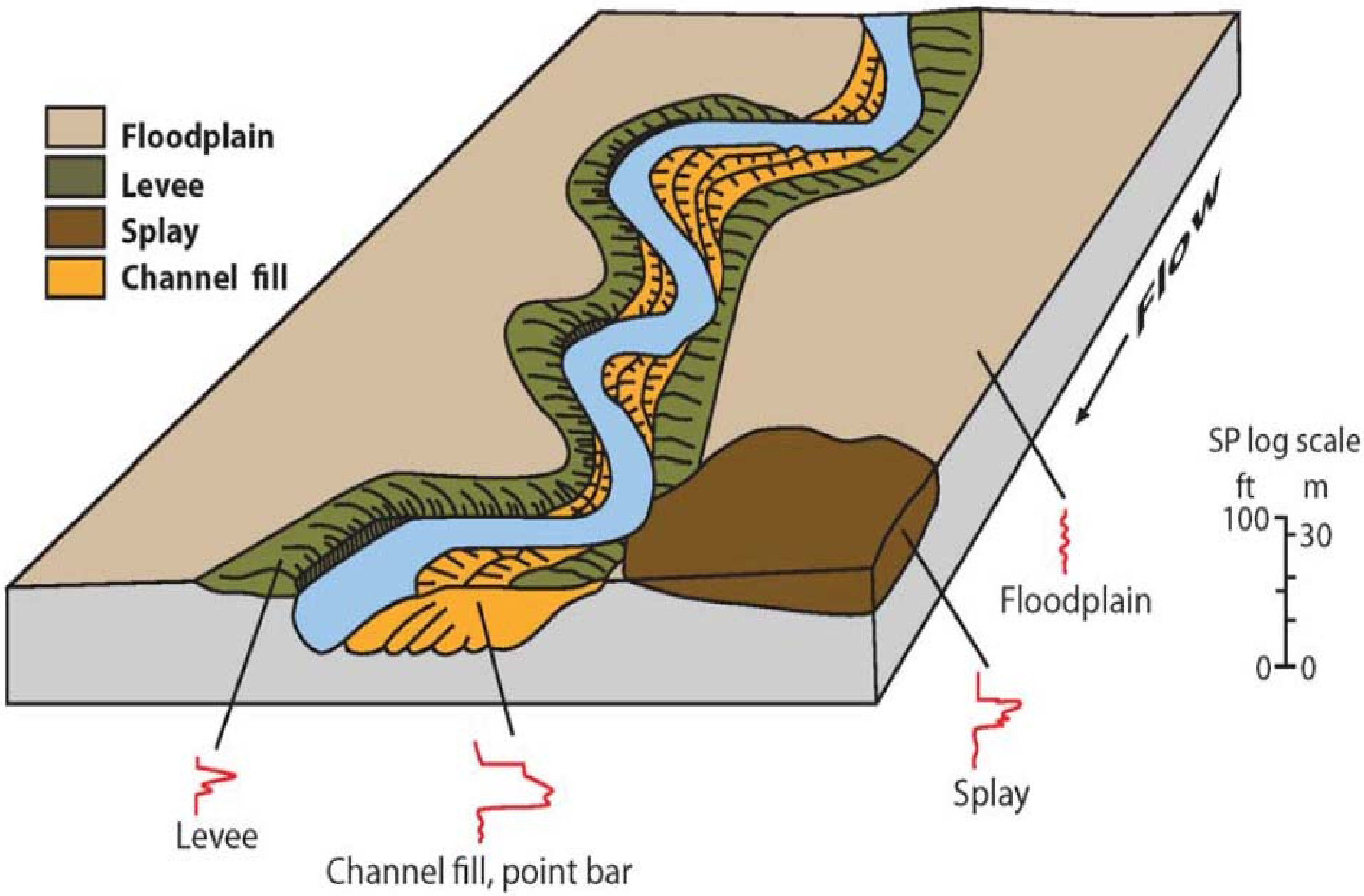
Depositional environments have distinctive vertical grain size distributions…





CR10

Example of buried channel depositional system

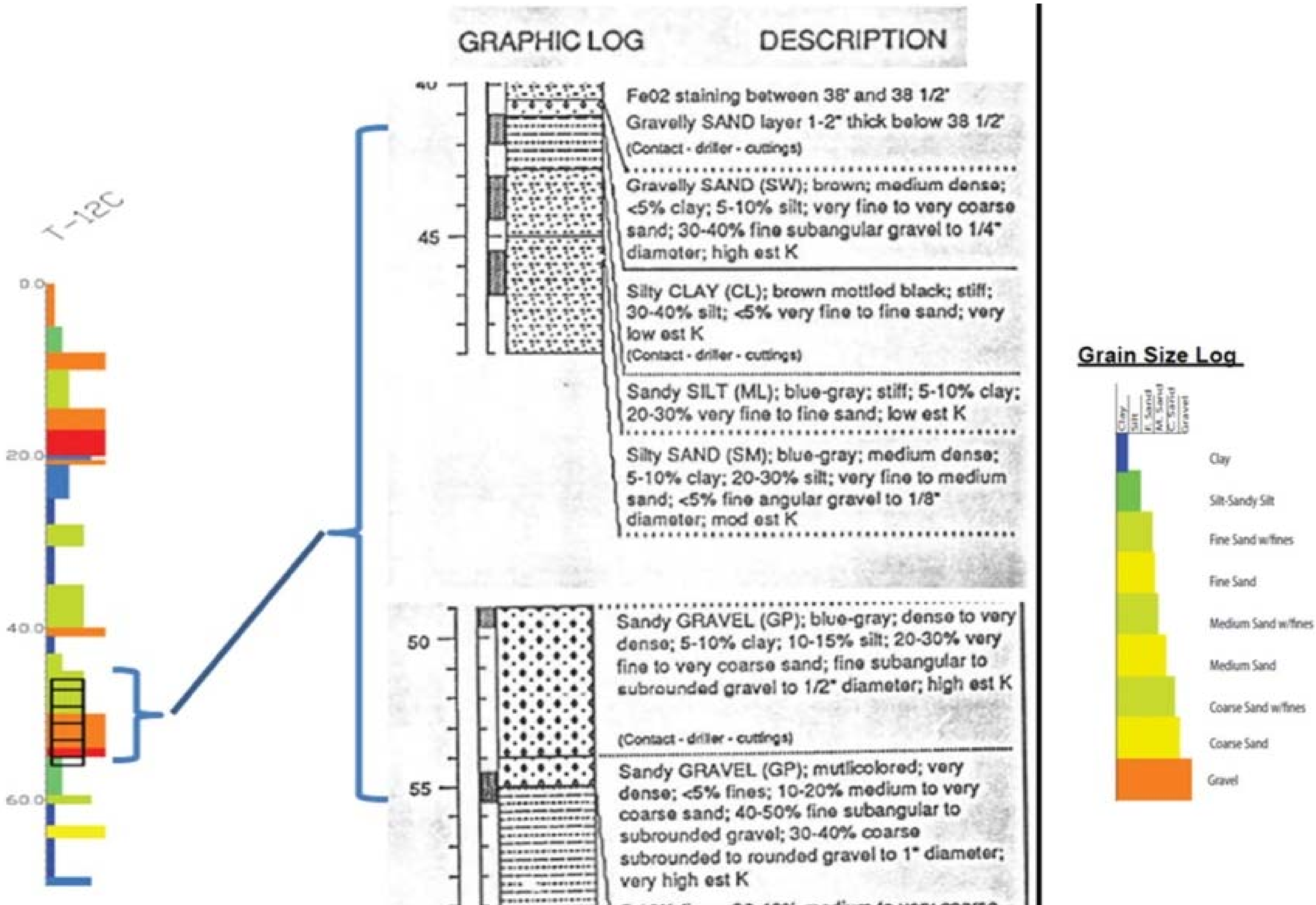


Slide 10

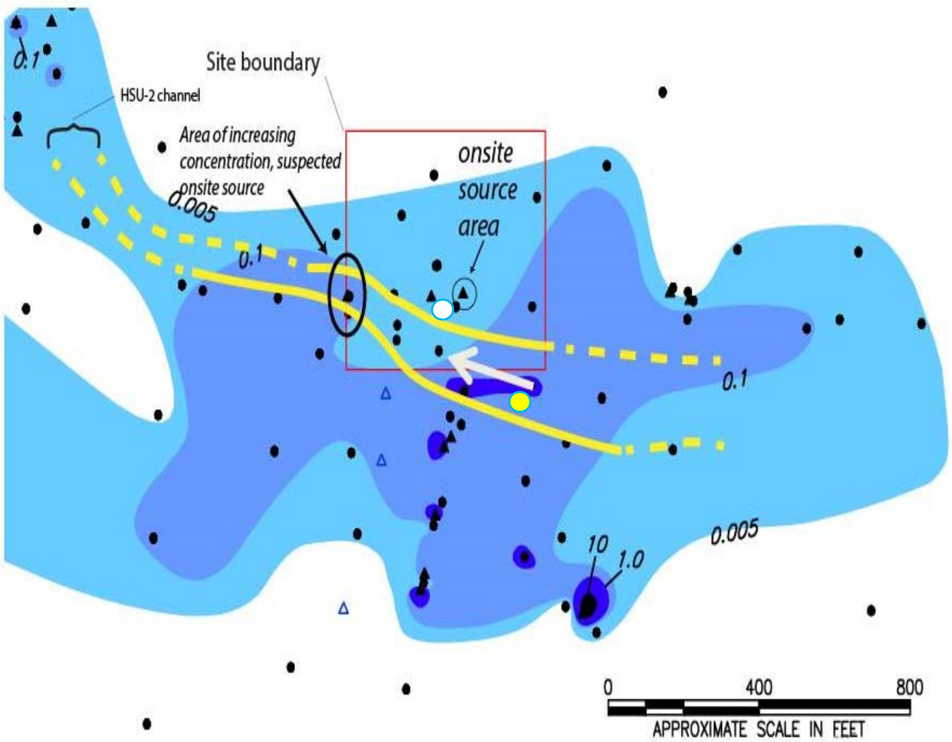
CR10 Cramer, Rick, 9/20/2016

CR9 revise to take out splay
Cramer, Rick, 9/20/2016

Forensic Tool:
Fining-upward Grainsize Pattern = Channel Deposit

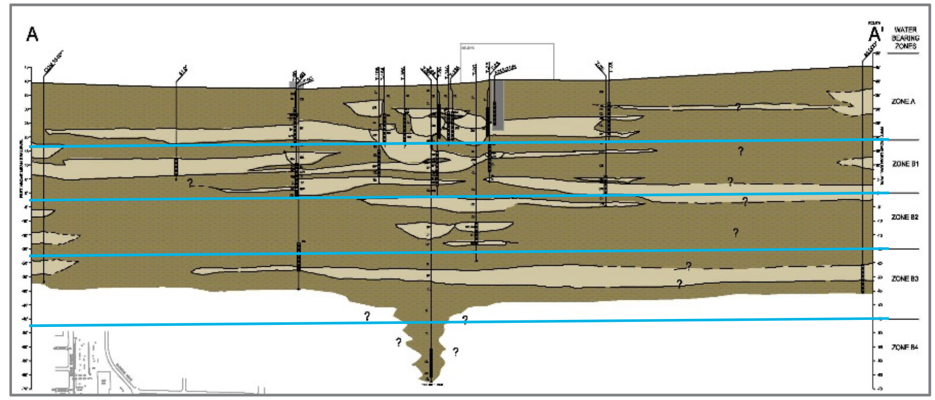


Geologic Best Practice

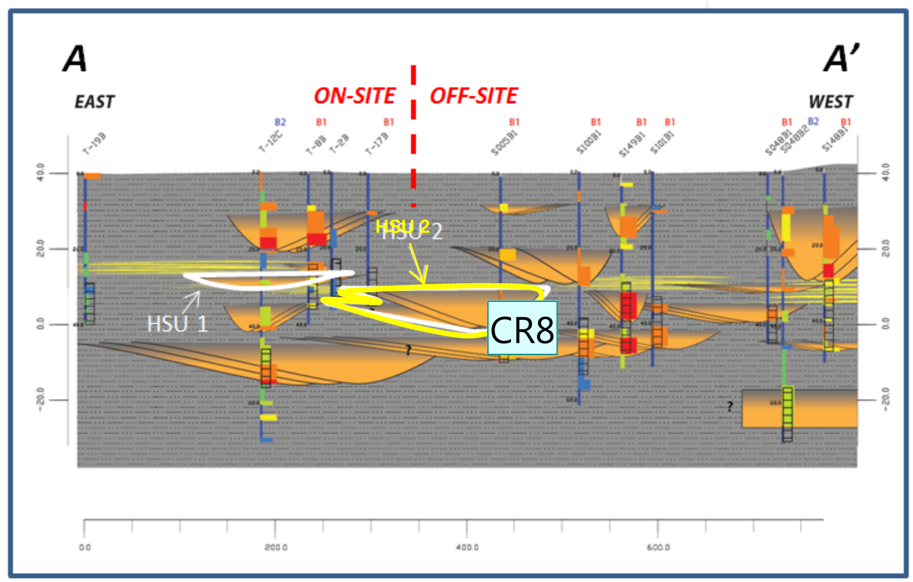


= Off site source area

Original CSM



ESS-based CSM



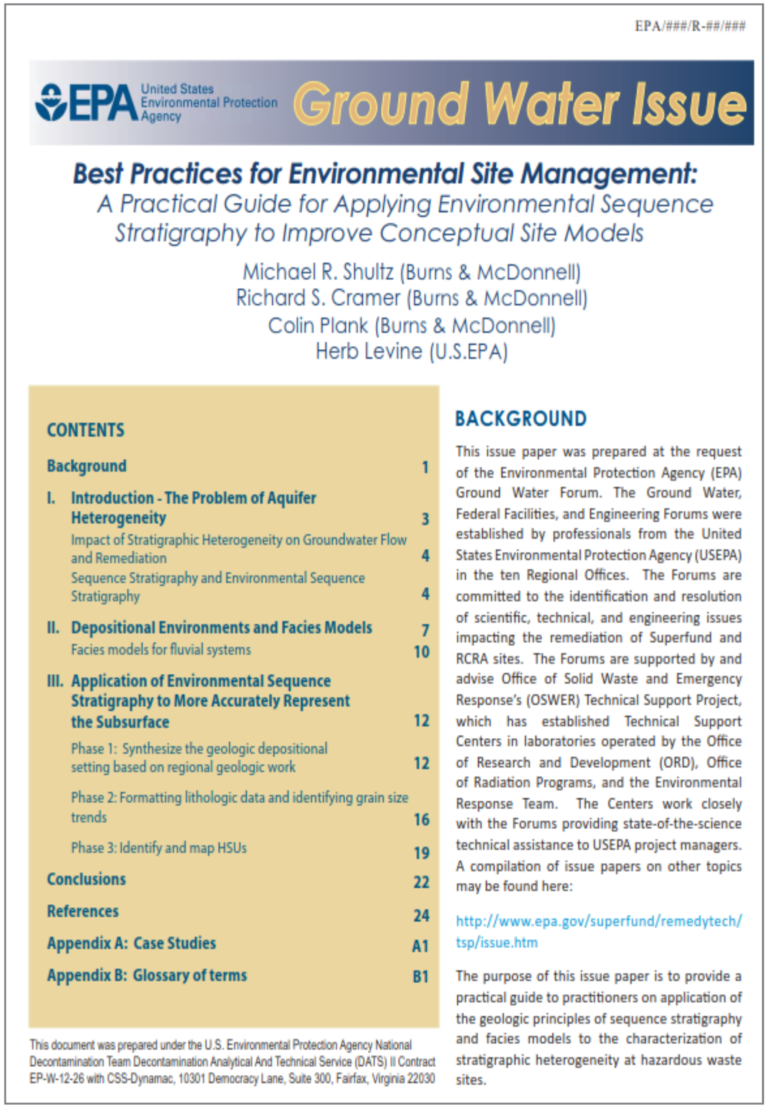
Slide 12

CR8 include additional xsectons that show where the channel is going

Cramer, Rick, 9/20/2016

Summary

- ESS based CSM can provide insight to groundwater and contaminant flowpaths
- EPA ESS Issue Paper publication imminent, will be announced on EPA's monthly Tech Direct and will be located on Clu-in
- EPA will expect sites to follow this methodology when starting new CSMs or updating existing CSMs
- Who does this work?



EPA/###/R-##/###

EPA United States Environmental Protection Agency **Ground Water Issue**

Best Practices for Environmental Site Management:

A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models

Michael R. Shultz (Burns & McDonnell)
Richard S. Cramer (Burns & McDonnell)
Colin Plank (Burns & McDonnell)
Herb Levine (U.S.EPA)

CONTENTS

This document was prepared under the U.S. Environmental Protection Agency National Decontamination Team Decontamination Analytical And Technical Service (DATS) II Contract EP-W-12-26 with CSS-Dynamac, 10301 Democracy Lane, Suite 300, Fairfax, Virginia 22030

BACKGROUND

This issue paper was prepared at the request of the Environmental Protection Agency (EPA) Ground Water Forum. The Ground Water, Federal Facilities, and Engineering Forums were established by professionals from the United States Environmental Protection Agency (USEPA) in the ten Regional Offices. The Forums are committed to the identification and resolution of scientific, technical, and engineering issues impacting the remediation of Superfund and RCRA sites. The Forums are supported by and advise Office of Solid Waste and Emergency Response's (OSWER) Technical Support Project, which has established Technical Support Centers in laboratories operated by the Office of Research and Development (ORD), Office of Radiation Programs, and the Environmental Response Team. The Centers work closely with the Forums providing state-of-the-science technical assistance to USEPA project managers. A compilation of issue papers on other topics may be found here:

http://www.epa.gov/superfund/remedytech/tsp/issue.htm

The purpose of this issue paper is to provide a practical guide to practitioners on application of the geologic principles of sequence stratigraphy and facies models to the characterization of stratigraphic heterogeneity at hazardous waste sites.

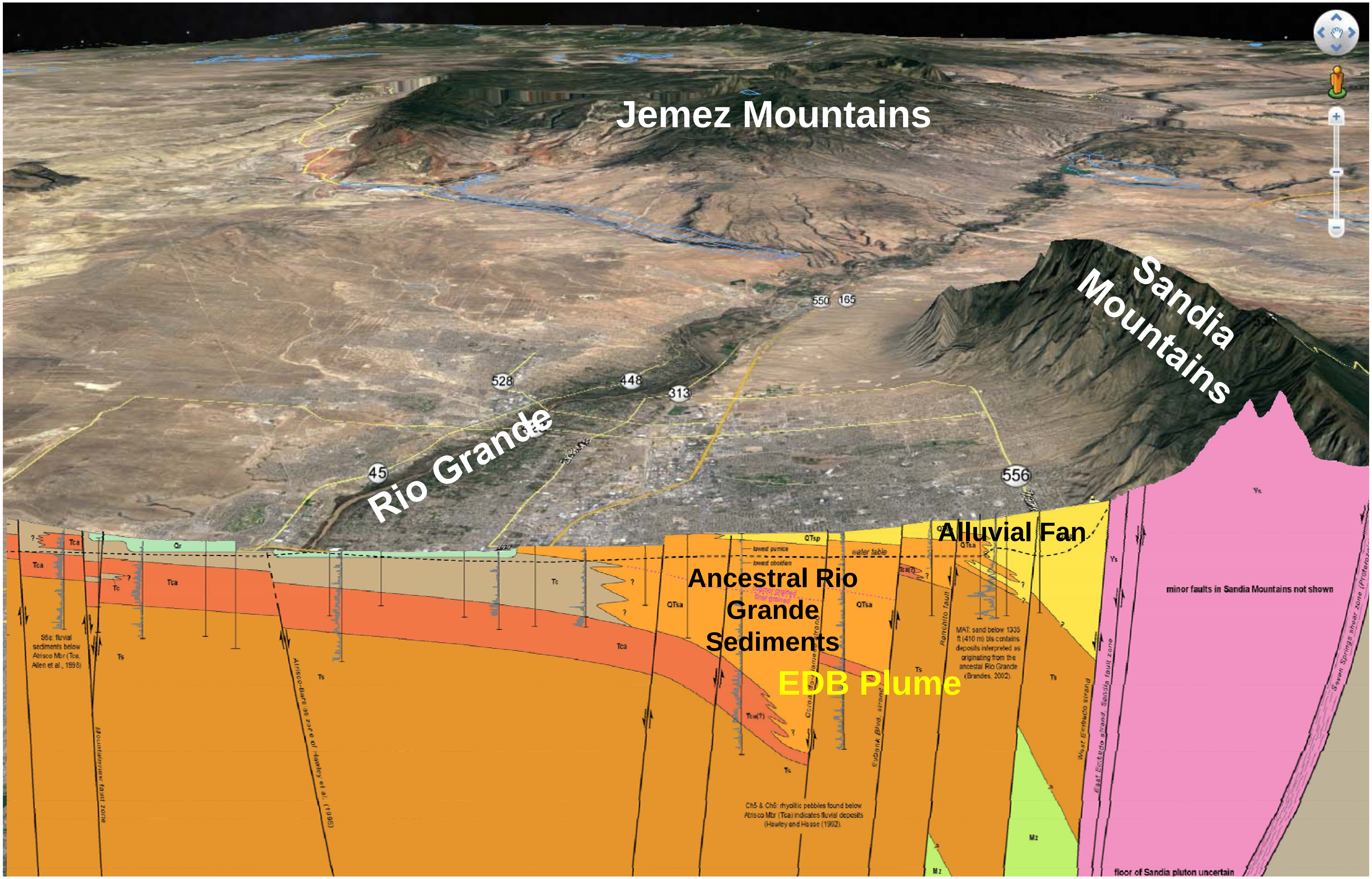
Environmental Restoration Complex Site Initiative

Adria Bodour, PhD
AFCEC/CZRX
25 May 17

Site Description

Location	Albuquerque, New Mexico
Climate	Semi arid climate
Geology	Alluvial deposits overlying ancestral braided river deposits
Depth to Groundwater	450 to 480 feet below ground surface (bgs)
Contaminants of Concern	Fuel hydrocarbons and ethylene dibromide (EDB)
Community and Stakeholder Environment	Heavy community involvement including stakeholders, environmental action groups, neighborhood associations, City, Water Authority, State and Congressional Delegates

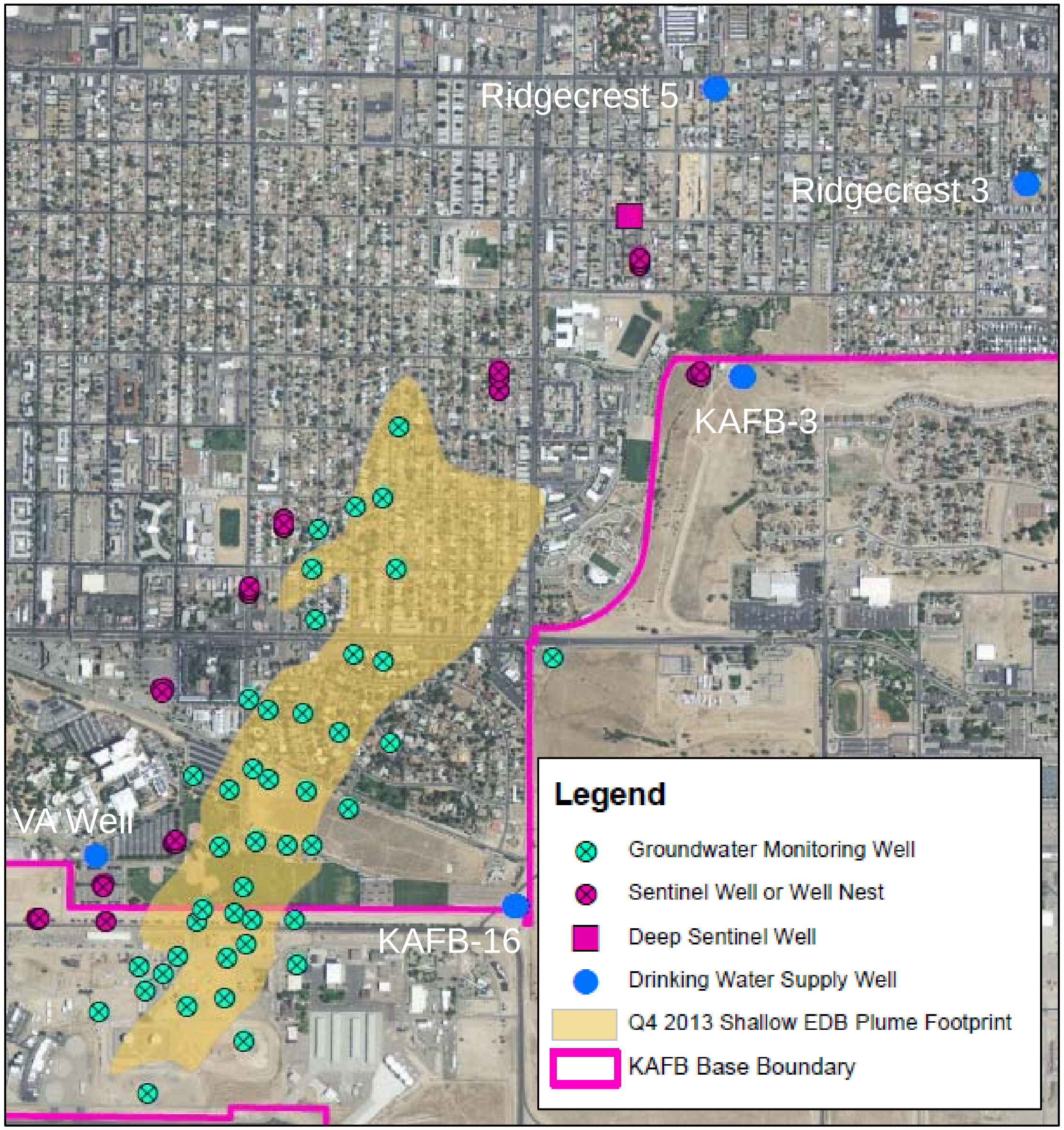
Regional Geology



Site History

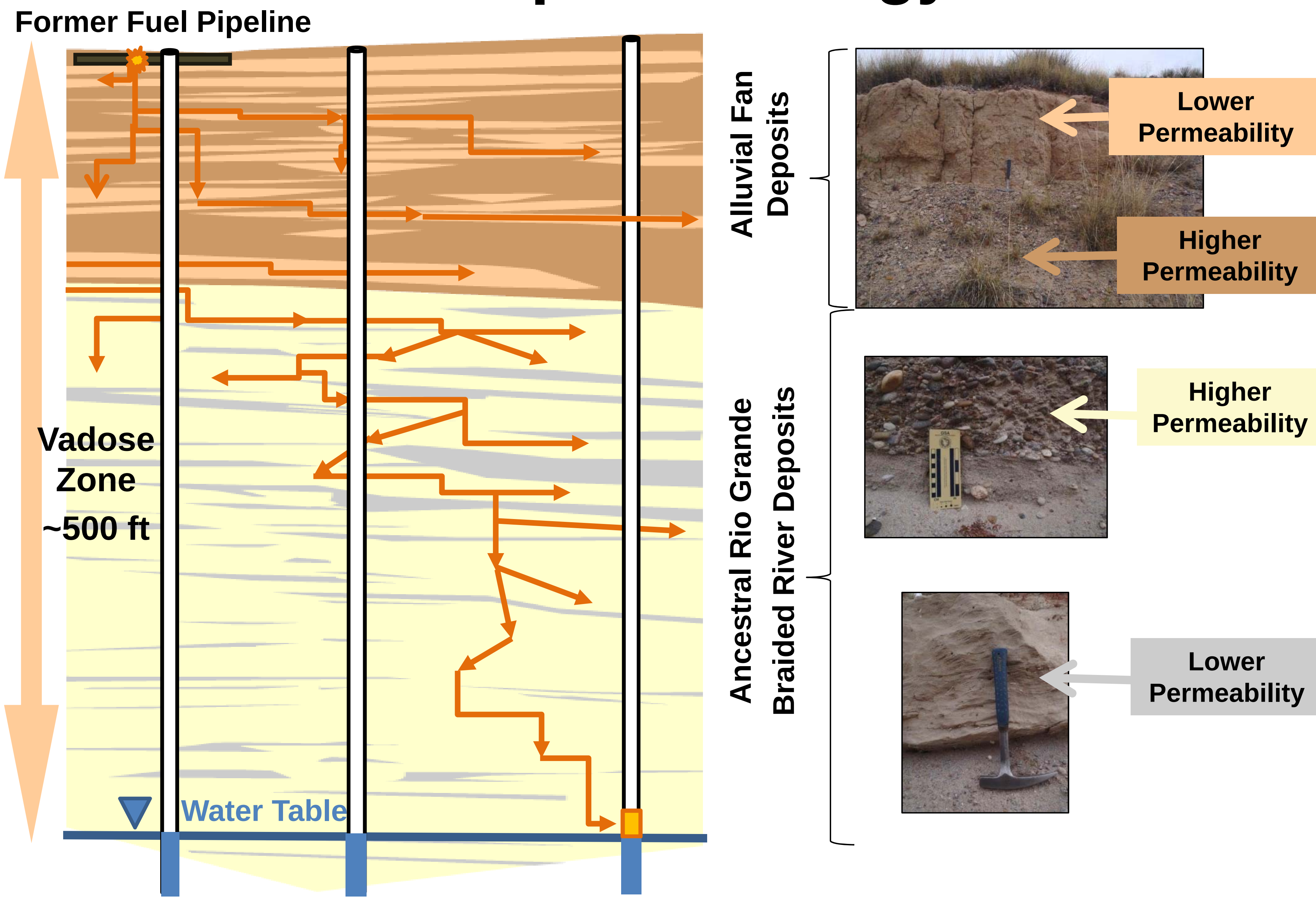
Date	Activity
1951-53	Kirtland Air Force Base (AFB) Bulk Fuels Facility (BFF) constructed
1953-75	Handled aviation gasoline (AvGas), which contained the additive EDB
1976-89	Switched to jet propellant (JP-4) which was phased out for JP-8 in the late 1980's
1999	Leak discovered, site characterization begins, LNAPL found in 2007
2003-15	Interim remedial actions implemented including soil vapor extraction, LNAPL skimming, bioslurpping, air sparging
2014-present	CSI implemented, interagency partnership created, data gaps identified and addressed, CSM updated
2016 - present	Focused interim measures implemented • Groundwater extraction, treatment and reuse/reinjection • Enhanced EDB bioremediation • Bioventing (source area vadose zone) • Coupled airlift bioventing (source area groundwater & smear zone)

Pre-CSI Understanding of Dissolved EDB Plume



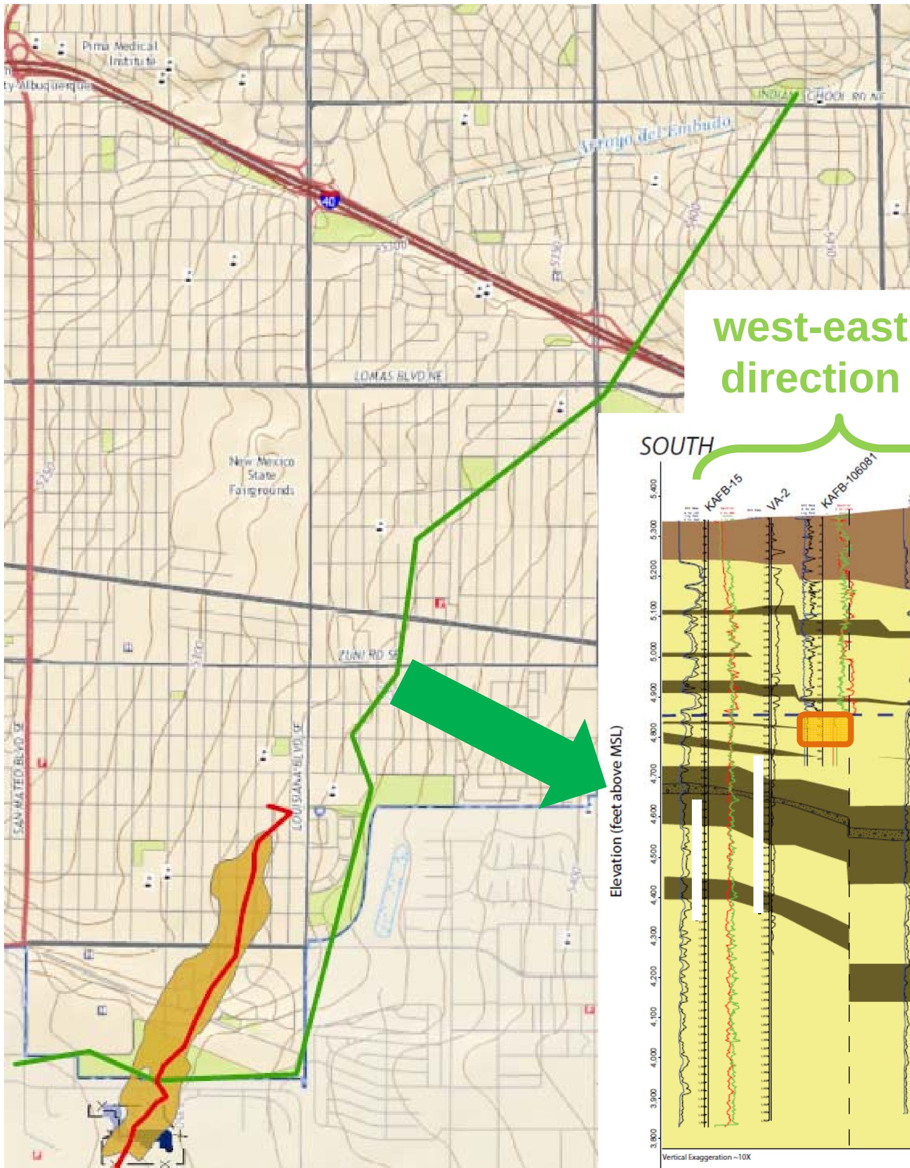
- **Previous CSM**
  - **Layered cake**
  - **Regional vs. plume scale**
  - **Modeling indicated 5-30 years contamination will reach production wells**
  - **Fluctuating water table, changing gradients, and artificial flow fields from production wells**
- **Politics were driving decisions; not data**

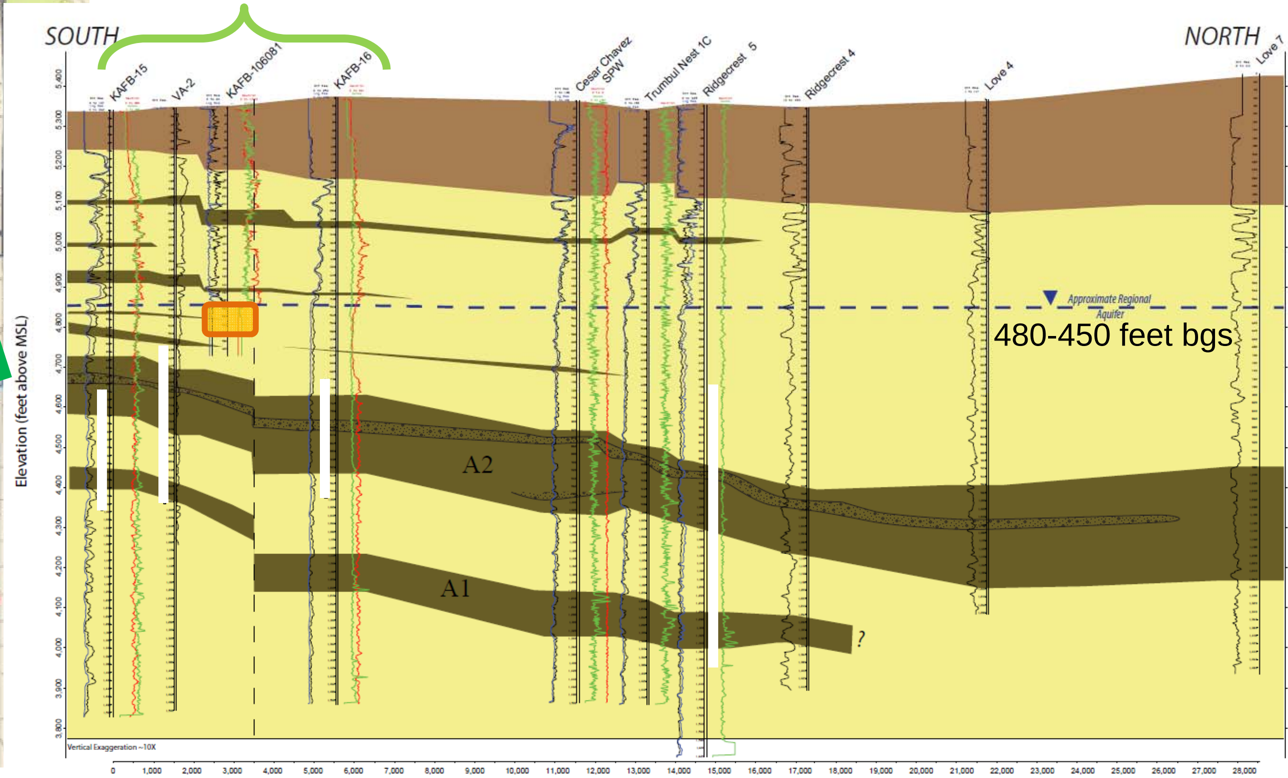
Complex Geology



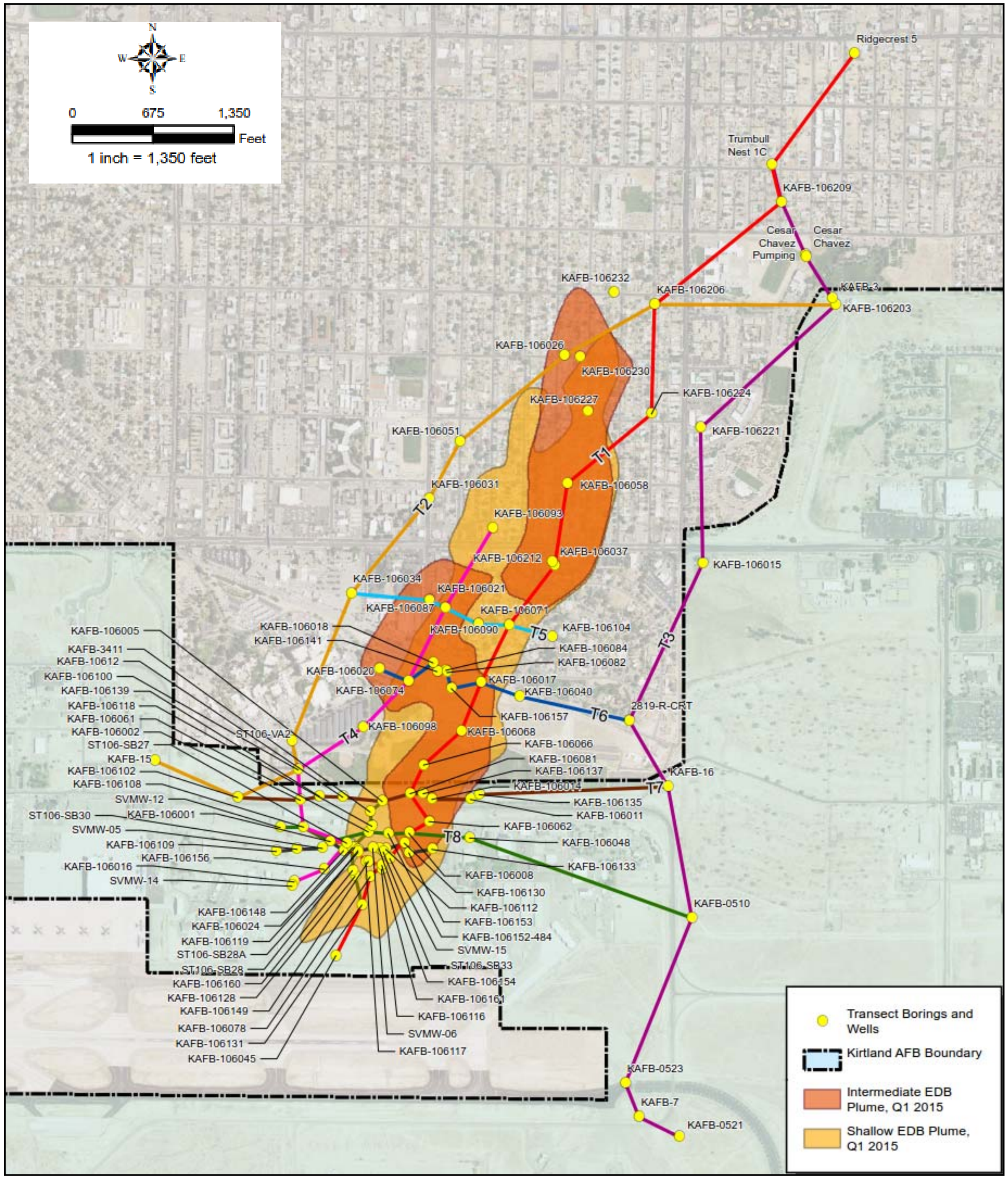
Regional Scale Geology

- **QTsp - Alluvial Fan Deposits**
- **QTsa - Ancestral Rio Grande Braided River Deposits**
- **A2 and A1 – fine-grain relatively continuous clay-rich layers**

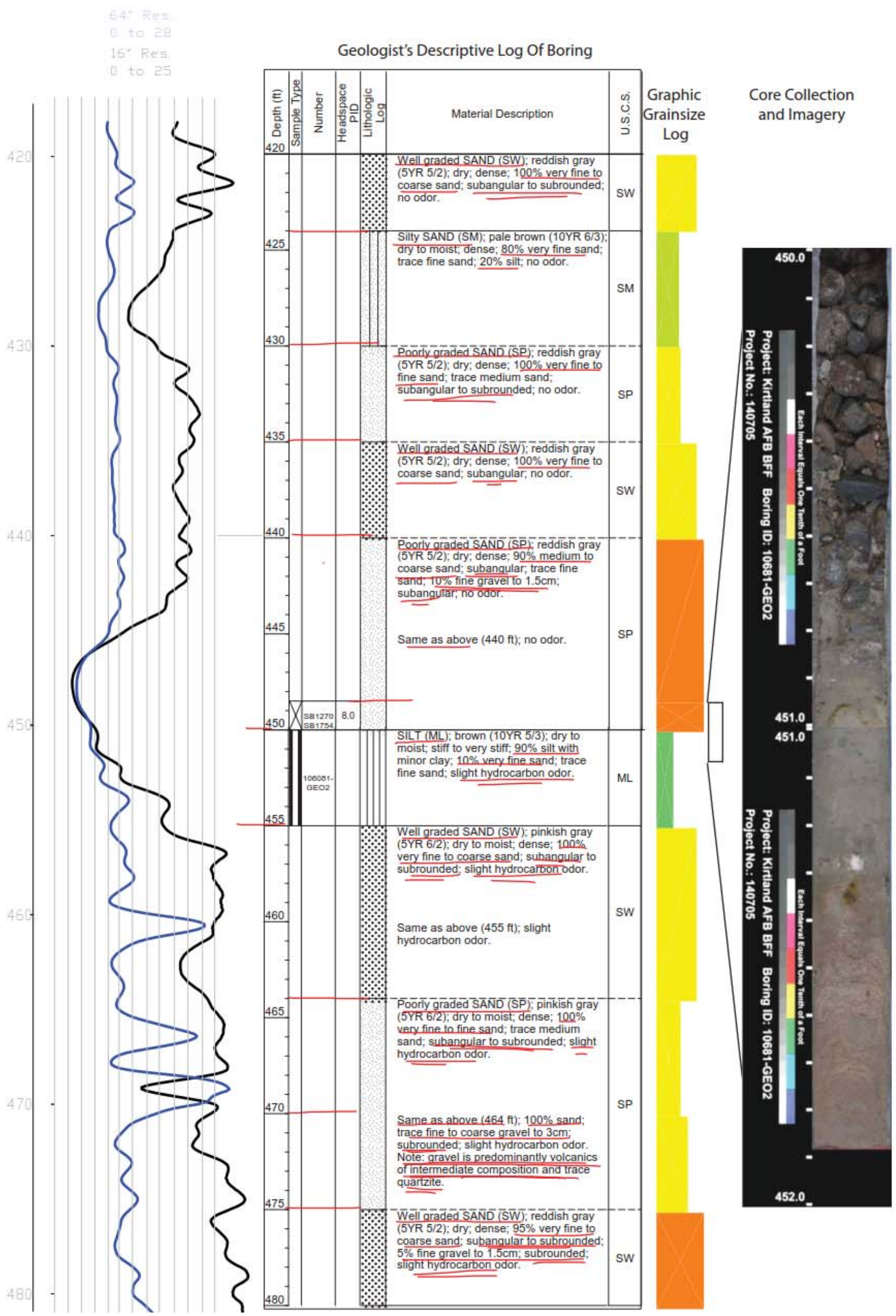




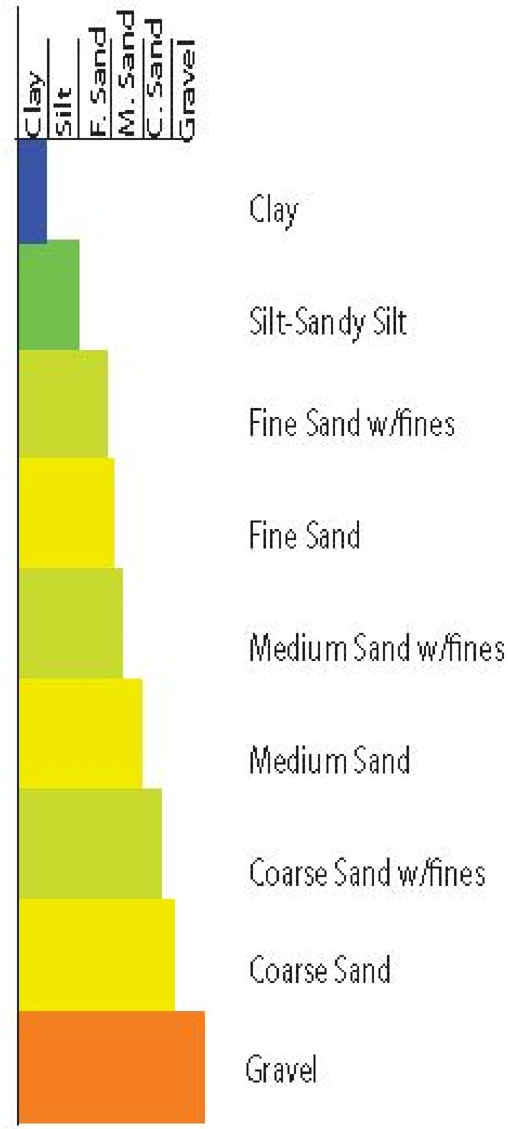
Environmental Sequence Stratigraphy (ESS) Refines the CSM



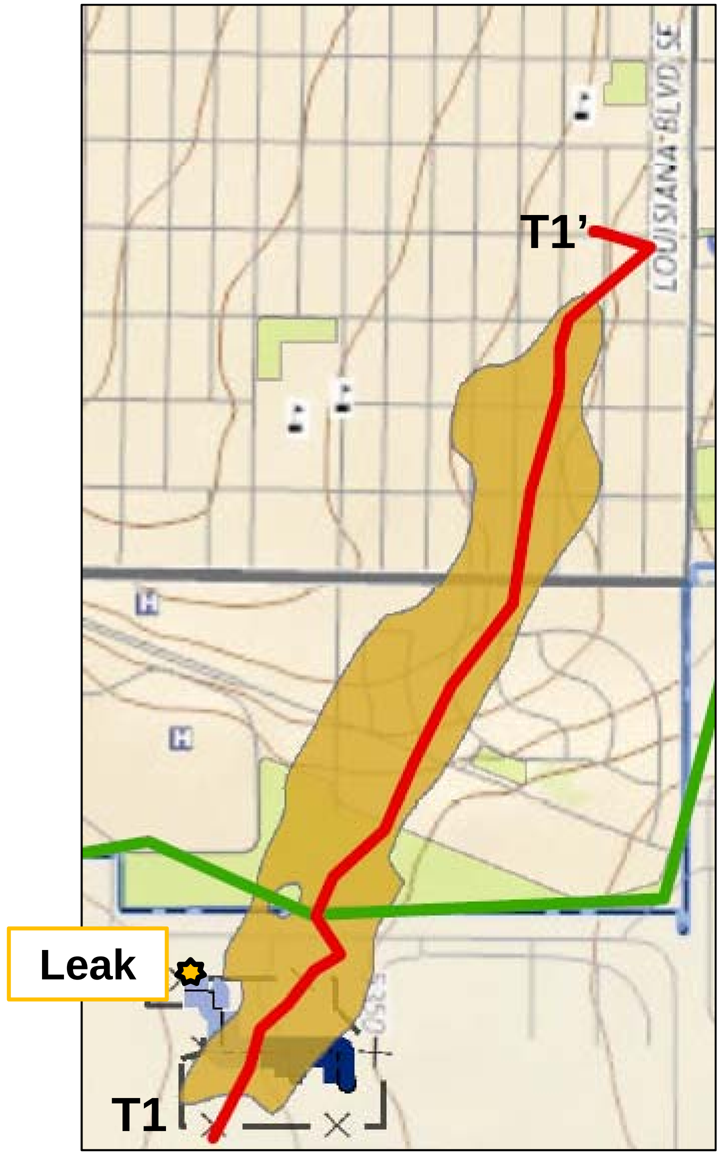
Subsurface Data



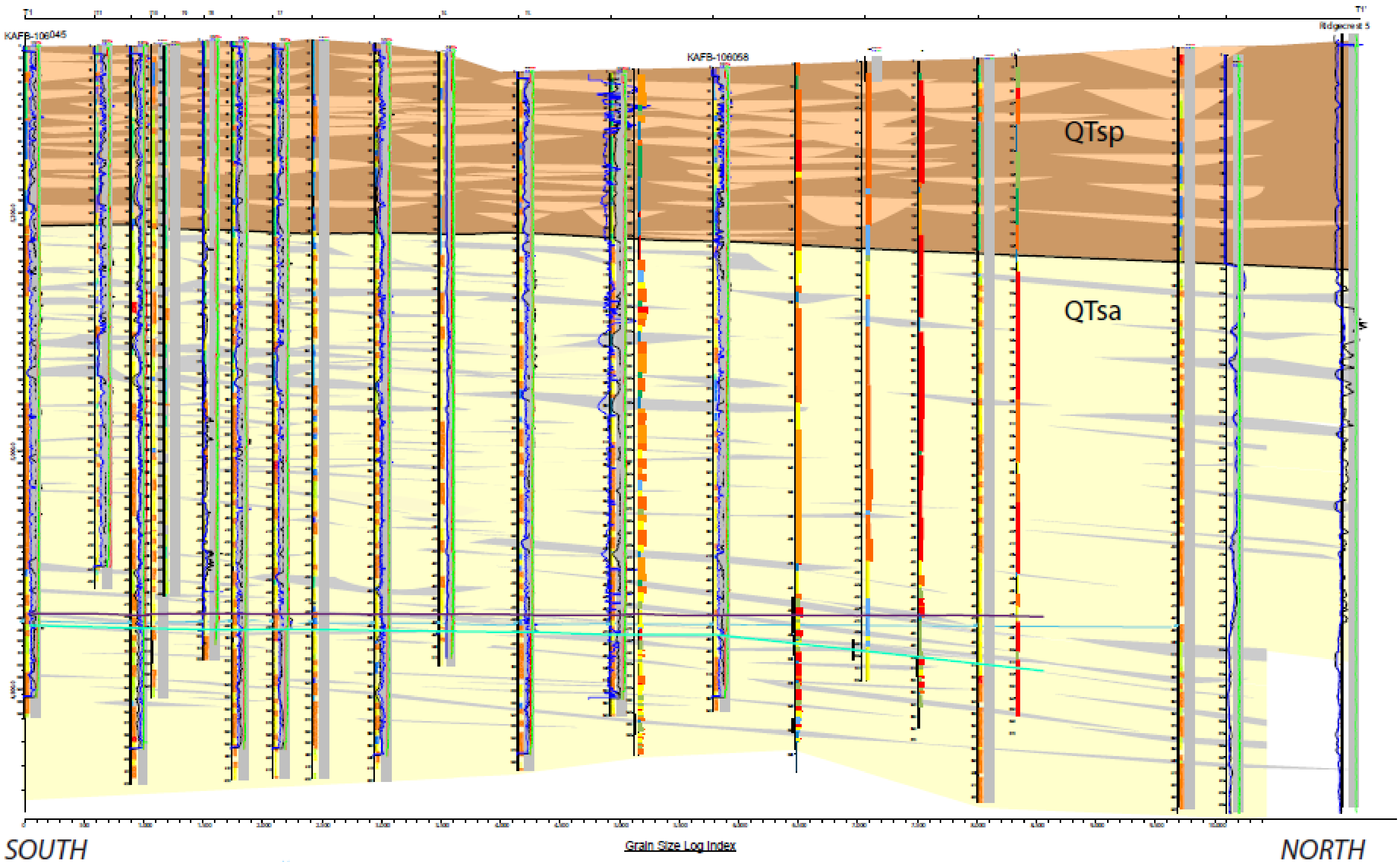
Graphic Grain Size Scale



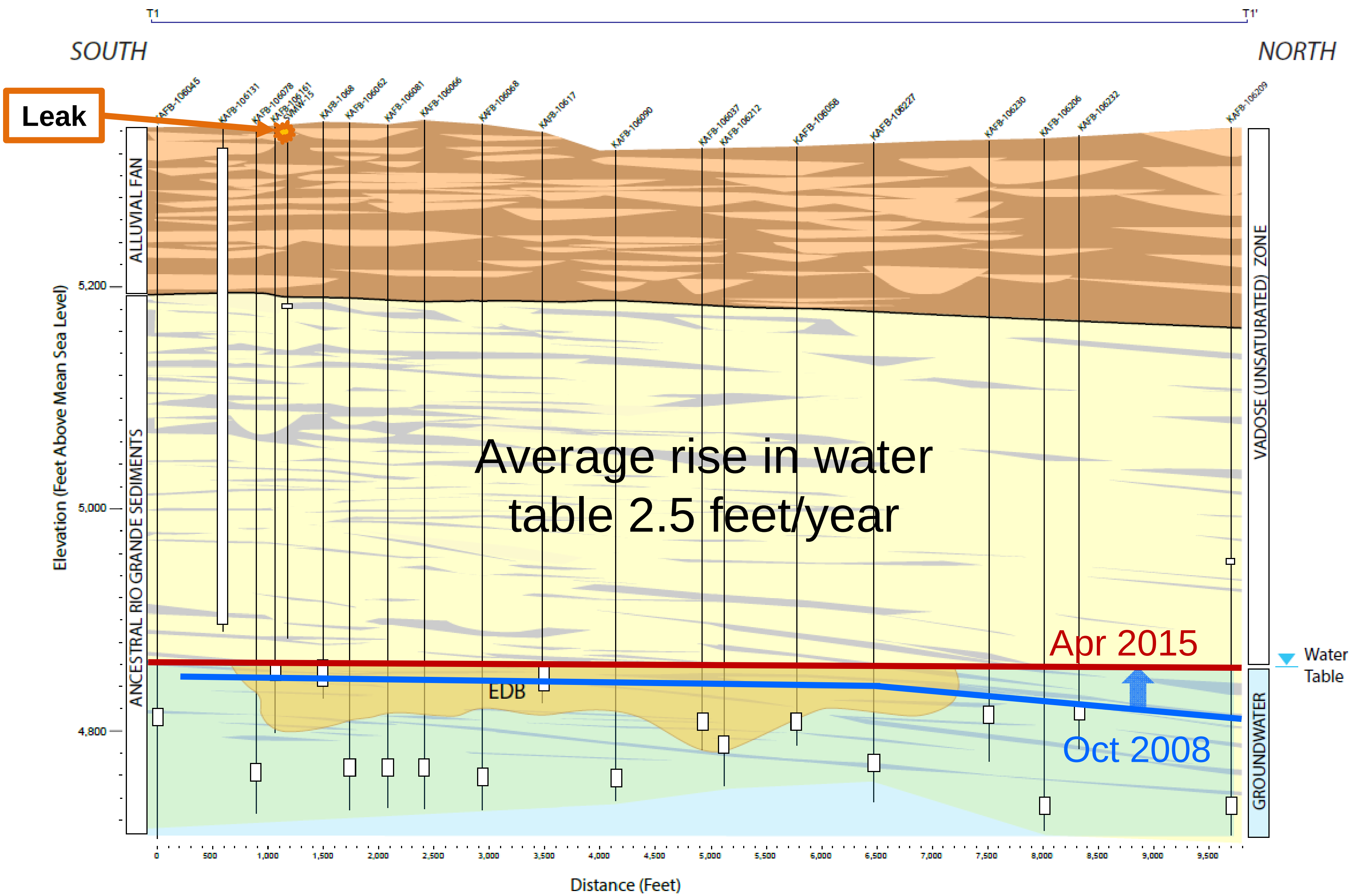
Plume Scale ESS



Plume Scale ESS Cross Section

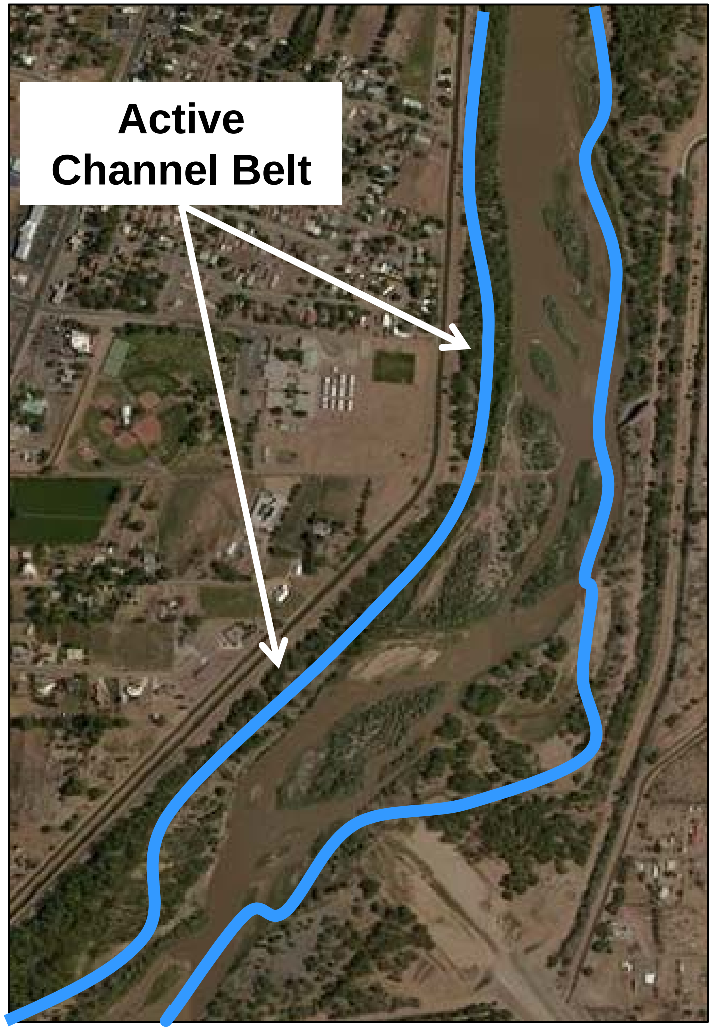


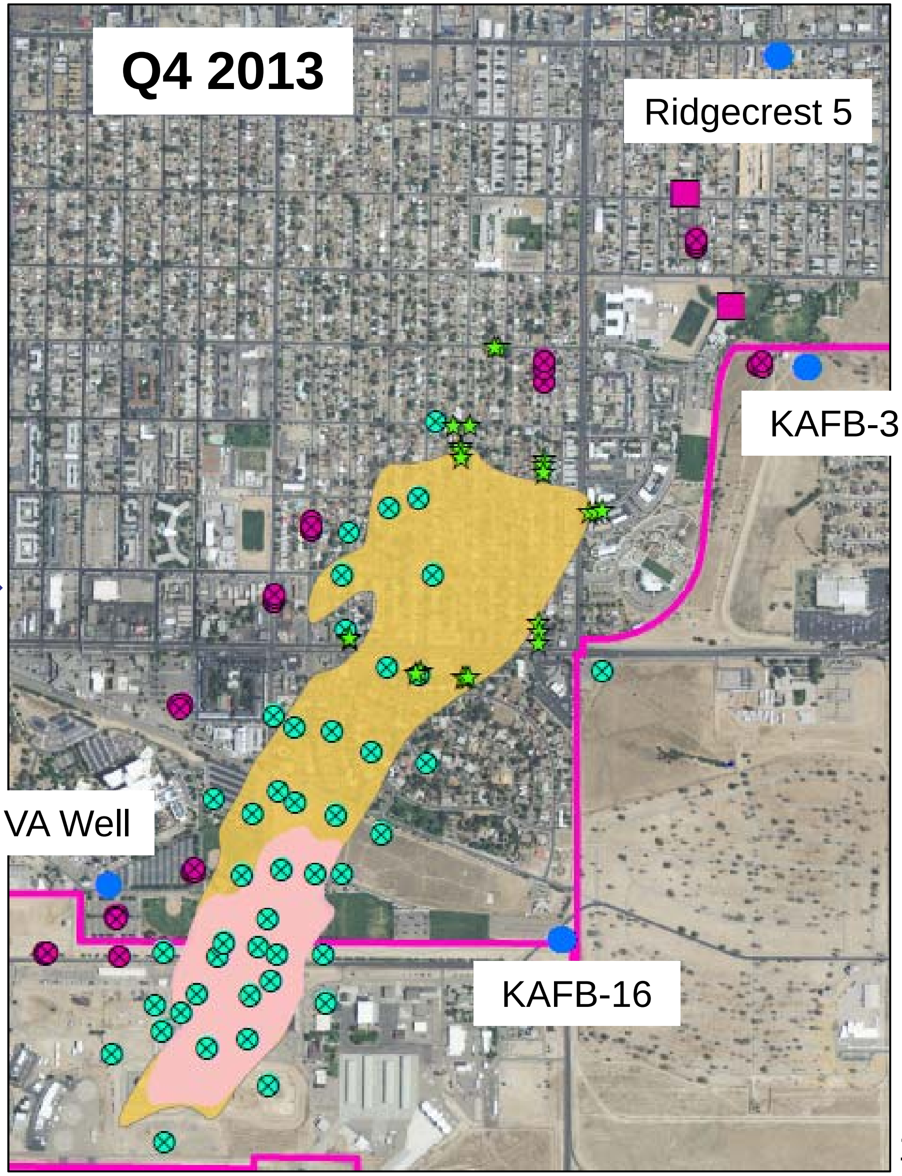
Rising Water Table



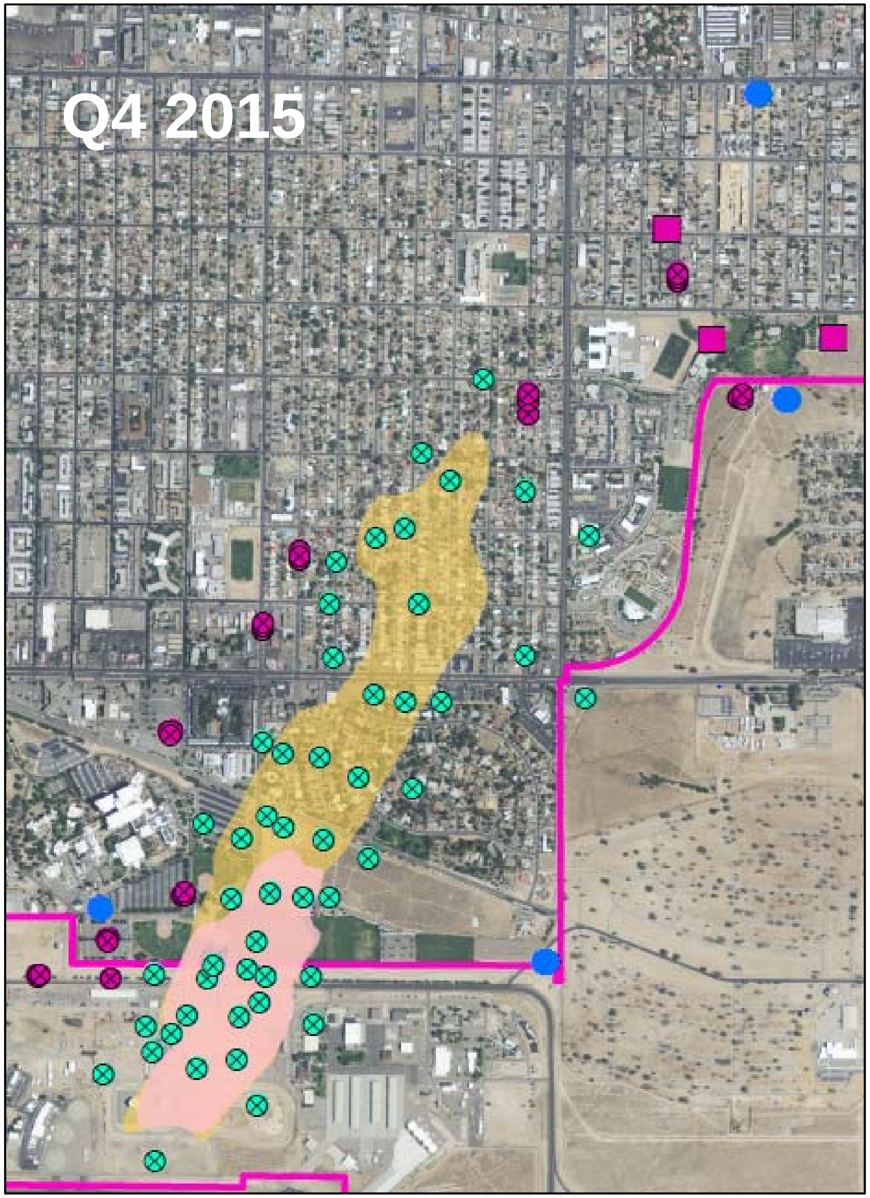
Plume Characterization

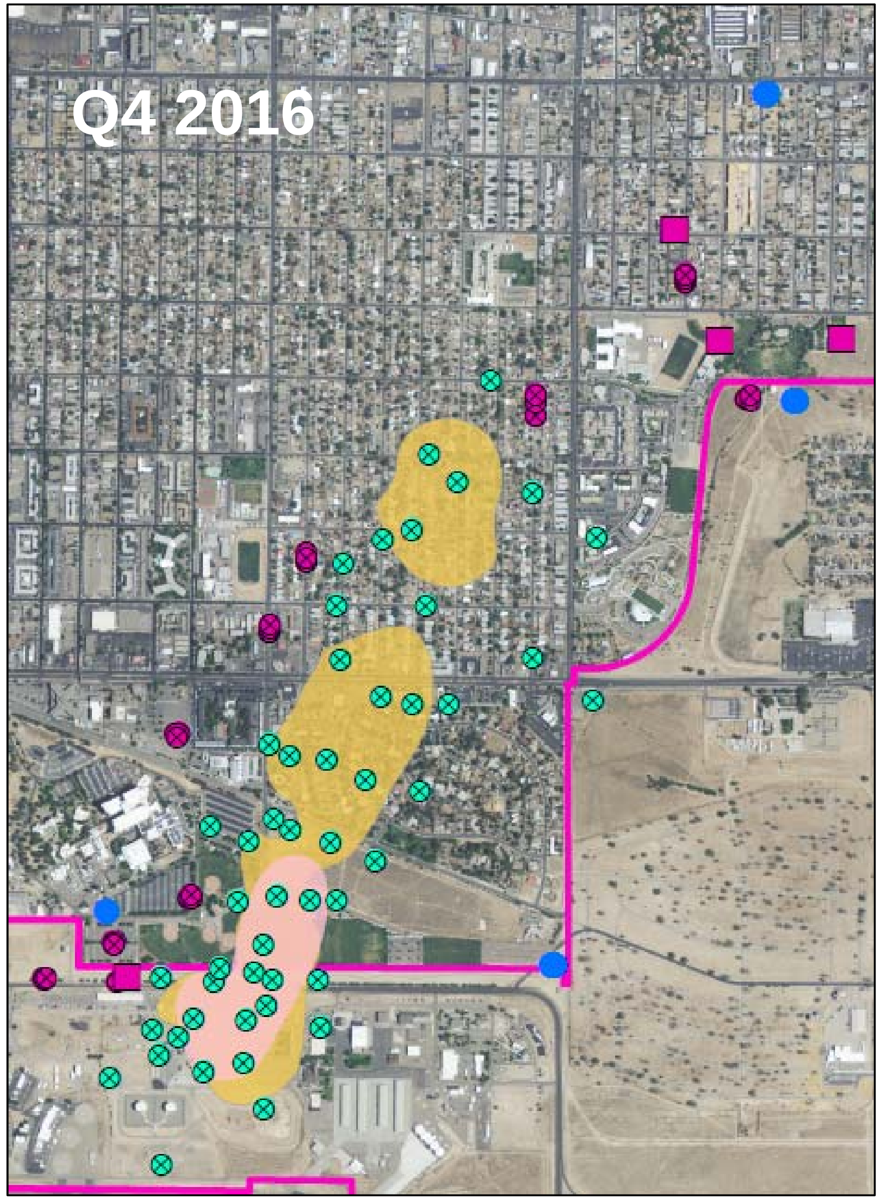
Rio Grande Braided Stream In Albuquerque South Valley



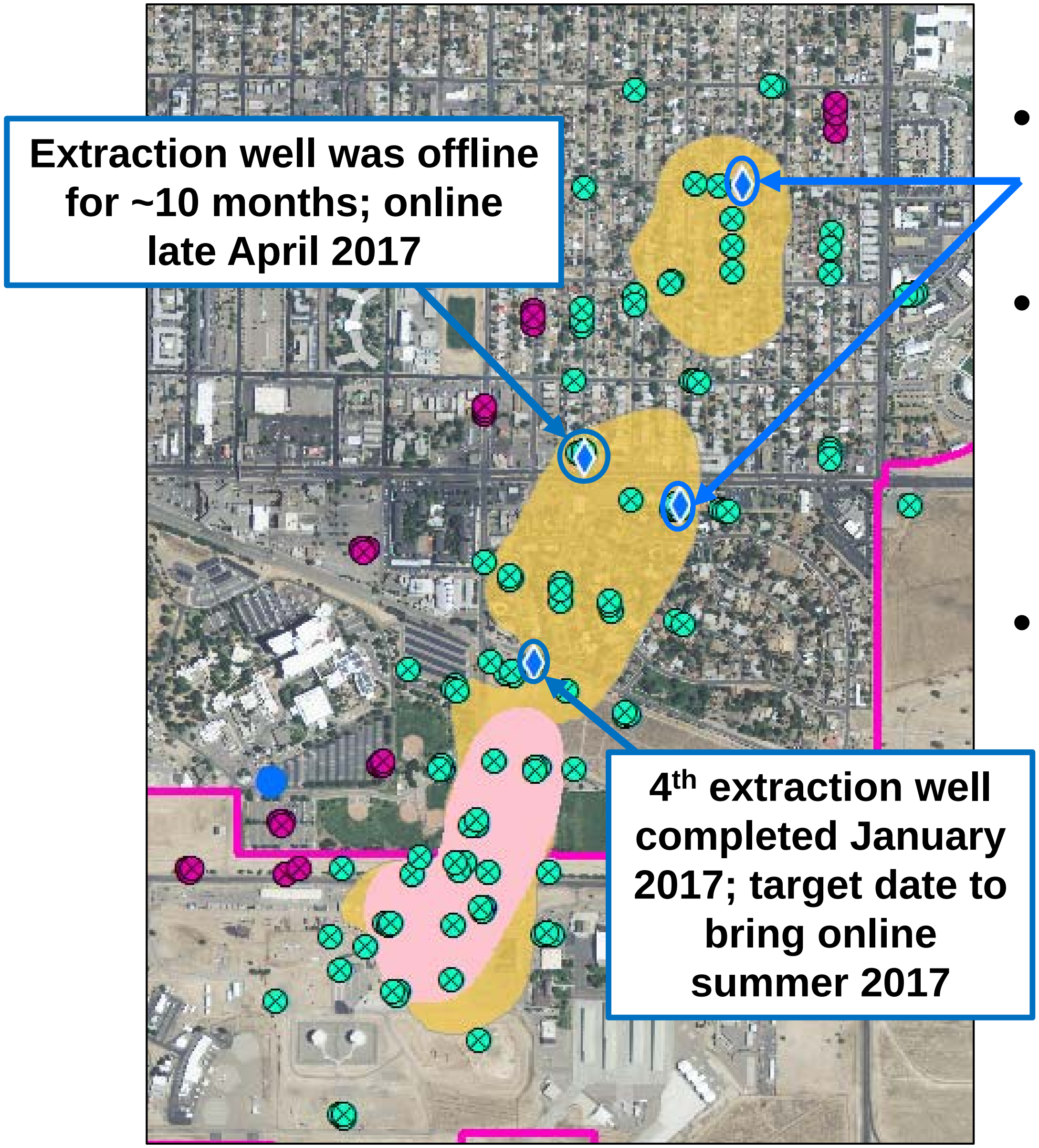


Dissolved Plume Extents





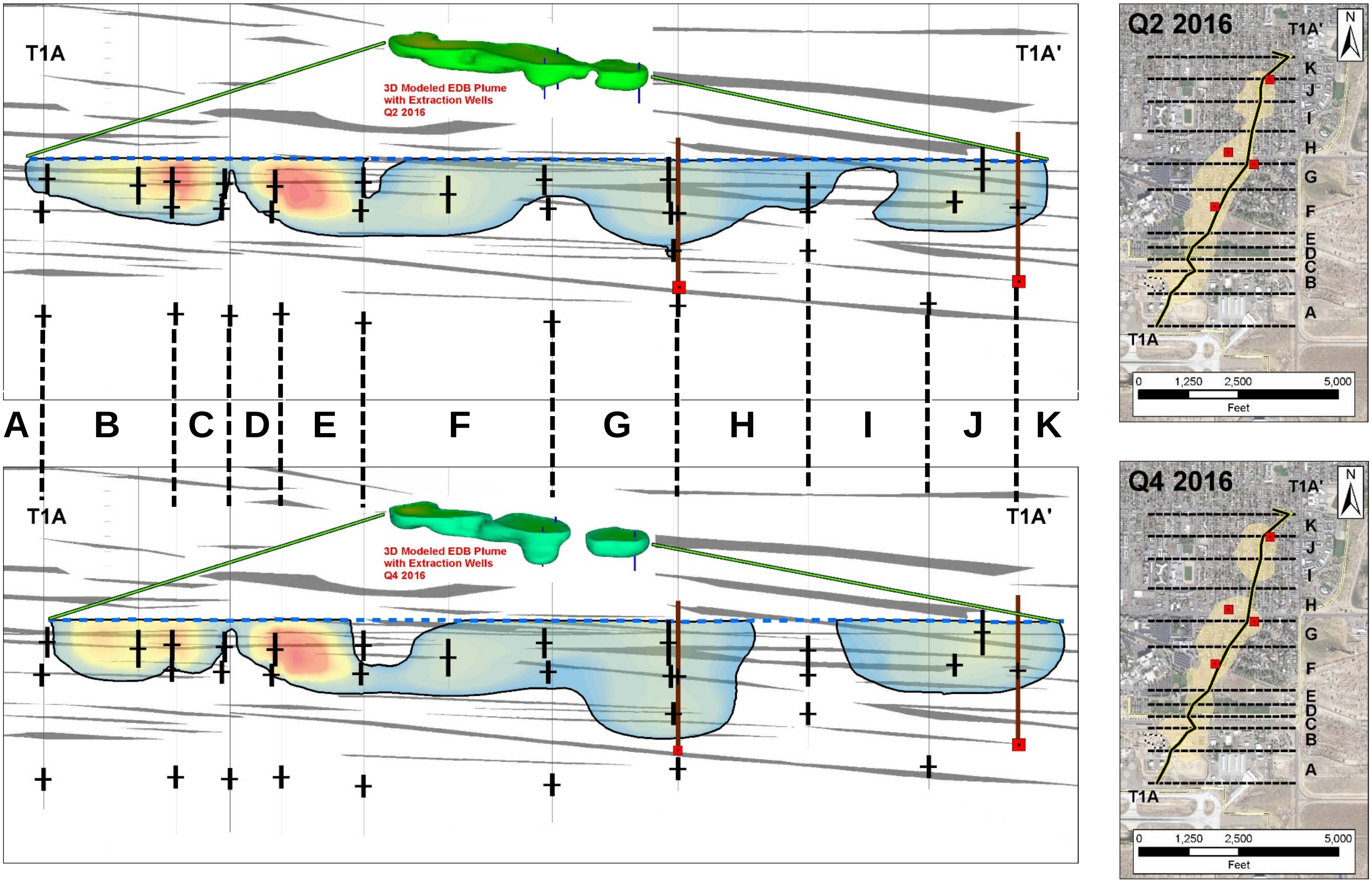
EDB Plume Collapse



- 3 extraction wells operational – total rate of ~450 gpm
- 187.2 million gallons of groundwater has been treated, with 57.7 grams of EDB removed
- EDB maximum contaminant level is 0.05 µg/L

Legend
- Drinking Water Supply Well
- Sentinel Well or Well Nest
- Groundwater Monitoring Well
- Extraction Well
- Q4 2016 Shallow Benzene Plume Footprint
- Q4 2016 Shallow EDB Plume Footprint
- KAFB Base Boundary

EDB Plume Capture



Conclusion

- **Evaluate all data available and leverage to the extent possible**
  - **Understand the strengths and weaknesses**
  - **Determine if specialized disciplines are needed**
  - **Collect more data to enhance CSM strategically**
- **Higher upfront costs can save substantially on the backend of the project**
- **Complex sites need specialized multidiscipline teams to be successful**

Path Forward for Complex Sites

- Sites will be evaluated for appropriate contracting (i.e., PBC, T&M, CPFF, etc.)
- Air Force CSI will evaluate current site conditions and incorporate lessons learned to develop OES performance metrics
- Success at complex sites requires a multidisciplinary approach
- Complex sites must have updated, accurate and complete CSMs to select and design remedial approaches
- Proposals will be reviewed for completeness of approach
  - Applicability of technologies
  - Realistic performance models
  - Appropriateness of performance monitoring (i.e., well network and analytical parameters)

U.S. AIR FORCE

BREAKING BARRIERS

SINCE 1947

AIR FORCE CIVIL ENGINEER CENTER

Adapting Remedial Design to Address Complex Geology

Tamzen W. Macbeth

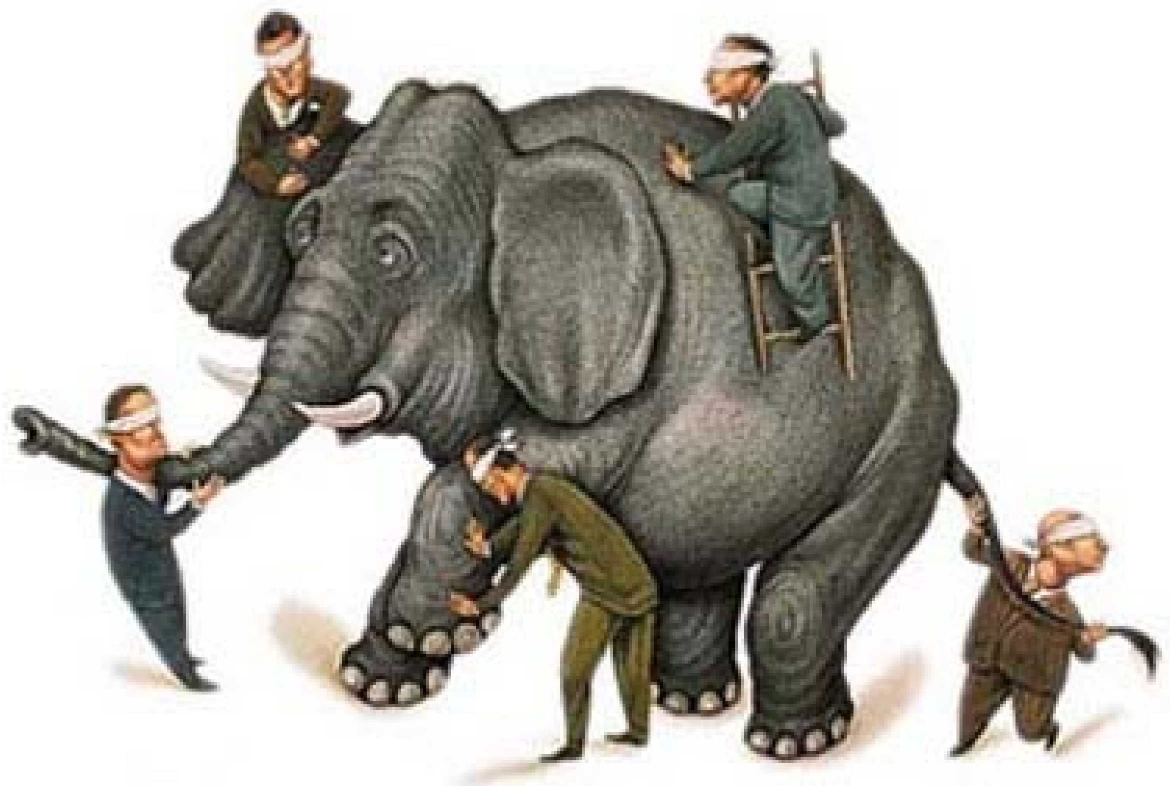
CDM Smith.

Battelle's Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies

Miami, Florida
May 22-25, 2017

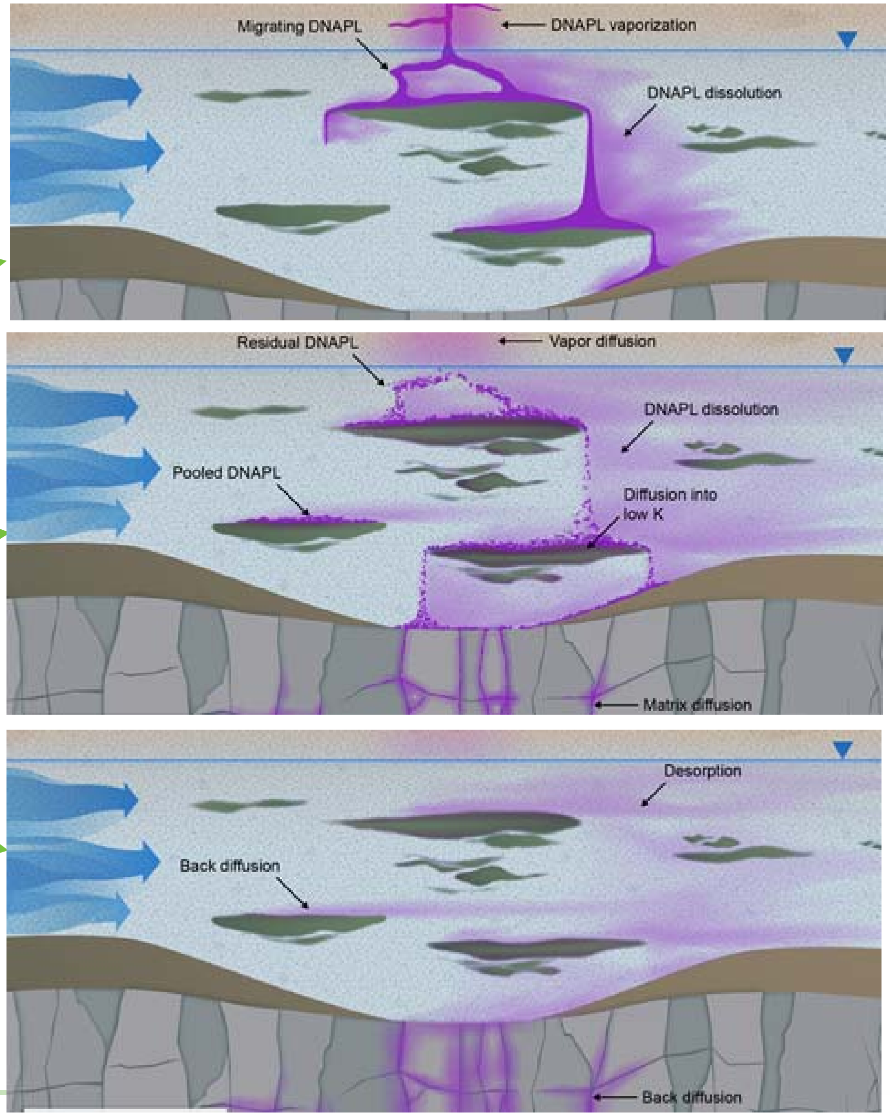
DNAPL Plume Mapping

- Understanding your DNAPL plume



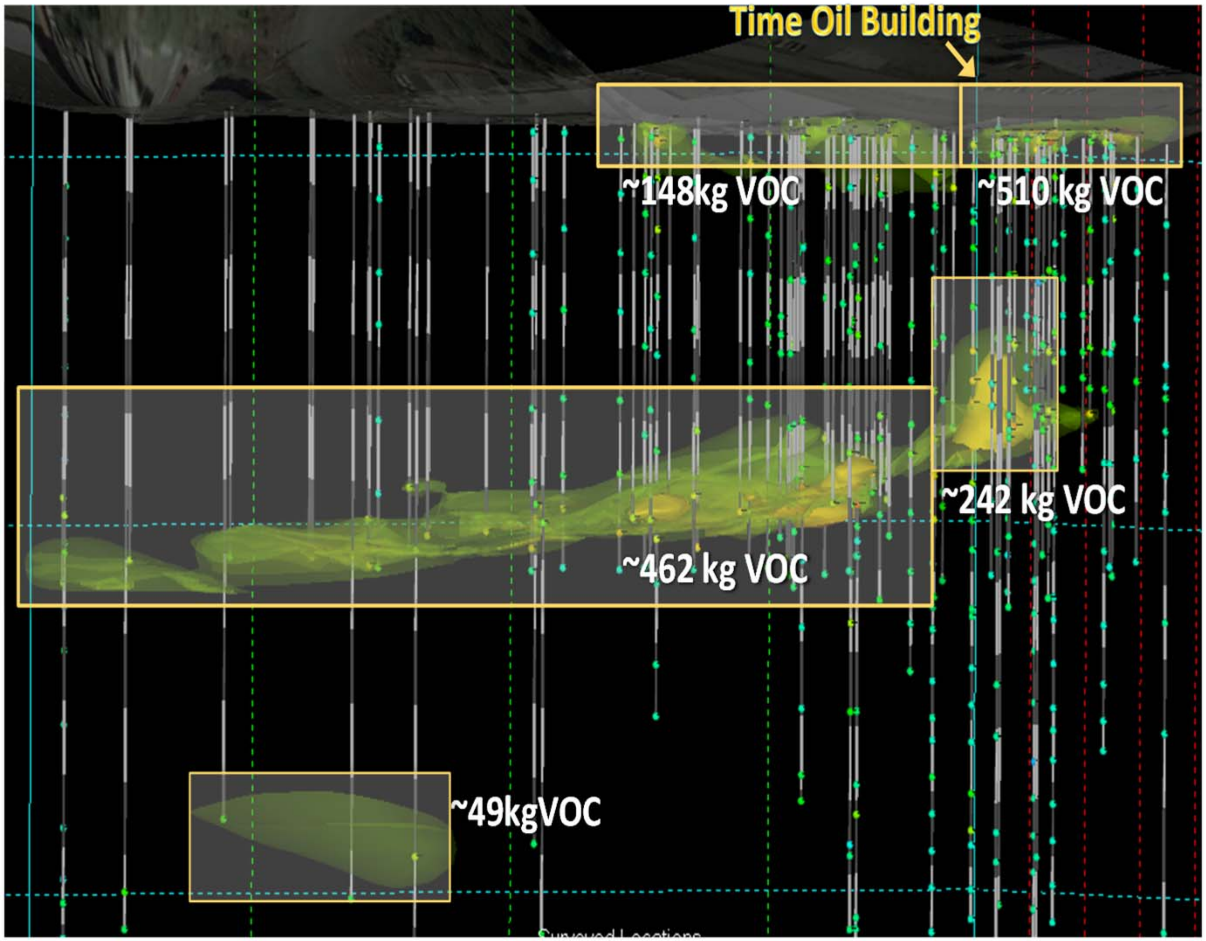
DNAPL Plume Life Cycle

- **Expanding Phase** Early Stage
- **Stable Phase** Middle Stage
- **Shrinking Phase** Late Stage



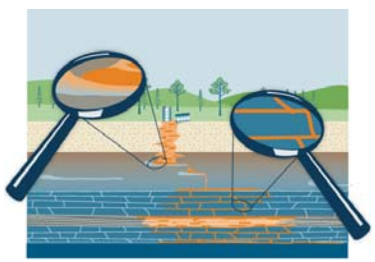
"Toolbox Approach"

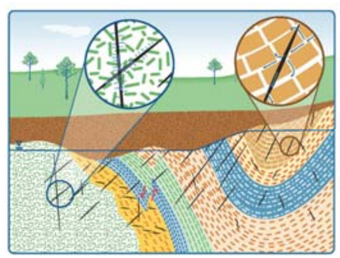
- High Resolution
- Multiple lines of evidence
- Screening tools contaminant mass
- High Resolution Hydraulic Conductivity Profiling
- Soil coring and sampling in high resolution
- On site groundwater and soil analyses by Mobile Lab (GC/MS)
- Modeling tools



ITRC: Characterization Tools

- Intrastate Technology Regulatory Council:
  - Integrated DNAPL Site Characterization and Tools Selection (ISC-1, 2015)
  - Characterization and Remediation of Fractured Rock- Fall 2017
- Contains over **100** tools
- Sorted by:
  - Characterization objective
    - Geology
    - Hydrogeology
    - Chemistry
  - Effectiveness in media
    - Unconsolidated/Bedrock
    - Unsaturated/Saturated
- Ranked by data quality
  - Quantitative
  - Semi-quantitative
  - Qualitative

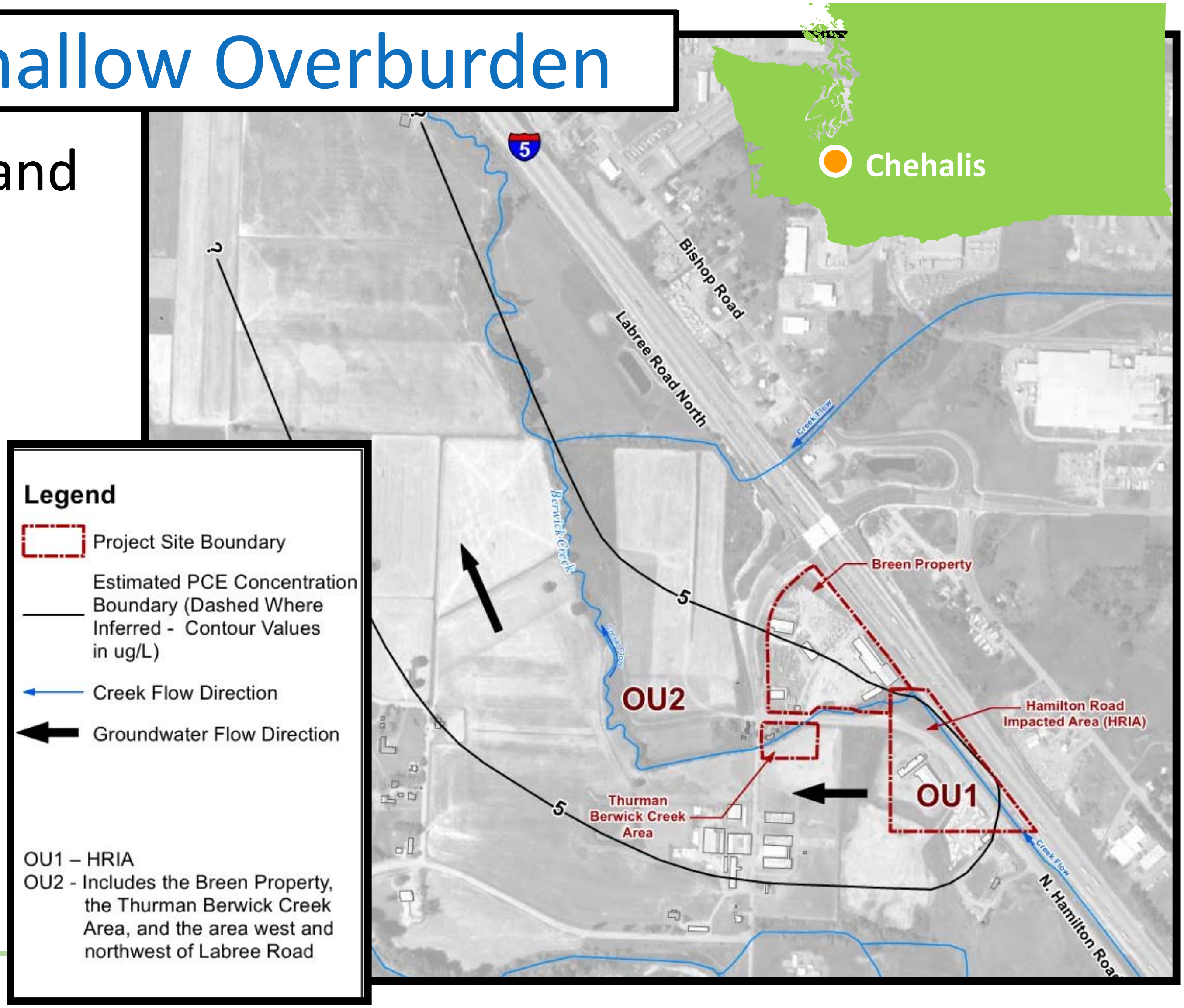




Tool	Data Quality	Sub surface		Zone	
		Bedrock	Unconsolidated	Unsaturated	Saturated
Geophysics					
Surface Geophysics					
Ground Penetrating Radar (GPR)	QL - Q	✓	✓	✓	✓
High Resolution Seismic Reflection (2D or 3D)	QL - Q	✓	✓		✓
Seismic Refraction	QL - Q	✓	✓	✓	✓
Multi-Channel Analyses of Surface Waves (MASW)	QL - Q	✓	✓	✓	✓
Electrical Resistivity Tomography (ERT)	QL - SQ	✓	✓	✓	✓
Very Low Frequency (VLF)	QL	✓	✓	✓	✓
ElectroMagnetic (EM) Conductivity	QL	✓	✓	✓	✓
Downhole Testing					
Magnetometric Resistivity	QL	✓	✓		✓
Induction Resistivity (Conductivity Logging)	QL - Q	✓	✓	✓	✓
Resistivity (Elog)	QL - SQ	✓			✓
GPR Cross-Well Tomography	QL - Q	✓	✓	✓	✓
Optical Televiewer	QL - Q	✓	✓	✓	✓
Acoustic Televiewer	QL - Q	✓			✓
Natural Gamma Log	QL - Q	✓	✓	✓	✓
Neutron (porosity) Logging	QL - Q	✓	✓		✓
Nuclear Magnetic Resonance Logging	QL - Q	✓	✓	✓	✓
Video Log	QL - SQ	✓	✓	✓	✓
Caliper Log	QL - Q	✓	✓	✓	✓
Temperature Profiling	QL - Q	✓	✓		✓
Full Wave Form Seismic	Q - QL	✓			✓

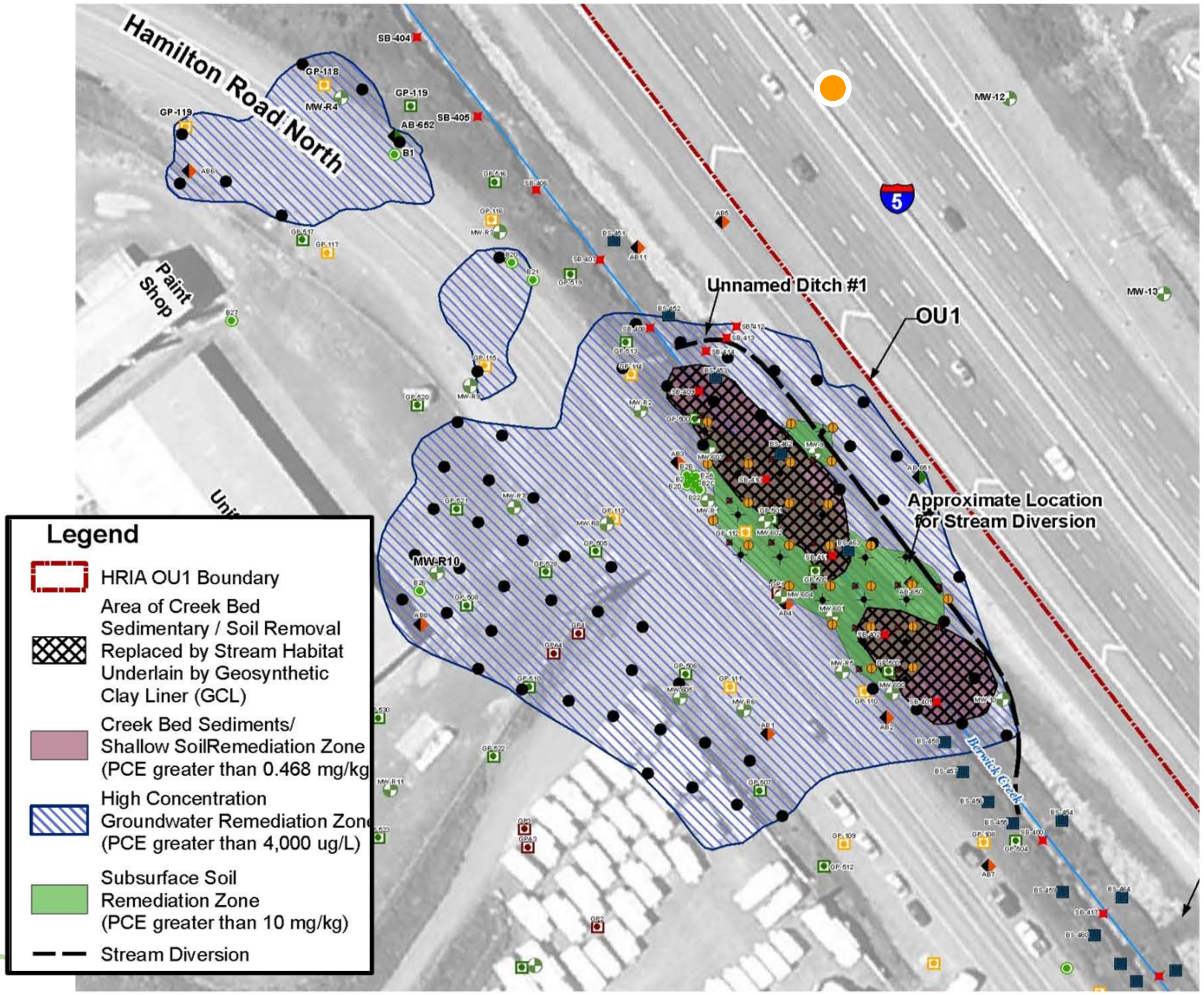
Case Study #1: Shallow Overburden

- Large (1-mile) PCE and TCE 1 -Impacting 6 Private Wells
- Multiple potential sources
- Most significant is thought to be OU1



Summary of OU1 Remedy

- PCE DNAPL Dump in Creek Bed.
- Thermal Treatment for DNAPL Removal
- Bioremediation for High Concentration Plume
- Remove DNAPL and Reduce Mass Discharge by 90%

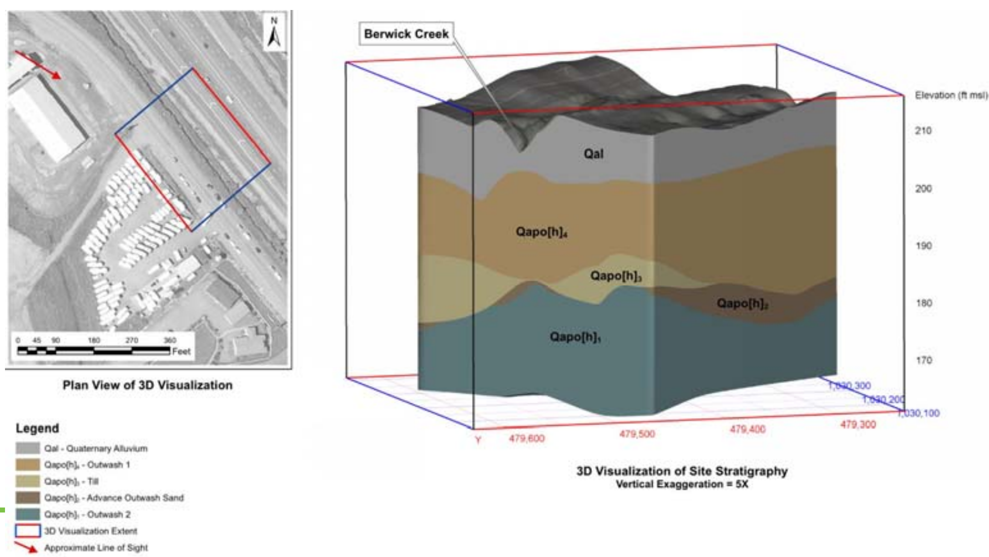


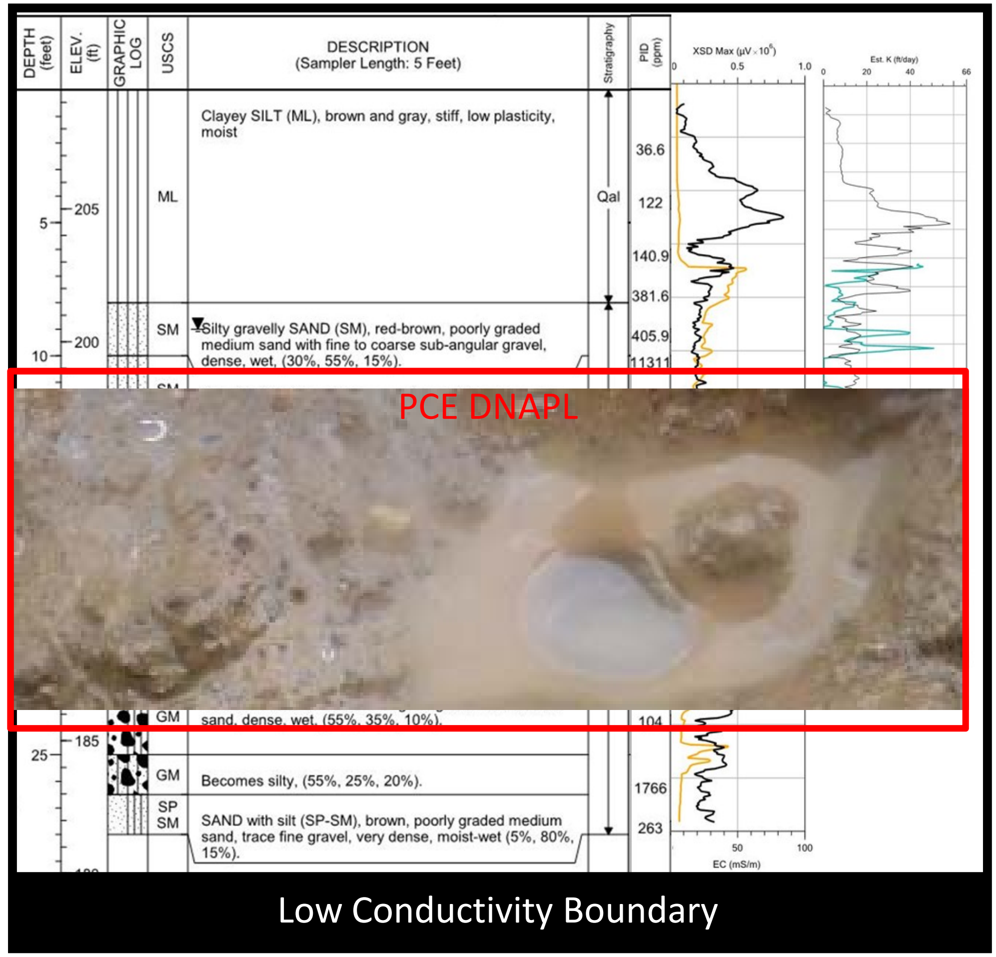
DNAPL and Plume Delineation

- 38 MiHPT Borings
  - 7 angled borings
- 14 Confirmation Soil Borings
- Groundwater transects with 12 borings for temporary grab groundwater samples.

Real-Time Data

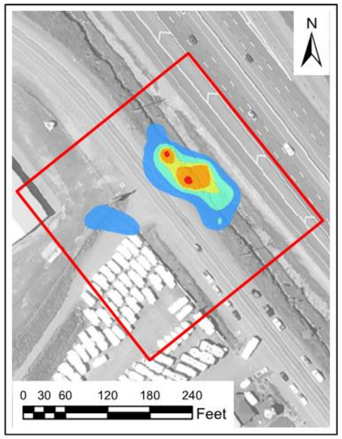
- ECD/XSD- PCE
- PID/FID- gross detectors for volatiles
- EC- lithology
- HPT- conductivity estimate
- Soil logging and sampling

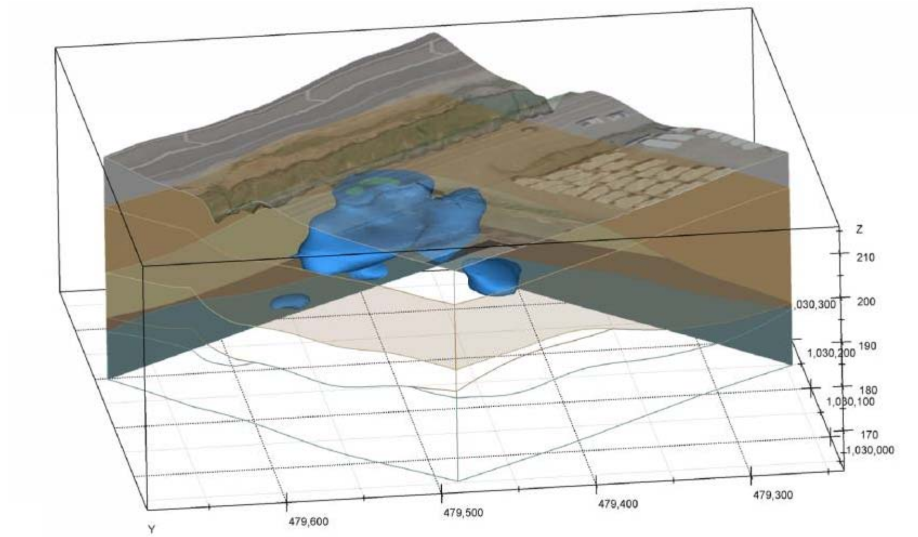




Distribution of Soil Mass

Notes:
Visualization of PCE extent was kriged in Ctech's MVS. The outline of PCE above 10 mg/kg is a 2D maximum extent for each geologic unit created from the 3D volume. Vertical exaggeration for 3D view is 3X.





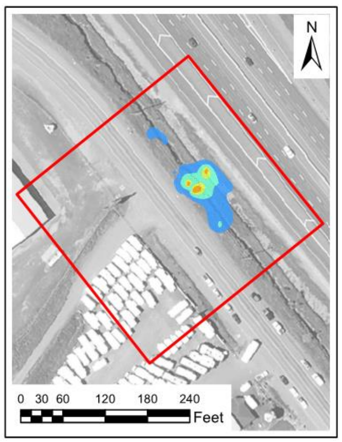
Legend

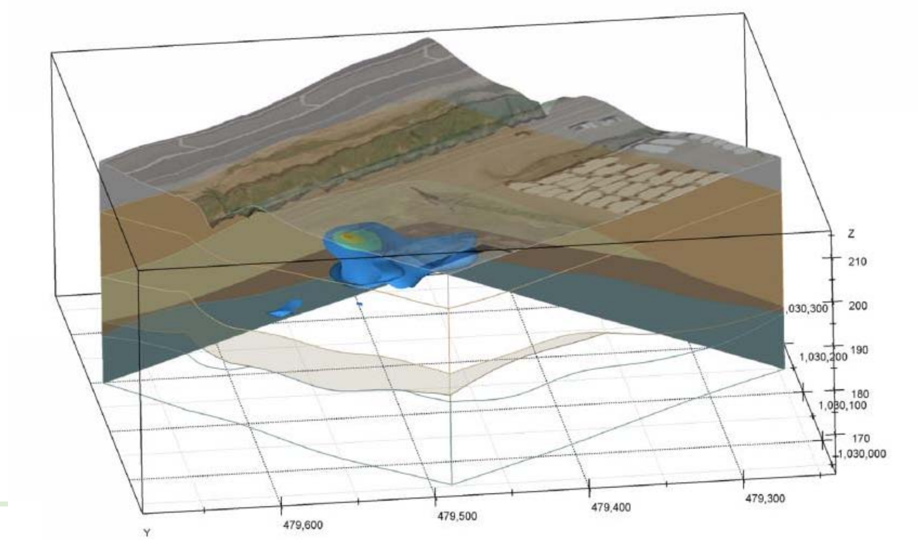
Kriged 2D Maximum - PCE

- 10 - 100 mg/kg
- 100 - 500 mg/kg
- 500 - 1,000 mg/kg
- 1,000 - 5,000 mg/kg
- > 5,000 mg/kg

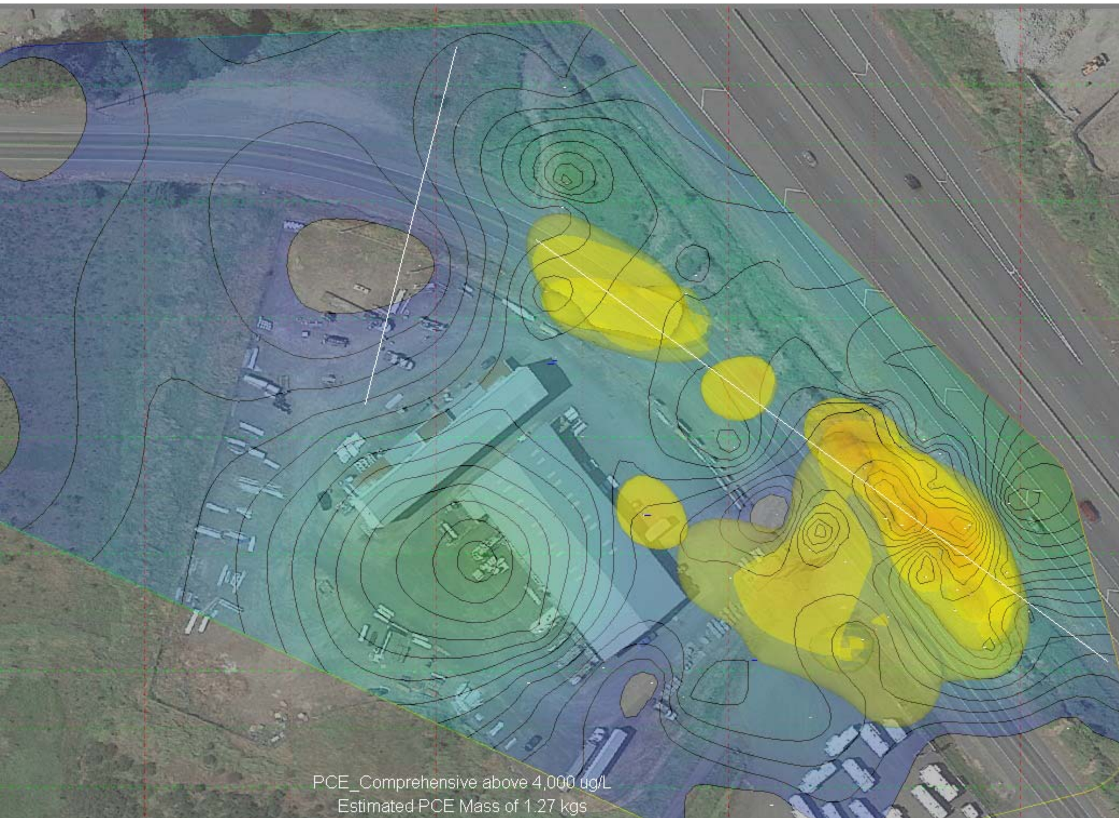
Geologic Interpretation

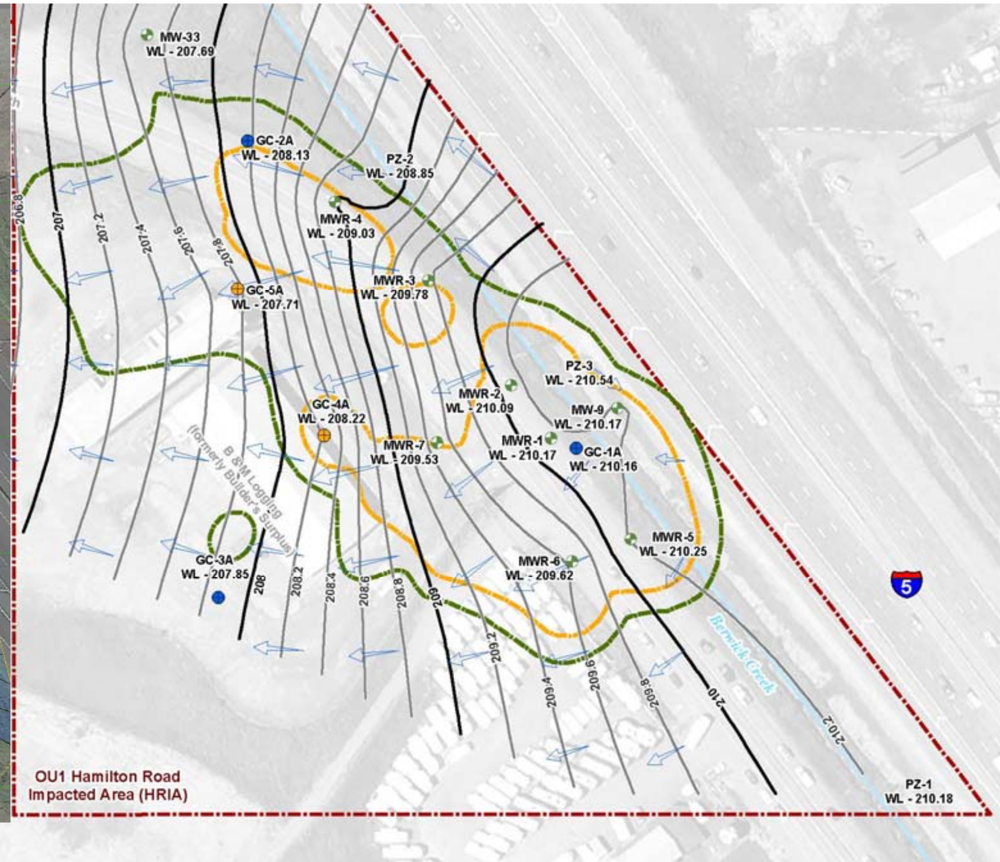
- Qal - Quaternary Alluvium
- Qapo[h]$_4$ - Outwash 1
- Qapo[h]$_3$ - Till
- Qapo[h]$_2$ - Advance Outwash Sand
- Qapo[h]$_1$ - Outwash 2
- 3D Display Extent



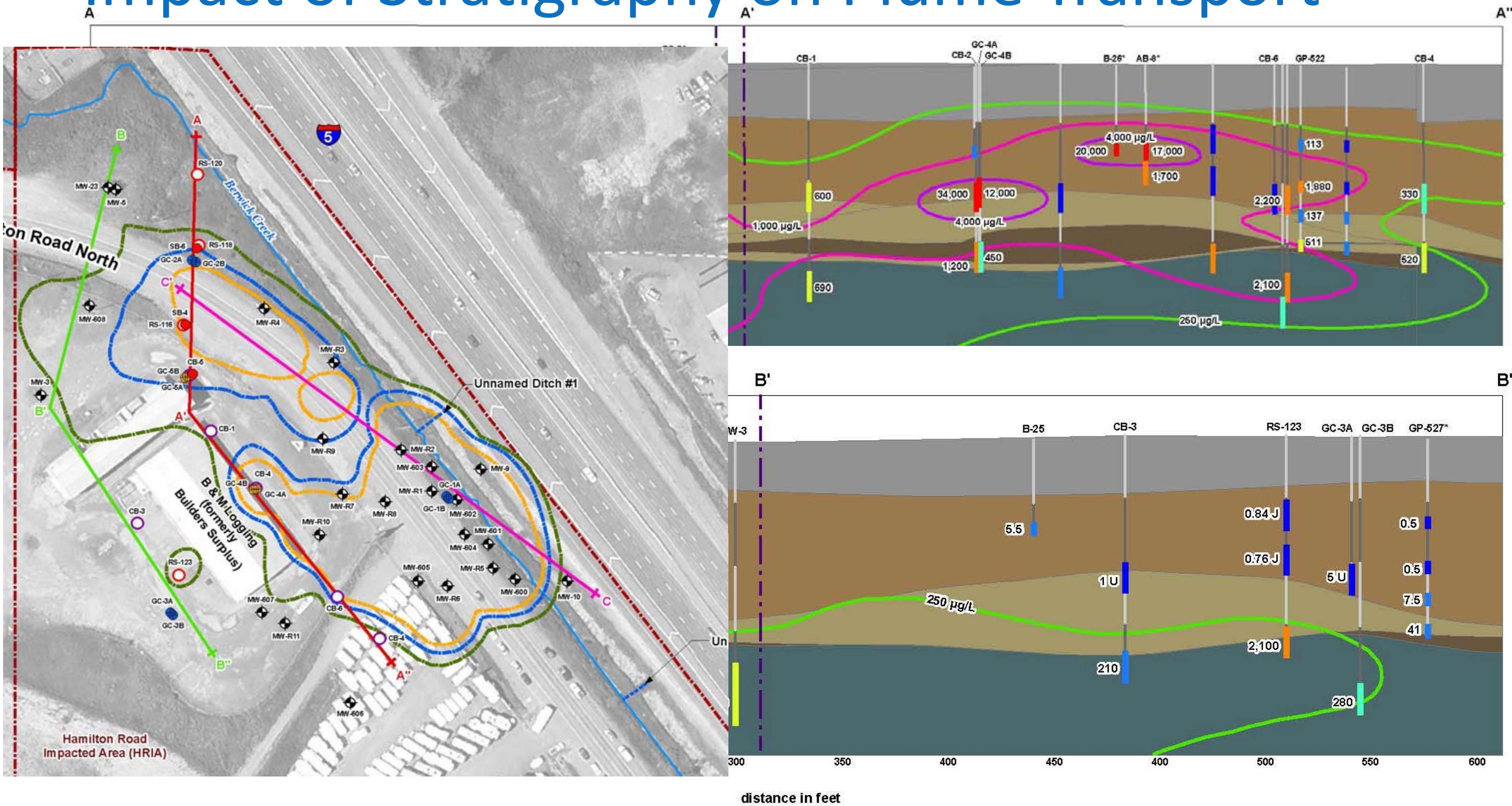


Impact of Stratigraphy on Groundwater flow





Impact of Stratigraphy on Plume Transport



Impact of Stratigraphy on Plume Transport

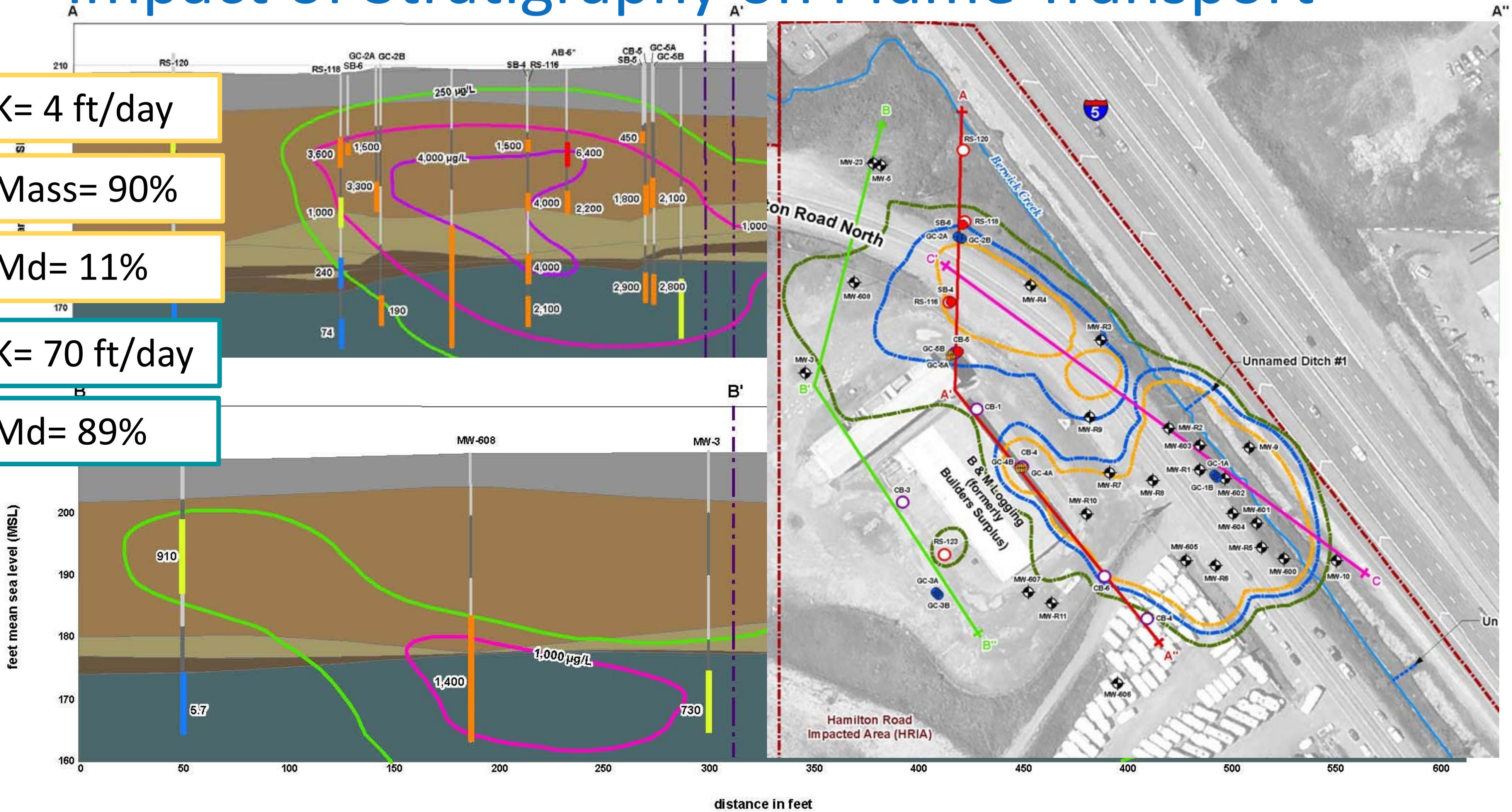
K= 4 ft/day

Mass= 90%

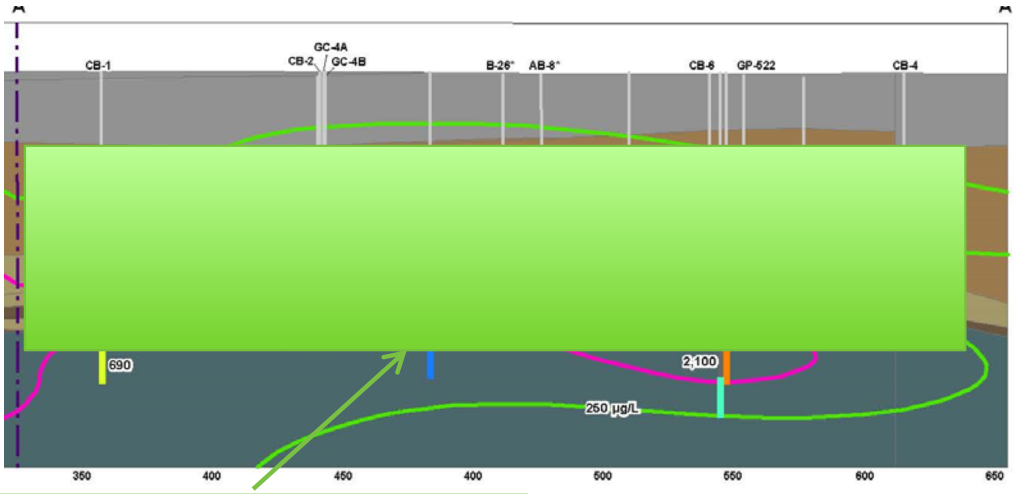
Md= 11%

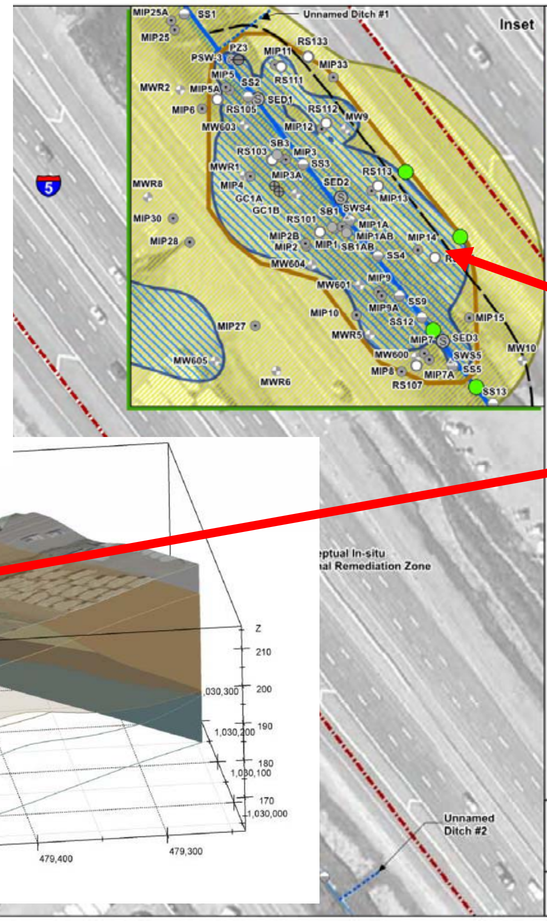
K= 70 ft/day

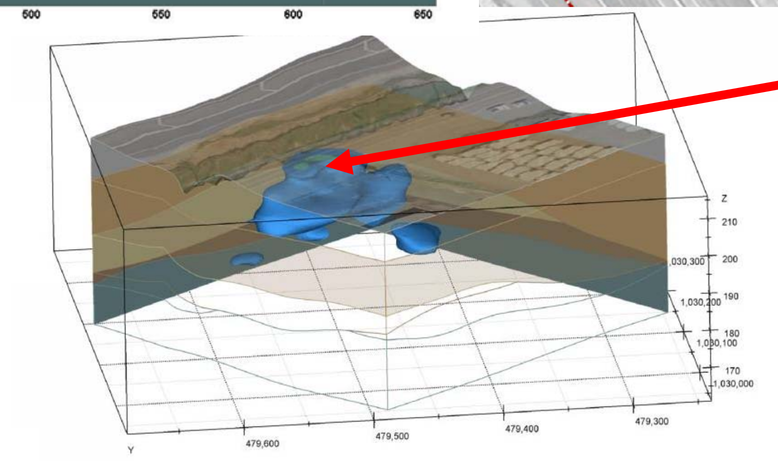
Md= 89%



Refined Treatment Zones: ISTR





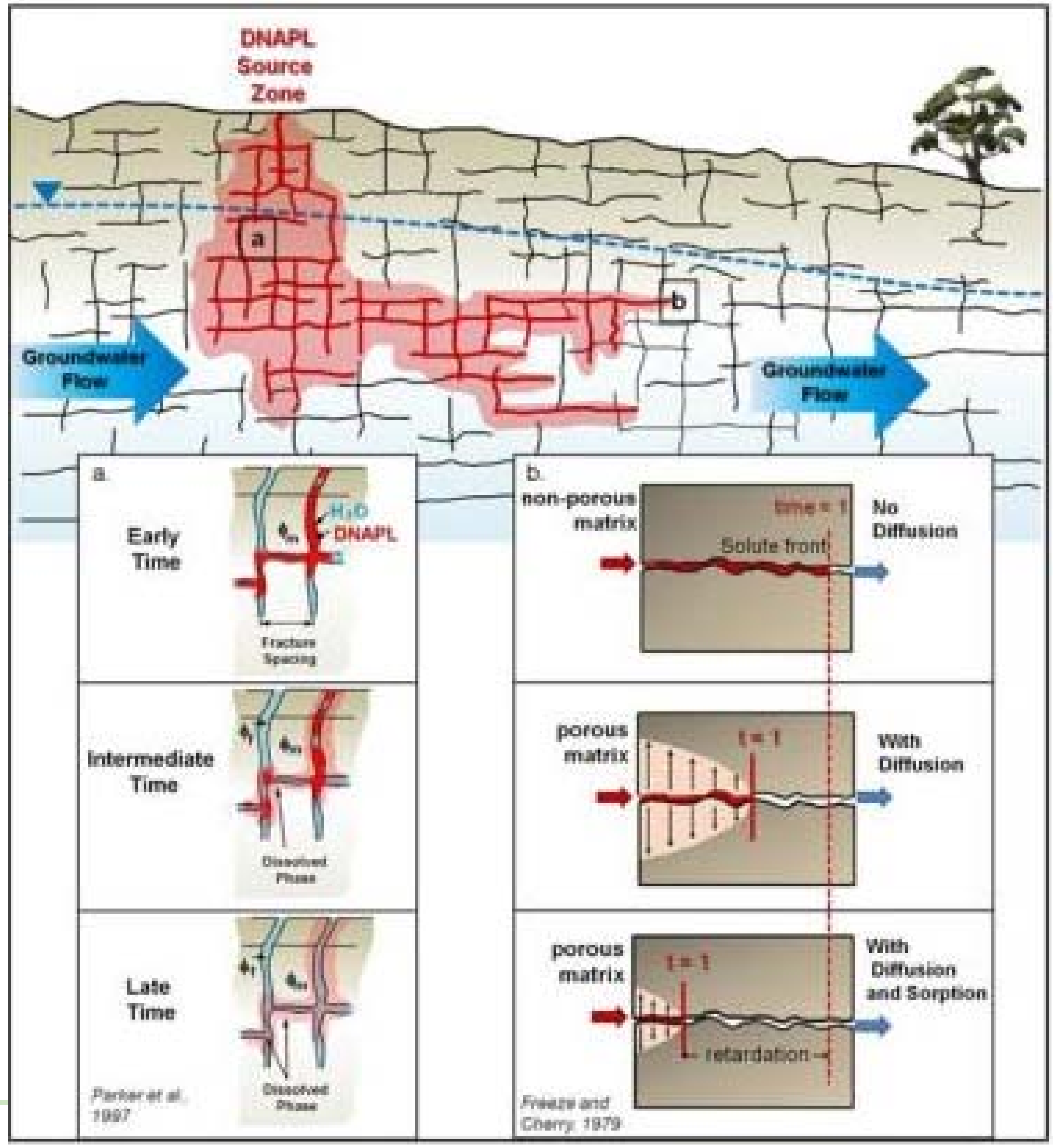


Instead of a 45 foot vertical interval for groundwater treatment- focus on 20 feet where majority (i.e. 90%) of plume conveyed.

Expanded thermal treatment zone laterally but reduced the vertical treatment interval from 15 m to 8m - reduced volume by 30%.

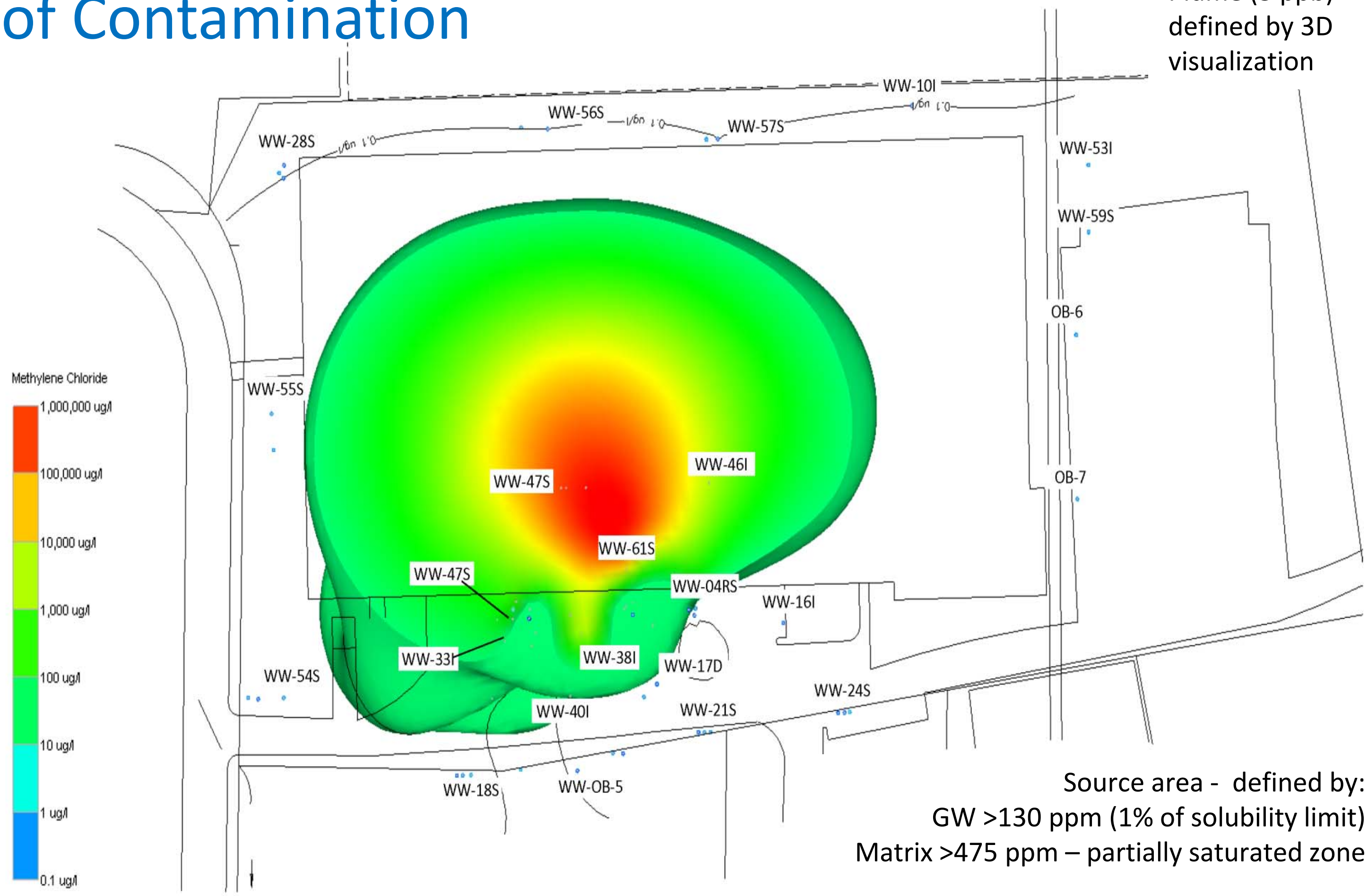
Case Study #3: Fractured Rock

- Pharmaceutical manufacturing facility from 1976 to 2005
- Discharge of dichloromethane (DCM) in mid-1980's
- GW P&T system operation from 1995 to 2009
- Shutdown in 2009 under NJDEP approved "biodegradation" pilot study
- Recovered ~4,600 lbs DCM (equivalent of >400 gallons)
- Concentrations are 7 orders of magnitude above cleanup level



Extent of Contamination

Plume (3 ppb) - defined by 3D visualization



Source area - defined by:
GW >130 ppm (1% of solubility limit)
Matrix >475 ppm – partially saturated zone

Advanced Characterization Tools to Develop CSM

Informational Need	Characterization Tool
Evaluate Secondary Source-Contaminant Diffusion in Rock Matrix	***Rock core analysis and diffusion modelling***
Evaluate Contaminant Flux and Groundwater Flux in Transmissive Fracture Zones	***Passive Flux Meter (PFM) and Hydraulic and Contaminant Transport Modelling***
Evaluate Contaminant Biodegradation in the Source and Plume-	Compound Specific Isotope Analysis (CSIA)
Evaluate Contaminant Biodegradation in the Source and Plume-	Microbial Metagenomics

Rock Core Analysis Program

1. Collected 277 bedrock matrix core samples
   a) Initially focus on historical GW treatment zone
   b) Sampled depths from 6 to 72 ft BGS
   c) Analyzed DCM concentration in all cores
      - Analyzed a subset for bulk density, porosity, and organic carbon to calculate porewater concentrations.
2. Delineated source area and high concentration plume horizontally and vertically
   a) Advanced along bedding plane from the historical UST leak (original source)
   b) Consistent with regional fractured bedrock strike and dip

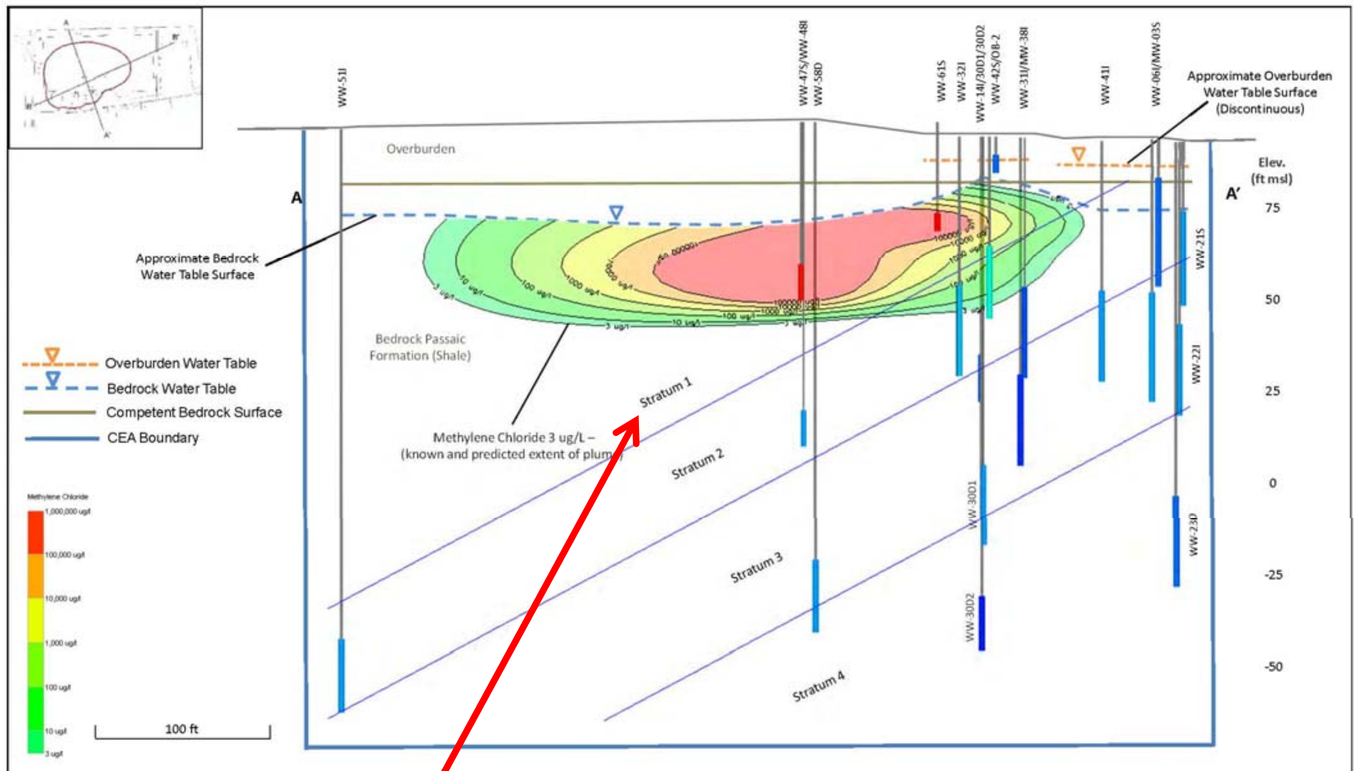
Site Geology

Shale Bedrock – primary permeability low to negligible

Layered sedimentary rock – layers (beds) dip gently northwest

Fractures along bedding and also higher angle fractures aligned northeast and northwest

Groundwater flows in fractures but low yielding

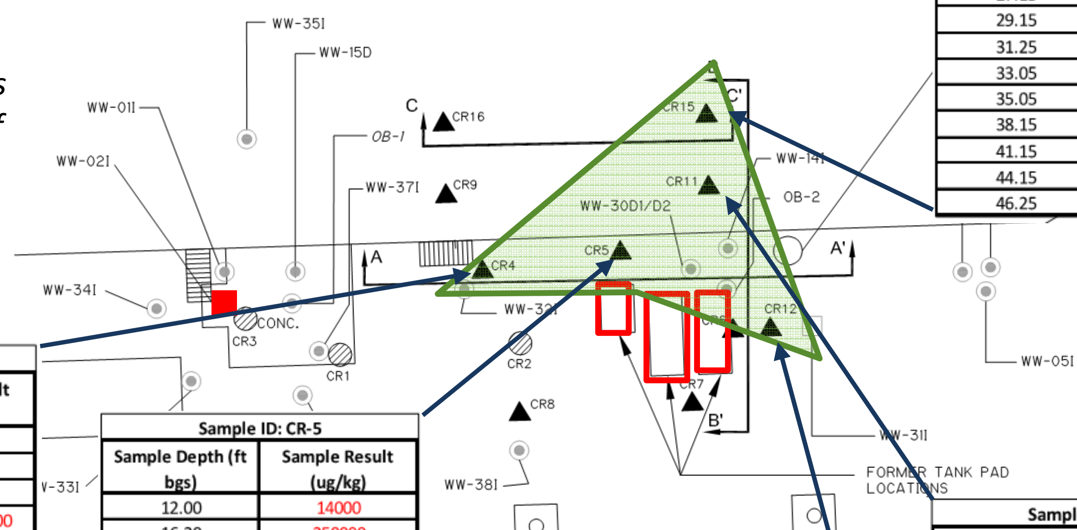


Estimated Seepage Velocity: ~600 - 1900 ft/year in Stratum 1 contaminant zone

DCM Concentrations in Rock Cores

The 5 highest rock core concentrations are north & west of former USTs

CR 11, 15, 4, 5 & 12



Sample ID: CR-15	
Sample Depth (ft bgs)	**Sample Result (ug/kg)**
6.25	ND (33)
11.25	7.9J
16.20	16J
20.85	640000
23.25	820000
25.25	880000
27.15	610000, 360000
29.15	350000
31.25	550000, 380000
33.05	380000
35.05	140000
38.15	3700
41.15	82000
44.15	210
46.25	130

Sample ID: CR-4	
Sample Depth (ft bgs)	**Sample Result (ug/kg)**
12.00	ND (51)
16.00	ND (40)
20.00	50000
26.00	770000, 780000
28.00	140000
30.00	210000
32.00	120000
34.00	67000
35.00	2100
37.00	15J
38.80	1400
42.00	19J
45.00	ND (30)
48.00	250
50.20	ND (24)

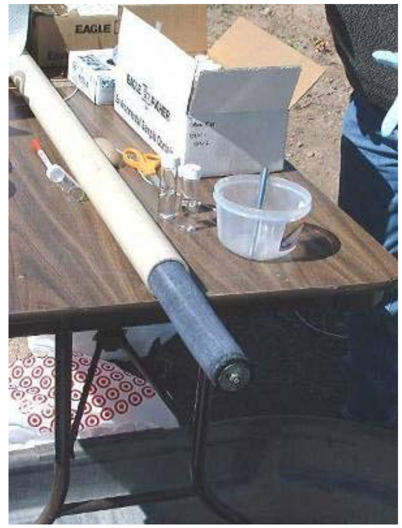
Sample ID: CR-5	
Sample Depth (ft bgs)	**Sample Result (ug/kg)**
12.00	14000
16.20	250000
20.30	540000
22.00	720000, 630000
26.00	410000
28.00	390000
30.00	330000
32.00	570000
33.80	1100
36.00	57
38.00	50
40.00	ND (29)
40.40	ND (26)

Sample ID: CR-12	
Sample Depth (ft bgs)	**Sample Result (ug/kg)**
10.00	ND (27)
15.00	ND (36)
20.00	2000, 5600
25.10	460000
29.90	250
35.00	16J
39.60	15J

Sample ID: CR-11	
Sample Depth (ft bgs)	**Sample Result (ug/kg)**
6.25	ND(29)
11.25	33000
16.25	2200
21.25	1100000
22.25	620000
26.65	510000
31.50	350000
36.45	110
41.15	ND (37)

Passive Flux Meter Deployment

- "One stop shop" for both flow and concentration
- Obtain high resolution profiles of groundwater velocity and contaminant flux within boreholes.
- Map fracture zones with high contaminant mass flux.
- Integrated with rock matrix data to evaluate matrix diffusion.



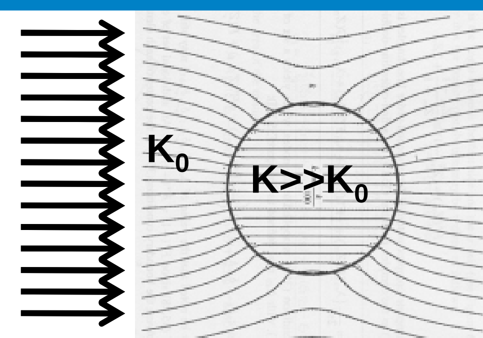
Vendor:
http://www.enviroflux.com/

Sampling

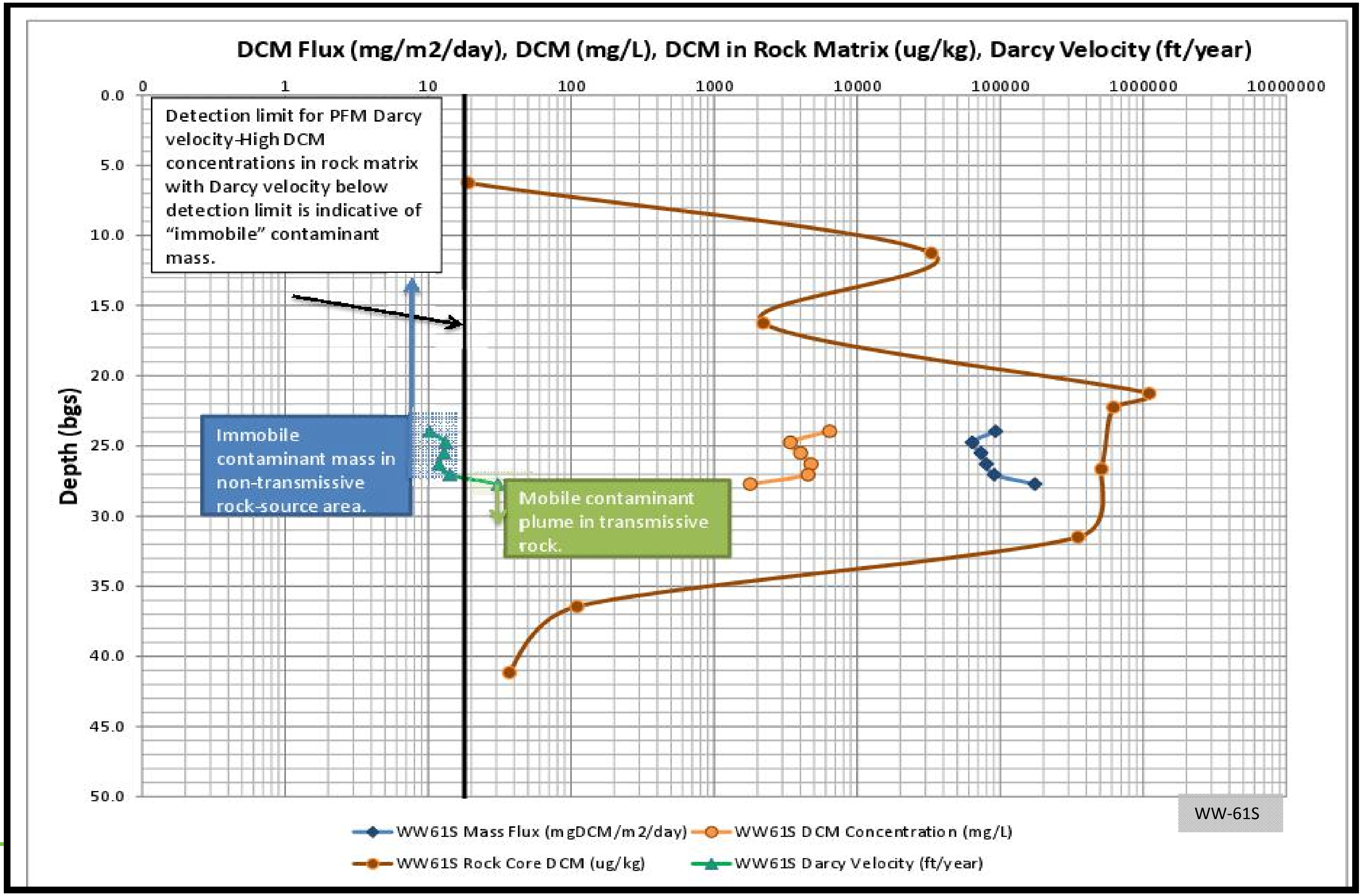
1. Contaminant adsorbed onto passive flux meter over time to get Concentration

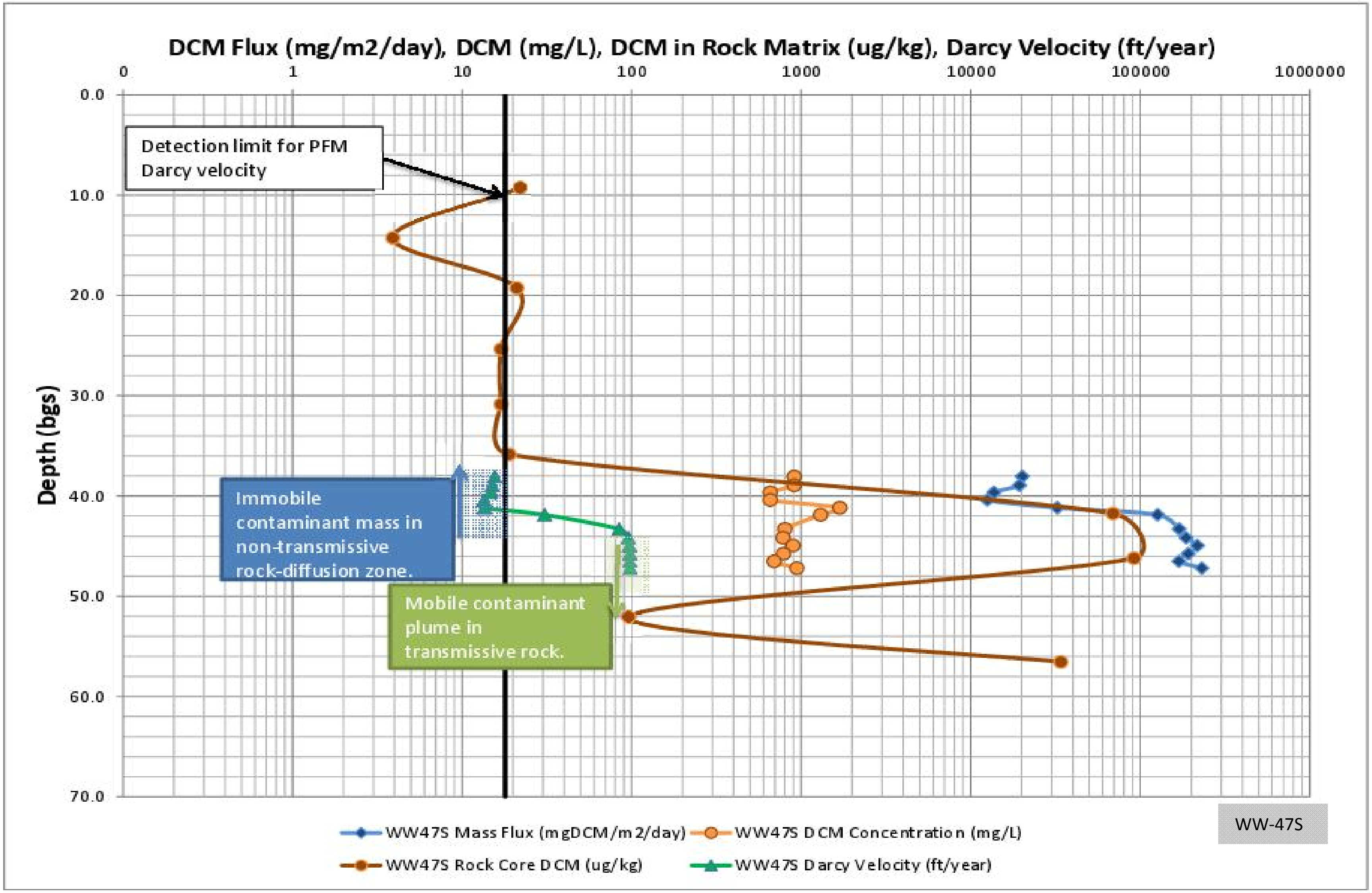
Photo: Dye intercepted in a meter

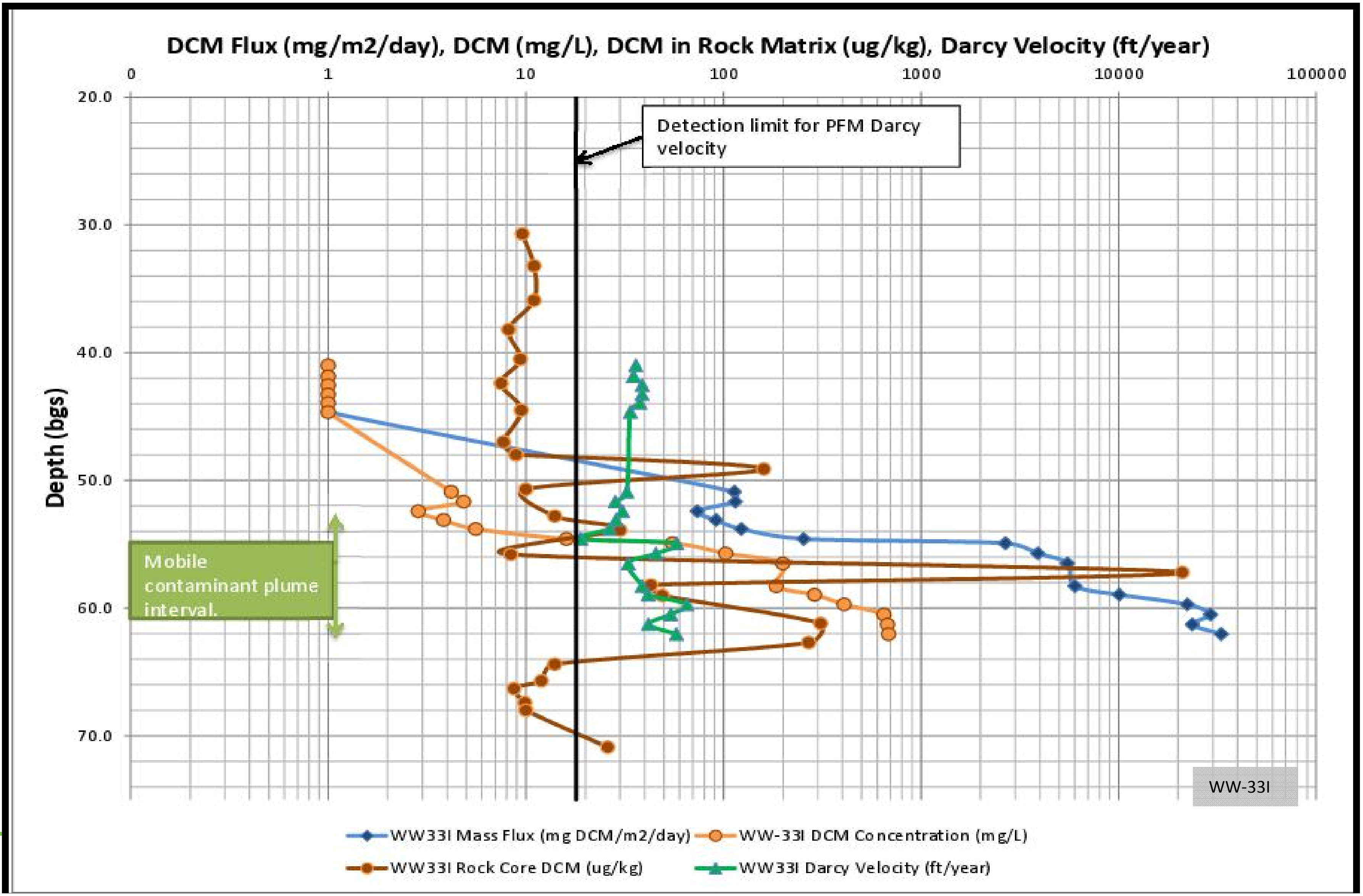
2. Tracer desorbs from passive flux meter to get Flow (Q)



Groundwater Flowlines


DCM Flux (mg/m2/day), DCM (mg/L), DCM in Rock Matrix (ug/kg), Darcy Velocity (ft/year)
0
1
10
100
1000
10000
100000
1000000
10000000
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Depth (bgs)
Detection limit for PFM Darcy velocity-High DCM concentrations in rock matrix with Darcy velocity below detection limit is indicative of "immobile" contaminant mass.
Immobile contaminant mass in non-transmissive rock-source area.
Mobile contaminant plume in transmissive rock.
WW-61S
WW61S Mass Flux (mgDCM/m2/day)
WW61S DCM Concentration (mg/L)
WW61S Rock Core DCM (ug/kg)
WW61S Darcy Velocity (ft/year)


DCM Flux (mg/m2/day), DCM (mg/L), DCM in Rock Matrix (ug/kg), Darcy Velocity (ft/year)
0
1
10
100
1000
10000
100000
1000000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Depth (bgs)
Detection limit for PFM Darcy velocity
Immobile contaminant mass in non-transmissive rock-diffusion zone.
Mobile contaminant plume in transmissive rock.
WW47S Mass Flux (mgDCM/m2/day)
WW47S DCM Concentration (mg/L)
WW47S Rock Core DCM (ug/kg)
WW47S Darcy Velocity (ft/year)
WW-47S



DCM Flux (mg/m2/day), DCM (mg/L), DCM in Rock Matrix (ug/kg), Darcy Velocity (ft/year)
0
1
10
100
1000
10000
100000
20.0
30.0
40.0
50.0
60.0
70.0
Depth (bgs)
Detection limit for PFM Darcy velocity
Mobile contaminant plume interval.
WW-33I
WW33I Mass Flux (mg DCM/m2/day)
WW-33I DCM Concentration (mg/L)
WW33I Rock Core DCM (ug/kg)
WW33I Darcy Velocity (ft/year)

Summary

1. Rock core analyses delineated non-mobile DNAPL mass source in rock matrix
2. PFMs determined mass flux and GW velocities at discrete fracture zones responsible for advective transport
3. CSIA used to demonstrate DCM biodegradation mechanism
4. Metagenomics identified DCM degrading genes/organisms consistent with CSIA conclusions
5. Data from the advanced characterization techniques support TI for source area and MNA for dissolved phase plume

Collaborators

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