An Overview of the Fundamentals of Sequence Stratigraphy and its Application to Developing Robust Conceptual Site Models and Remedial Strategies

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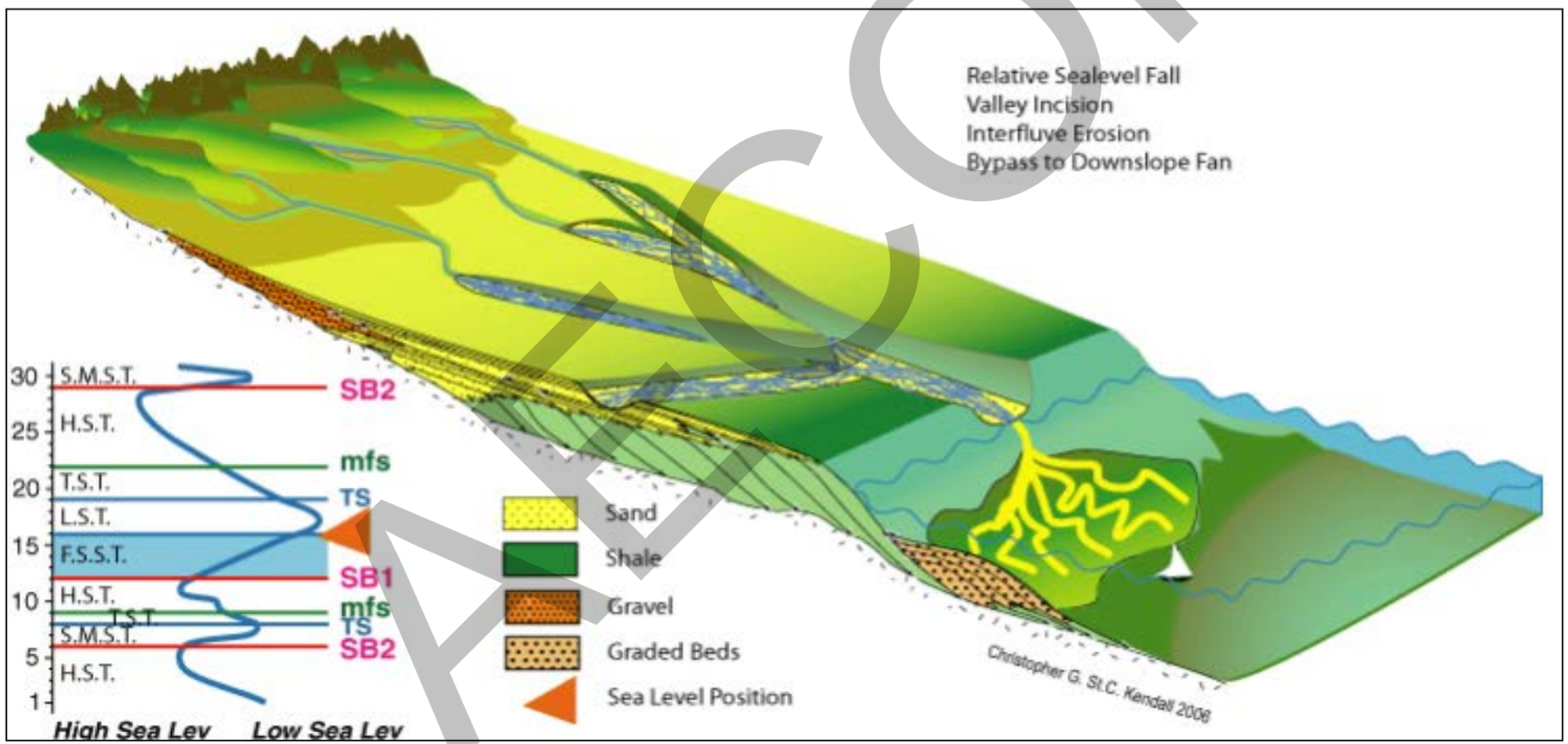


January 15th, 2020

Course Outline

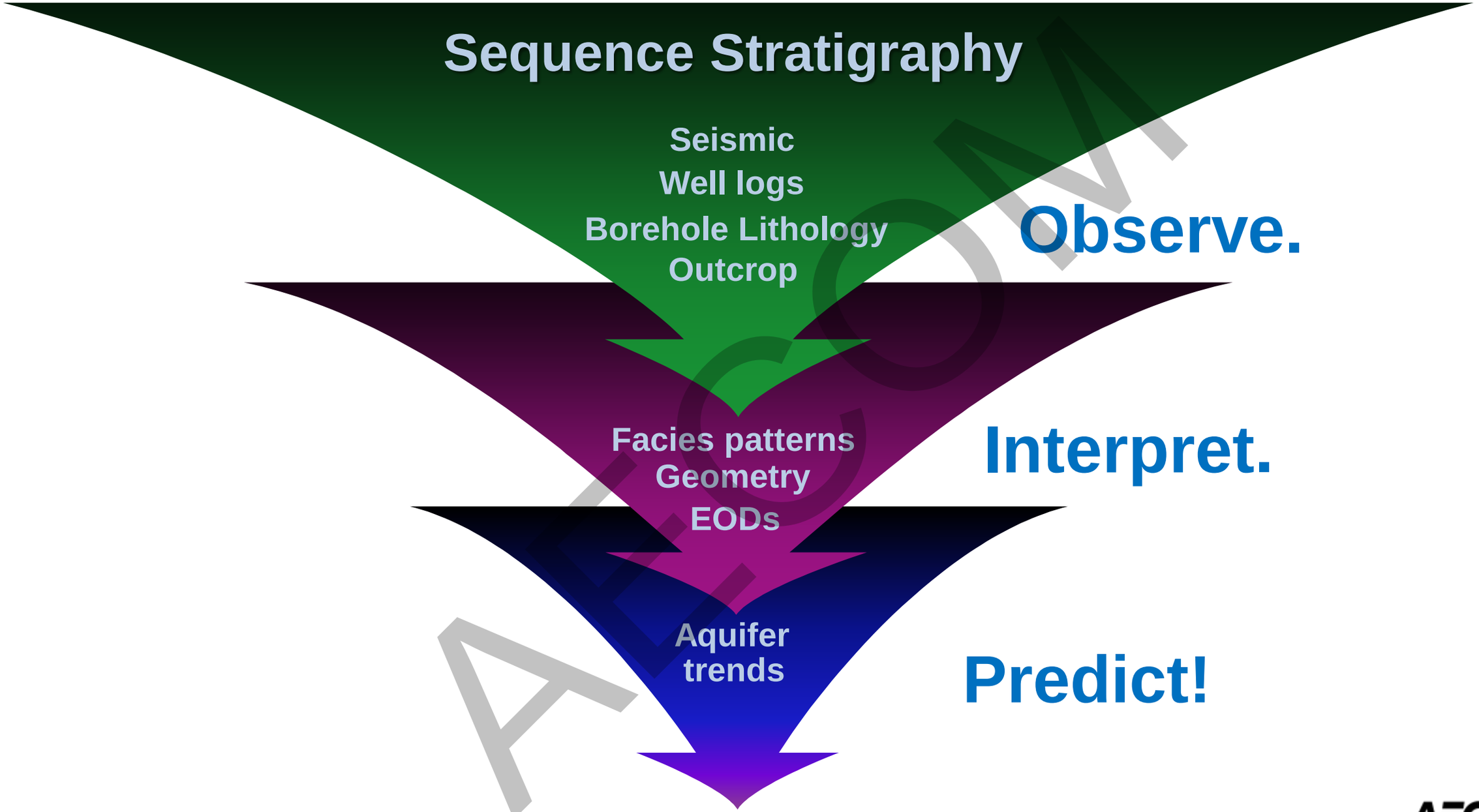
1. **Lithostratigraphy vs. Sequence Stratigraphy**
   - Background
   - What's wrong with lithostratigraphy?
   - Lithostratigraphy vs. Sequence Stratigraphy

2. **Fundamentals of Sequence Stratigraphy/Correlation**
   - Fundamentals of Sequence Stratigraphy
   - Walther's Law
   - Accommodation vs. Supply
   - The sea level curve and systems tracts
   - Parasequences
   - Exercise – Correlation walk-through

3. 5 Minute Q&A session

4. **PRISM® + Case Studies**
   - What is PRISM®?
   - Case Studies involving real environmental data sets!

5. Final Q&A


Sequence Stratigraphy
Seismic
Well logs
Borehole Lithology
Outcrop
Observe.
Facies patterns
Geometry
EODs
Interpret.
Aquifer
trends
Predict!

Course Objectives

At the end of the course, participants will be able to:

- Recognize the pitfalls of lithostratigraphic correlation.
- Recognize and distinguish clastic depositional systems using:
  - Lithologic logs
  - Geophysical/CPT logs
  - Established depositional models
- Use sequence stratigraphic concepts to predict facies (rock type) variations within clastic depositional systems.
- Understand the range of aquifer architectures and internal heterogeneities that occur in sedimentary deposits.
- Appreciate how sequence stratigraphic correlations can be beneficial to the environmental industry.

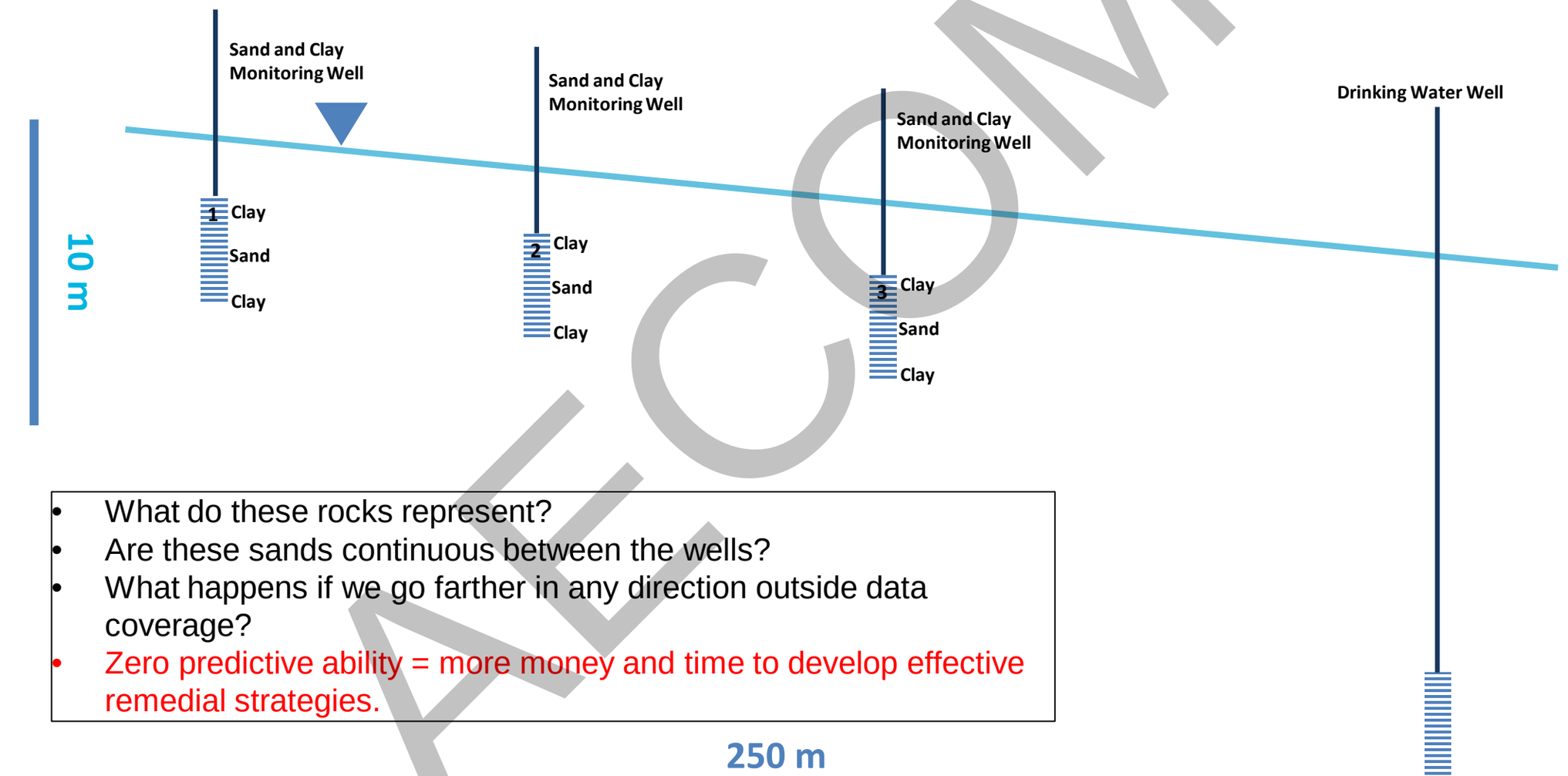
What is Stratigraphy?

How Many Types of Stratigraphy Can We Name?

- Lithostratigraphy
- Allostratigraphy
- Sequence Stratigraphy
  - Genetic
  - Depositional
- Pedostratigraphy
- Event Stratigraphy
- Biostratigraphy
- Chronostratigraphy
- Cyclostratigraphy
- Magnetostratigraphy
- Chemostratigraphy

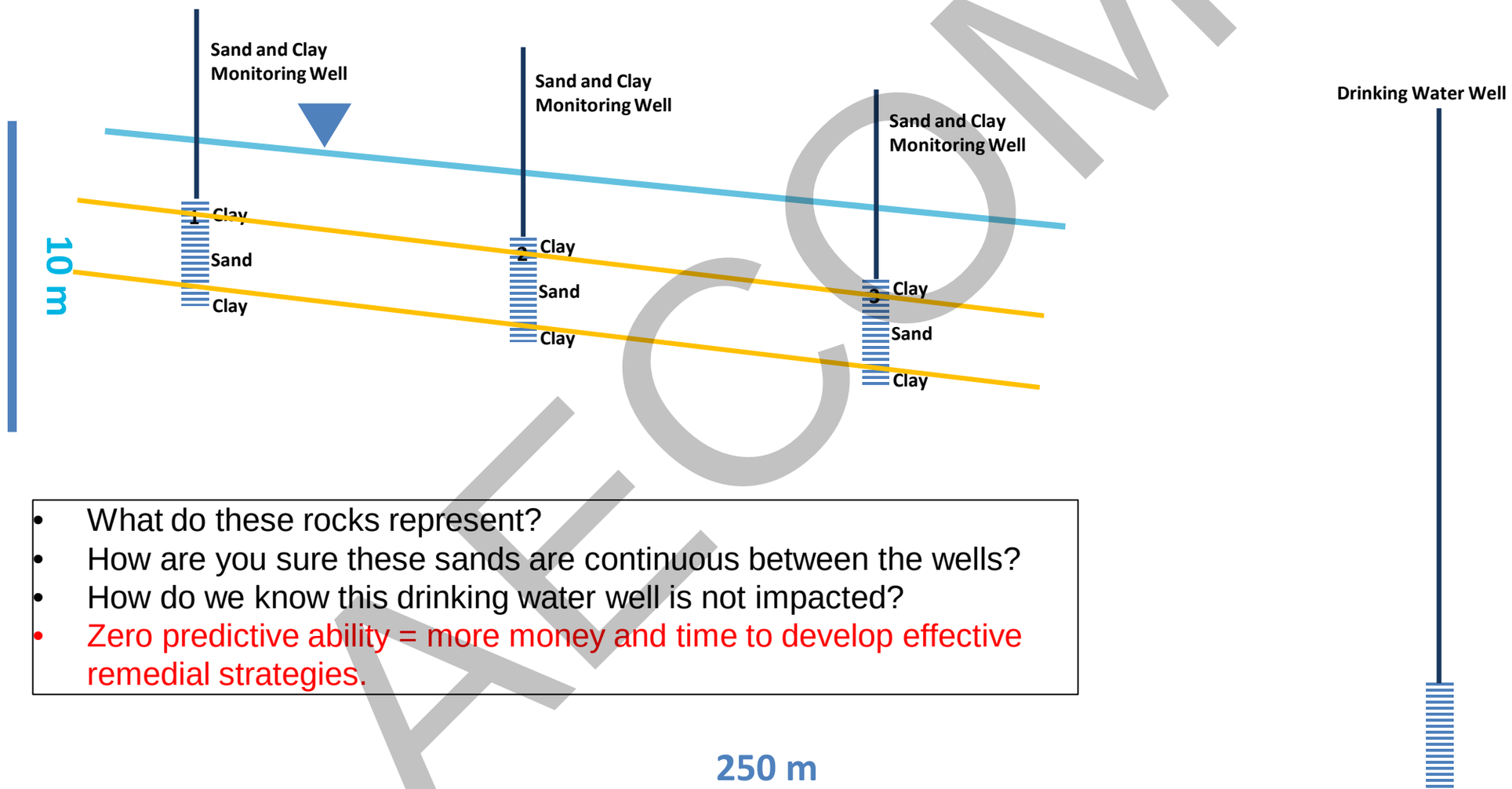
Various attempts to develop a coherent picture of the subsurface

The Challenge of Determining Subsurface Heterogeneity



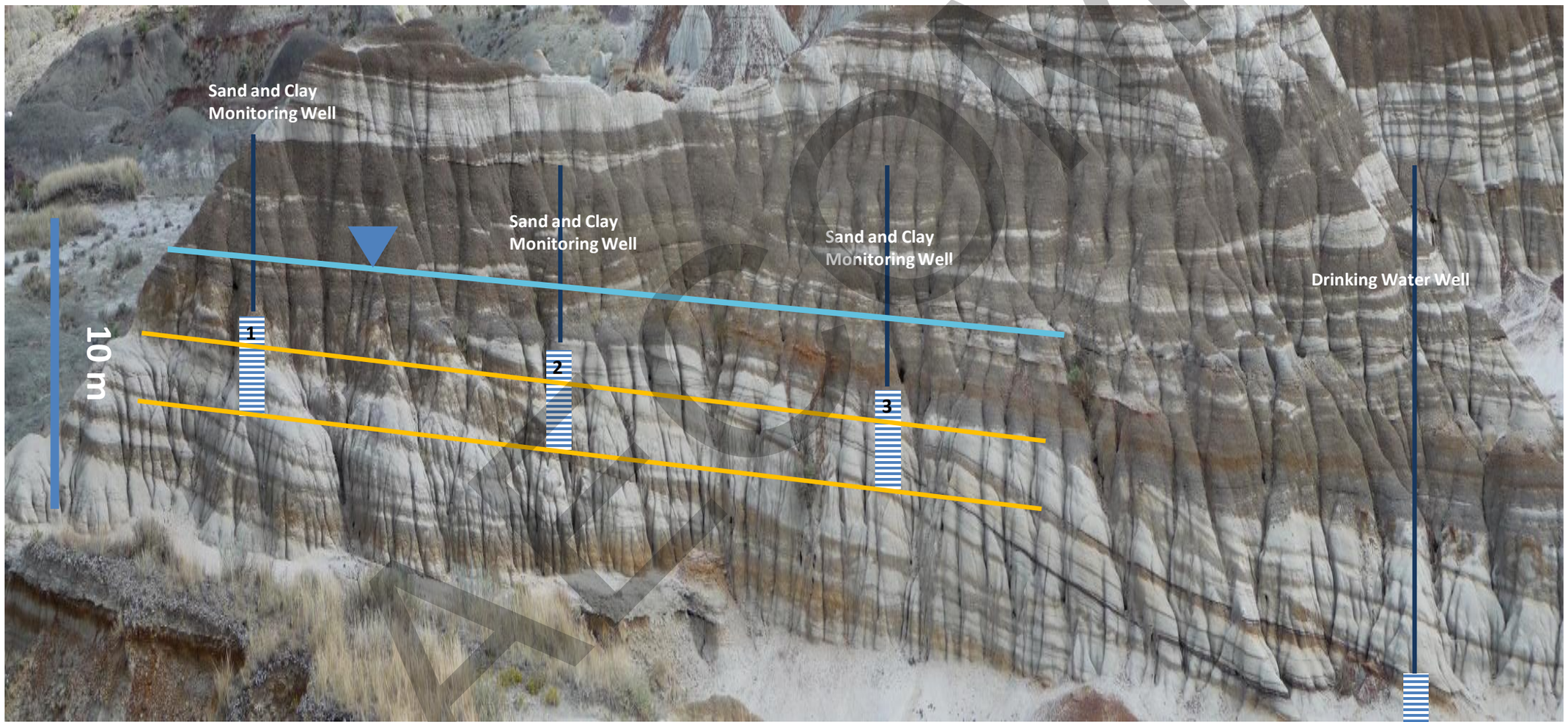
- What do these rocks represent?
- Are these sands continuous between the wells?
- What happens if we go farther in any direction outside data coverage?
- Zero predictive ability = more money and time to develop effective remedial strategies.

The Challenge of Determining Subsurface Heterogeneity

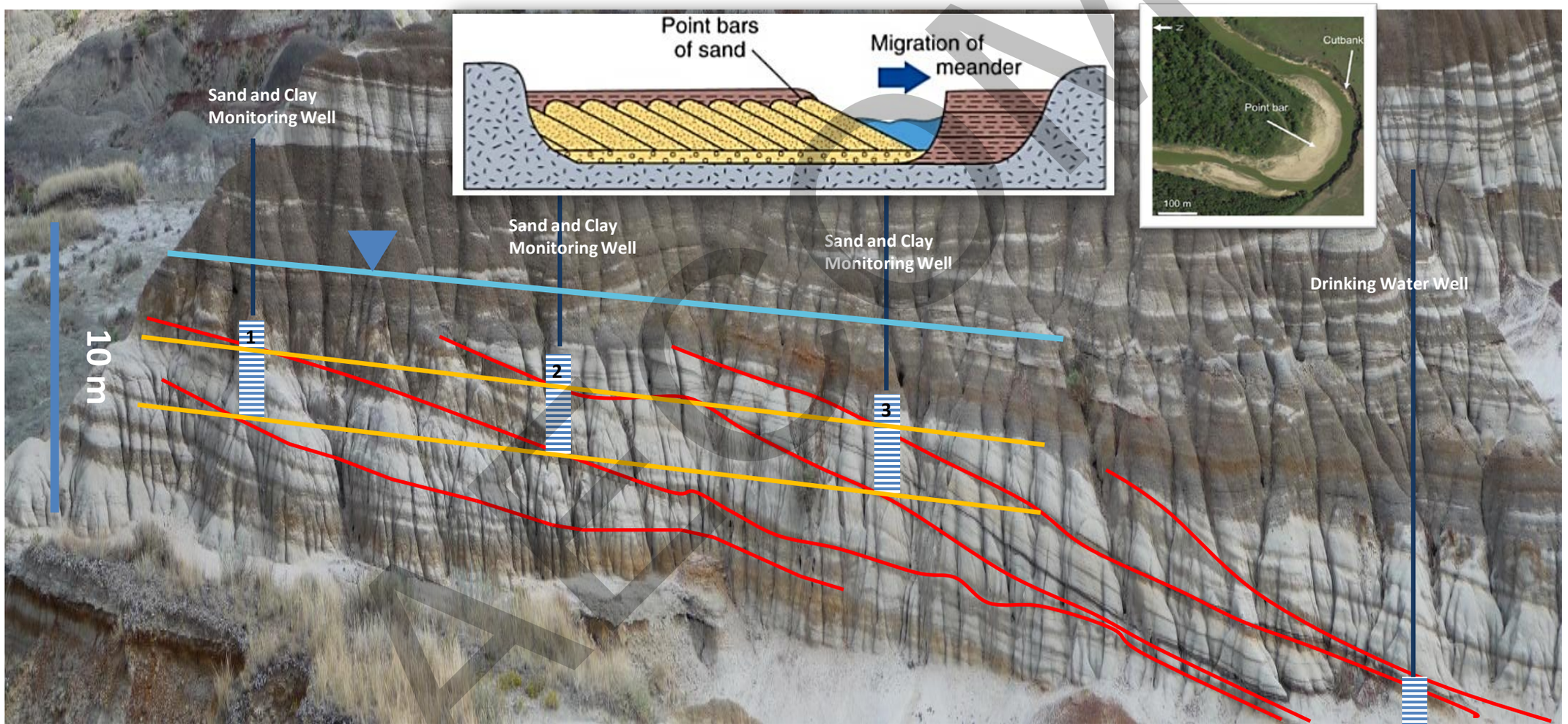


- What do these rocks represent?
- How are you sure these sands are continuous between the wells?
- How do we know this drinking water well is not impacted?
- Zero predictive ability = more money and time to develop effective remedial strategies.

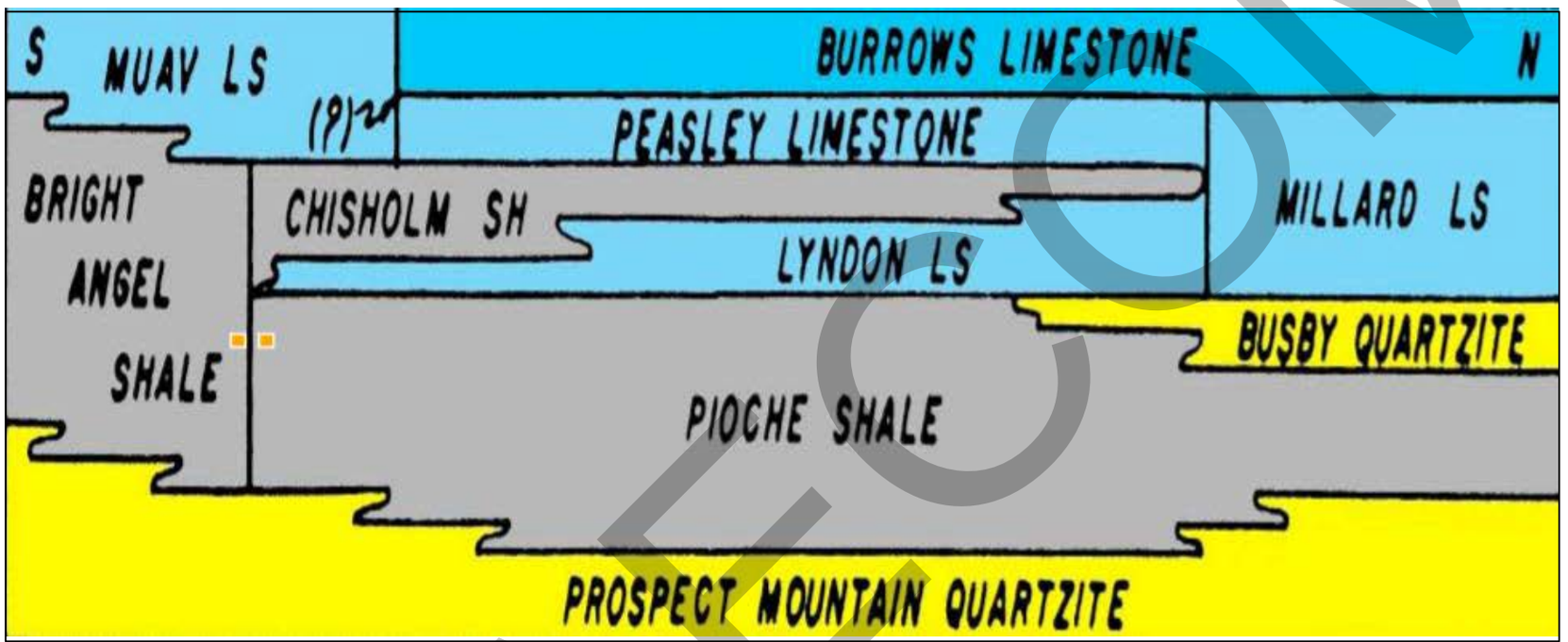
Addressing the True Heterogeneity of Depositional Environments



Addressing the True Heterogeneity of Depositional Environments

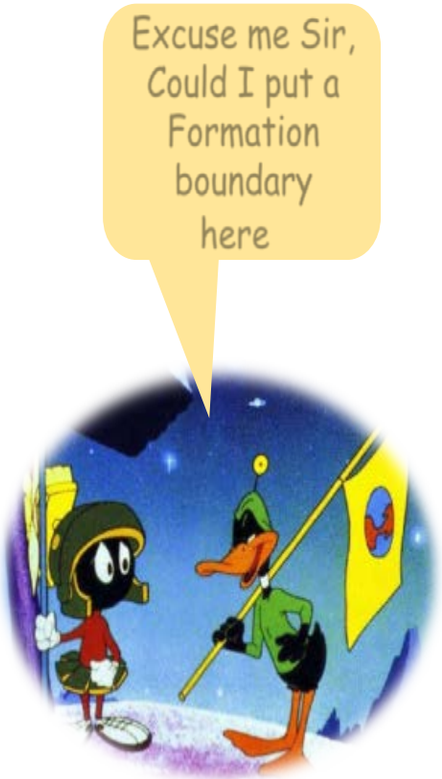


What's Wrong with Lithostratigraphy?



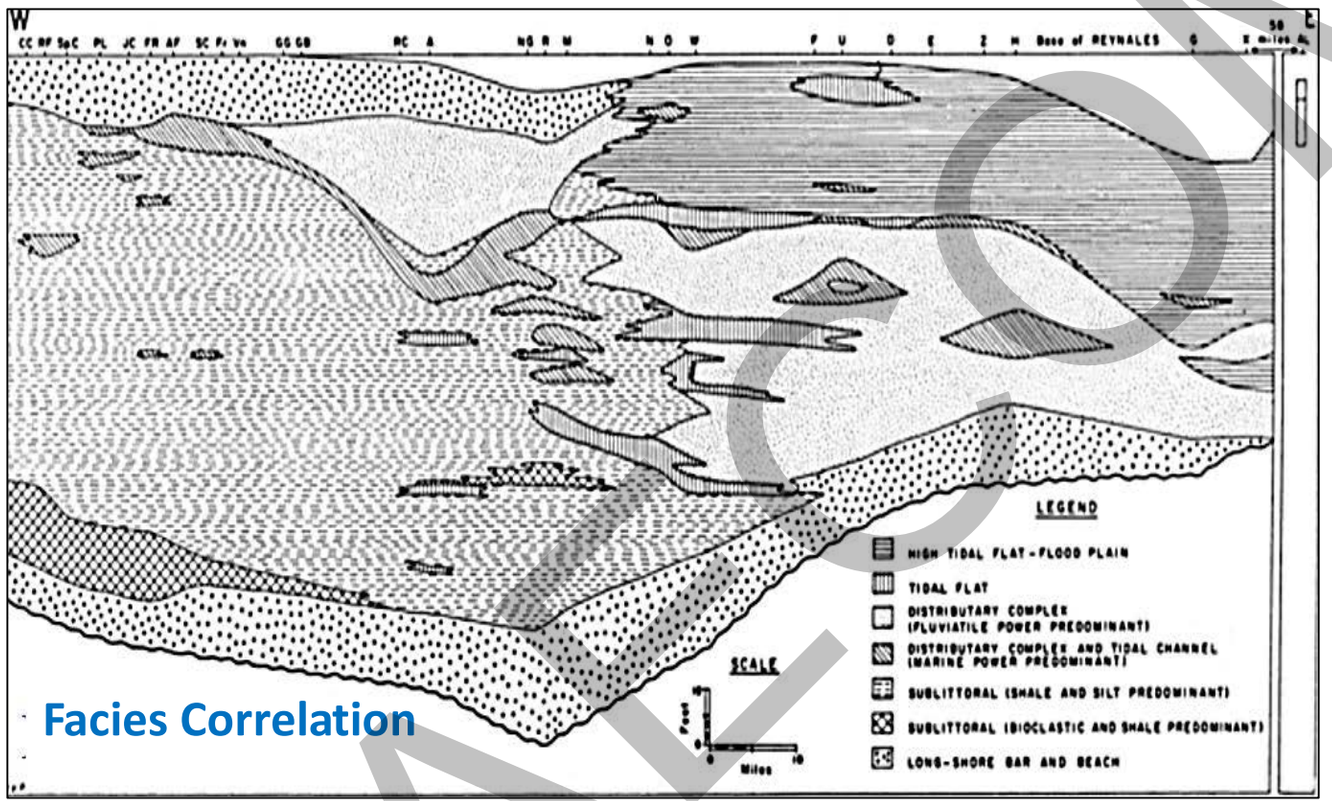
Cambrian Stratigraphy of the Wendover Area, Utah and Nevada

Wheeler and Mallory, 1956



State of the Art Stratigraphy in the 50s: a game of putting flags?

What's Wrong with Lithostratigraphy?

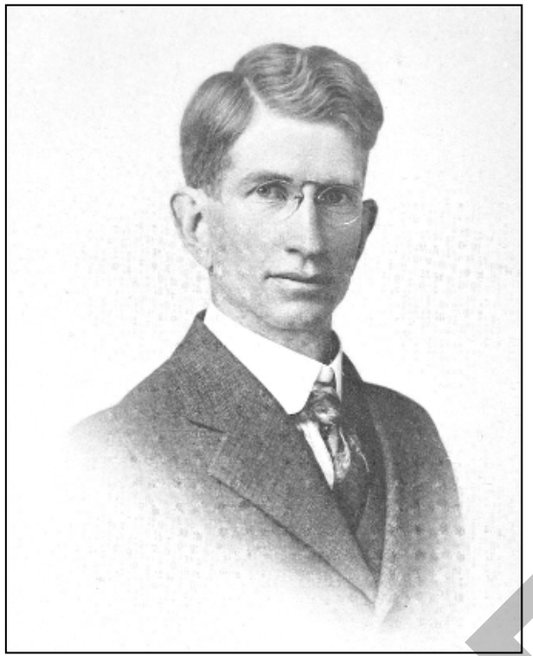


Schematic cross-section of Medina Formation along Niagara after Martini, 1971

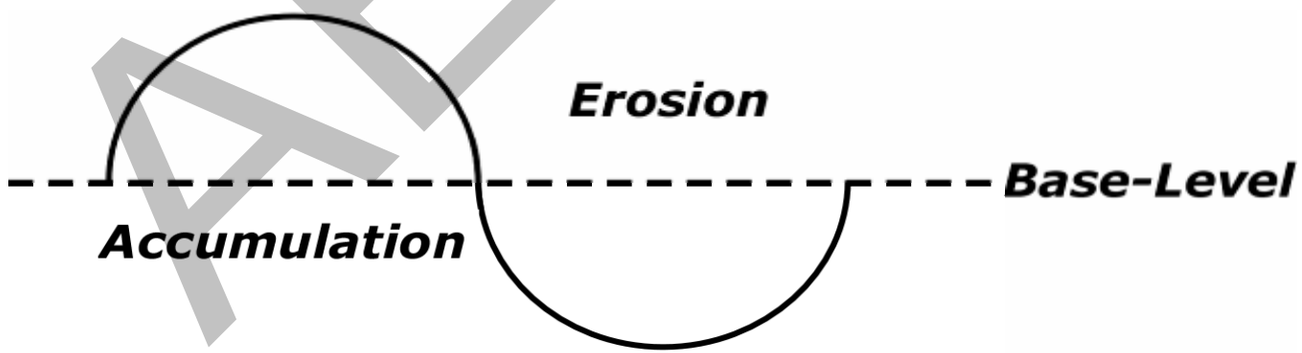
Facies: sum total of physical and biogenic characteristics of rock

State of the Art Stratigraphy in the 70s: a game changer?

History of Sequence Stratigraphy: Base Level



1917: Joseph Barrell stated the most fundamental events in geologic history--the time-space distribution of deposition and non-deposition: *the alternating rise and fall of Base-level.*



AECOM

Sequence Stratigraphy: Birth of a Revolution

Three Northwestern graduates join the stratigraphic research team of Exxon and begin to use sequence stratigraphic concepts to interpret **seismic data**:

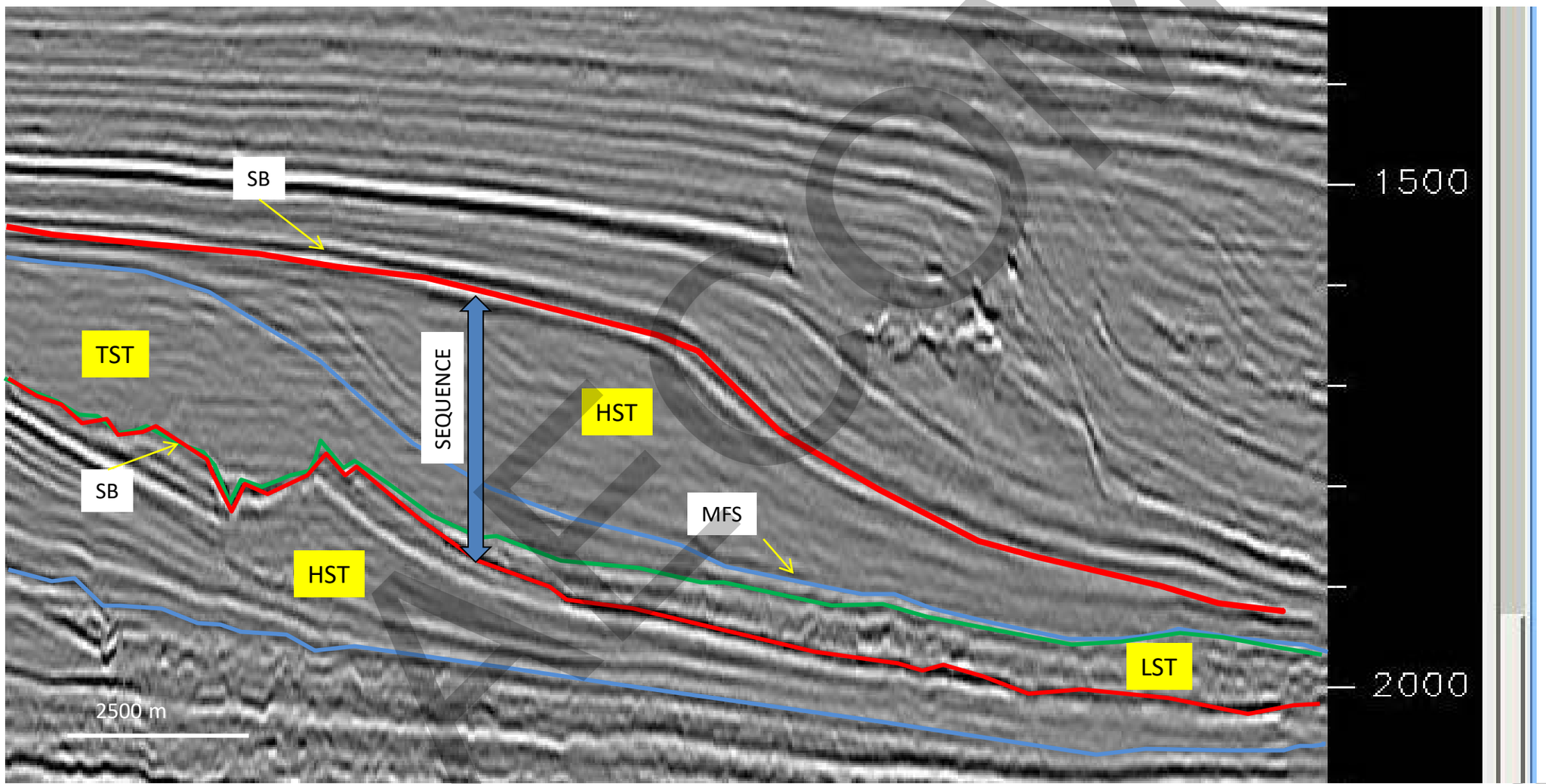
- Recognition and definition of unconformity-bounded units
- The time-transgressive nature of facies

Peter Vail:
PhD Northwestern 1956

Bob Mitchum:
PhD Northwestern 1954

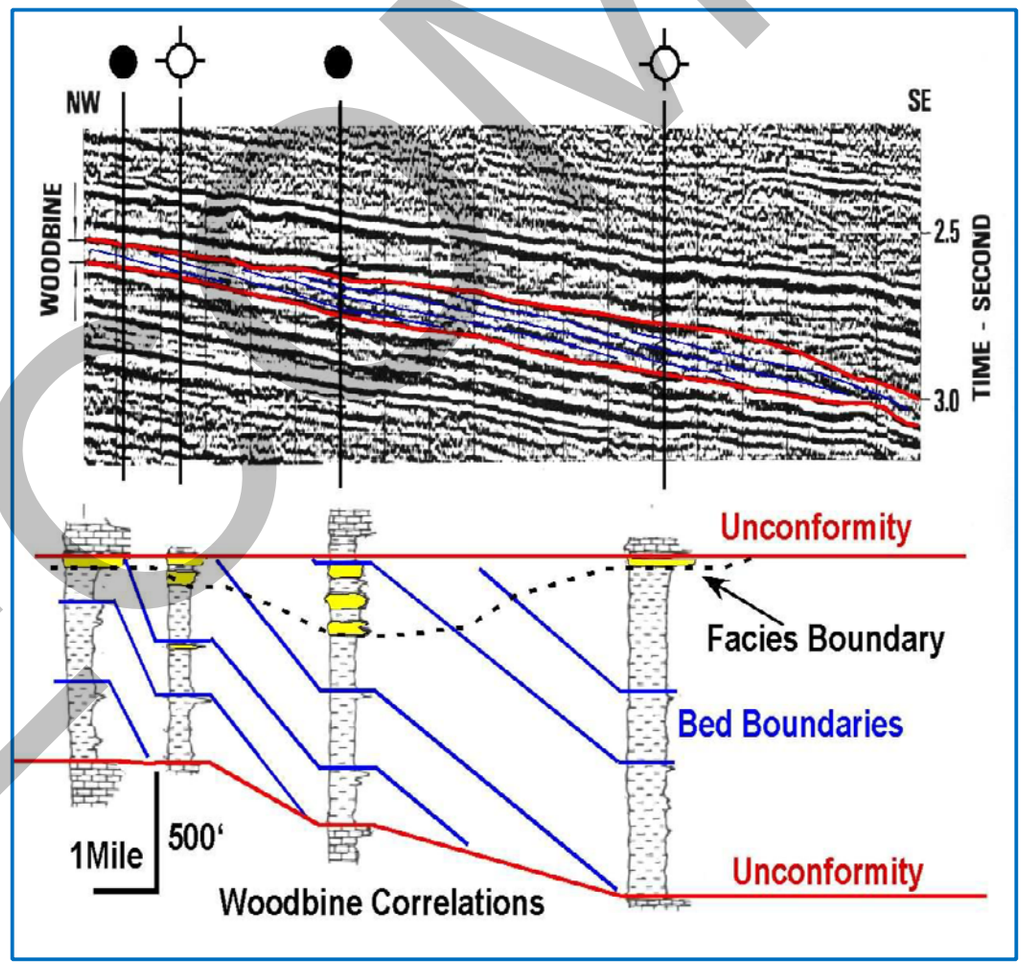
John Sangree:
PhD Northwestern 1959

Seismic Stratigraphic Horizons: Systems Tracts



Sequence Stratigraphy: *A Paradigm Shift in Correlation*

Sequence stratigraphy relies on correlation of coeval rocks in a depositional system. This gives us a predictive ability to infer sandbody pattern and facies change.

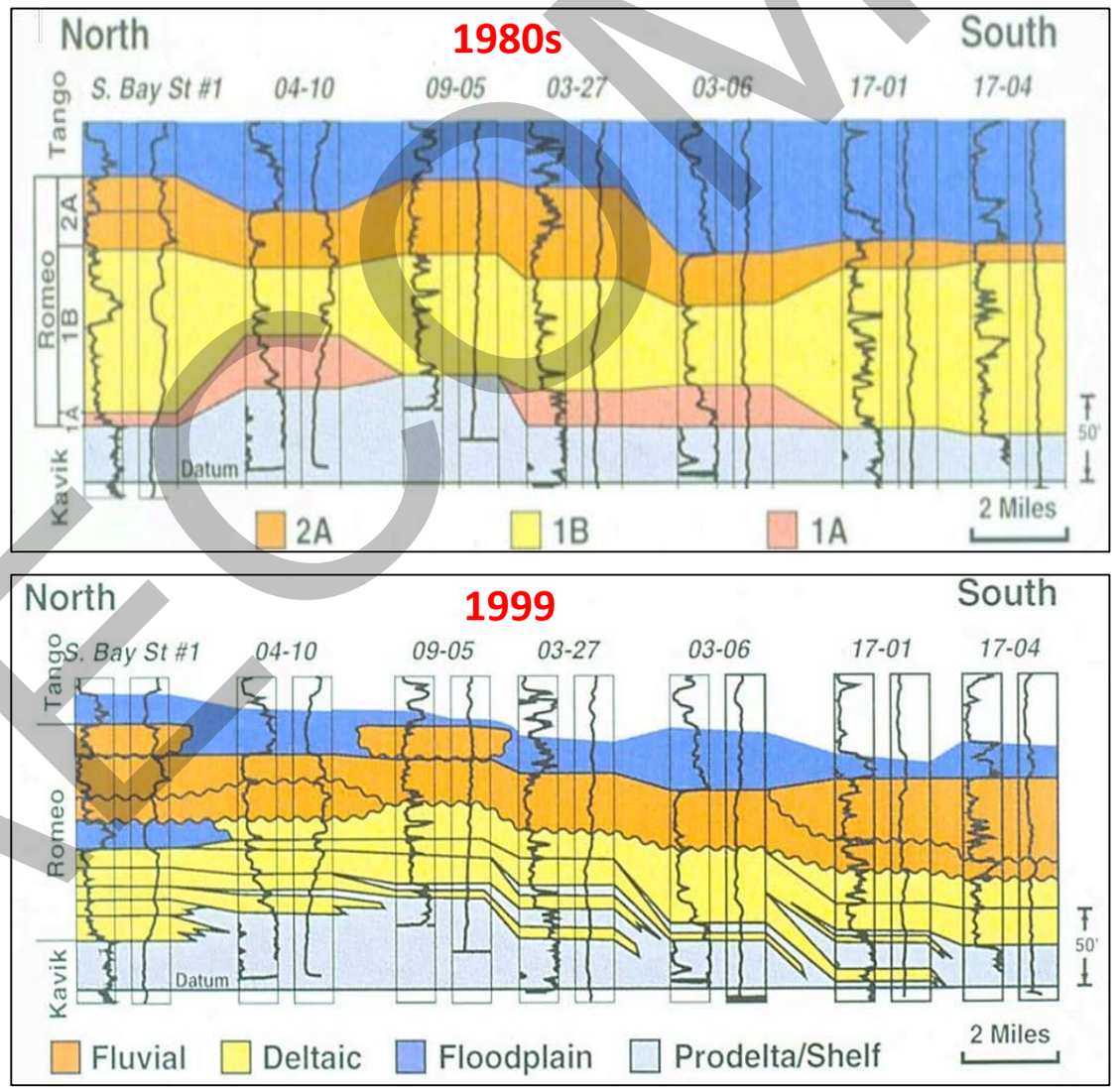


Vail et al., 1977.

AECOM

From Lithostratigraphy to Sequence Stratigraphy

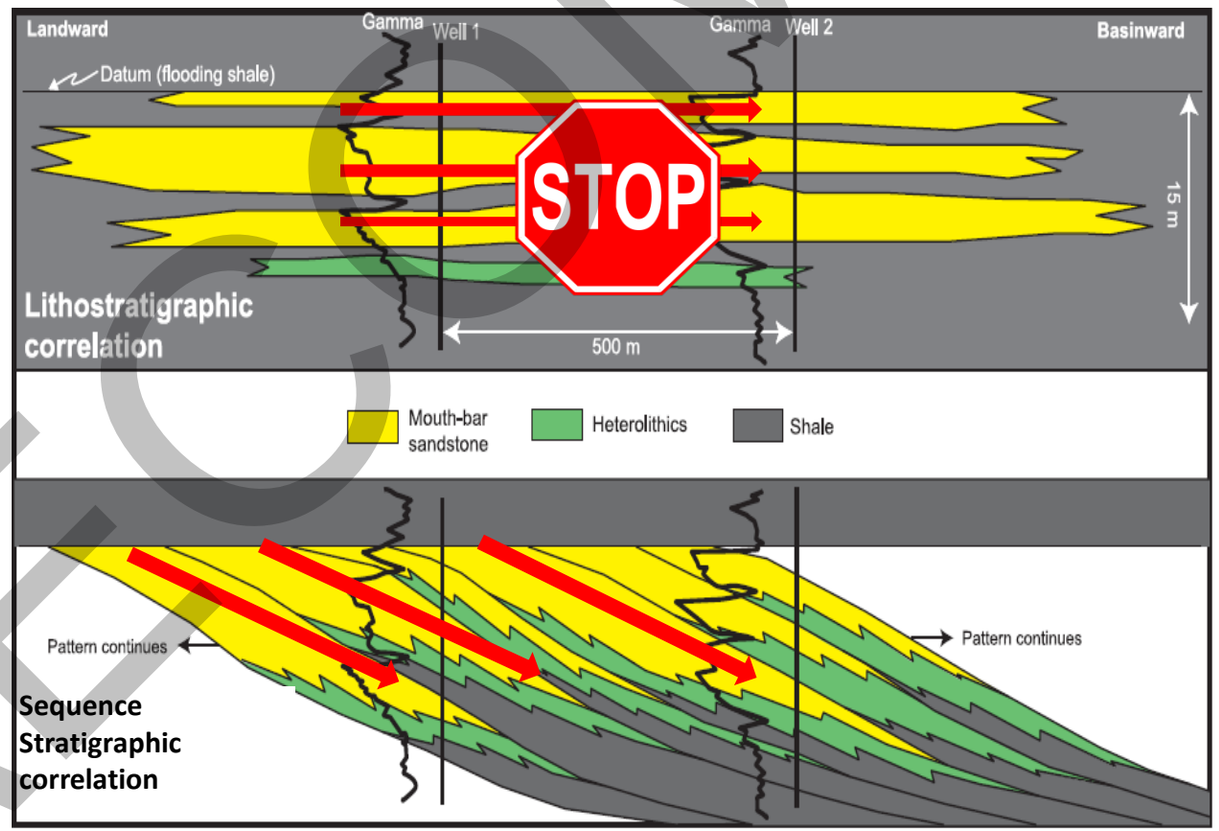
The petroleum industry soon saw the value of sequence stratigraphy in predicting reservoir architecture and heterogeneity



Arco's interpretation of Prudhoe Bay stratigraphy

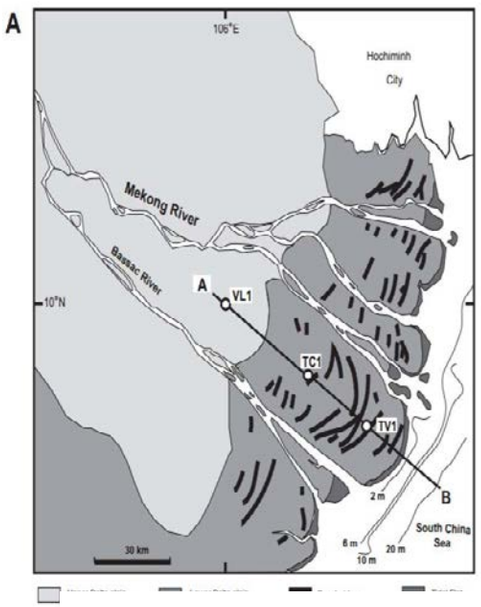
The Main Pitfall of Lithostratigraphy

- No genetic linkage of depositional environments (ignores time-lines)
- Zero predictive ability
- May correlate through transmissive barrier; therefore often fails to determine flow-path



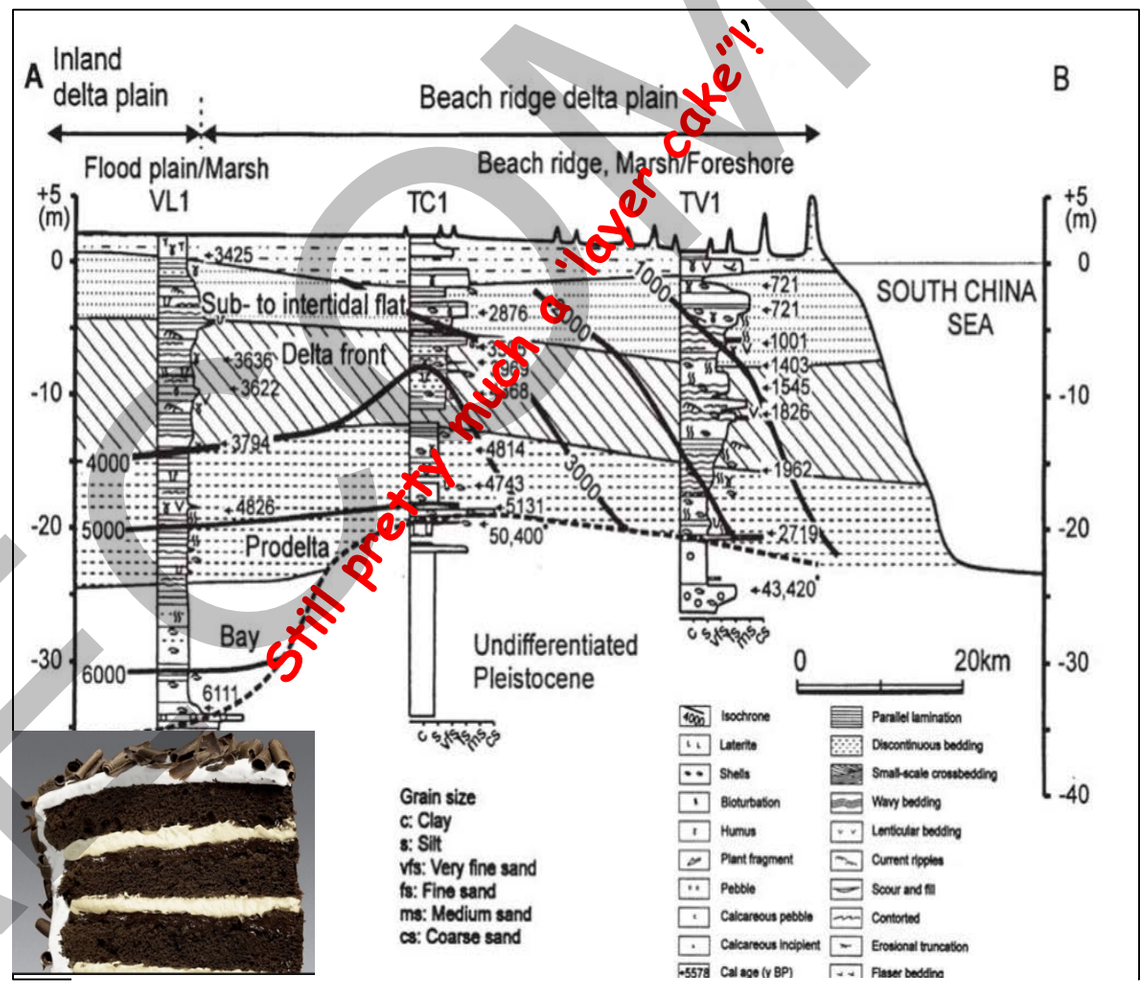
Ainsworth et al., 1999

Sequence Stratigraphy: *Catching Up in the Environmental Sector*



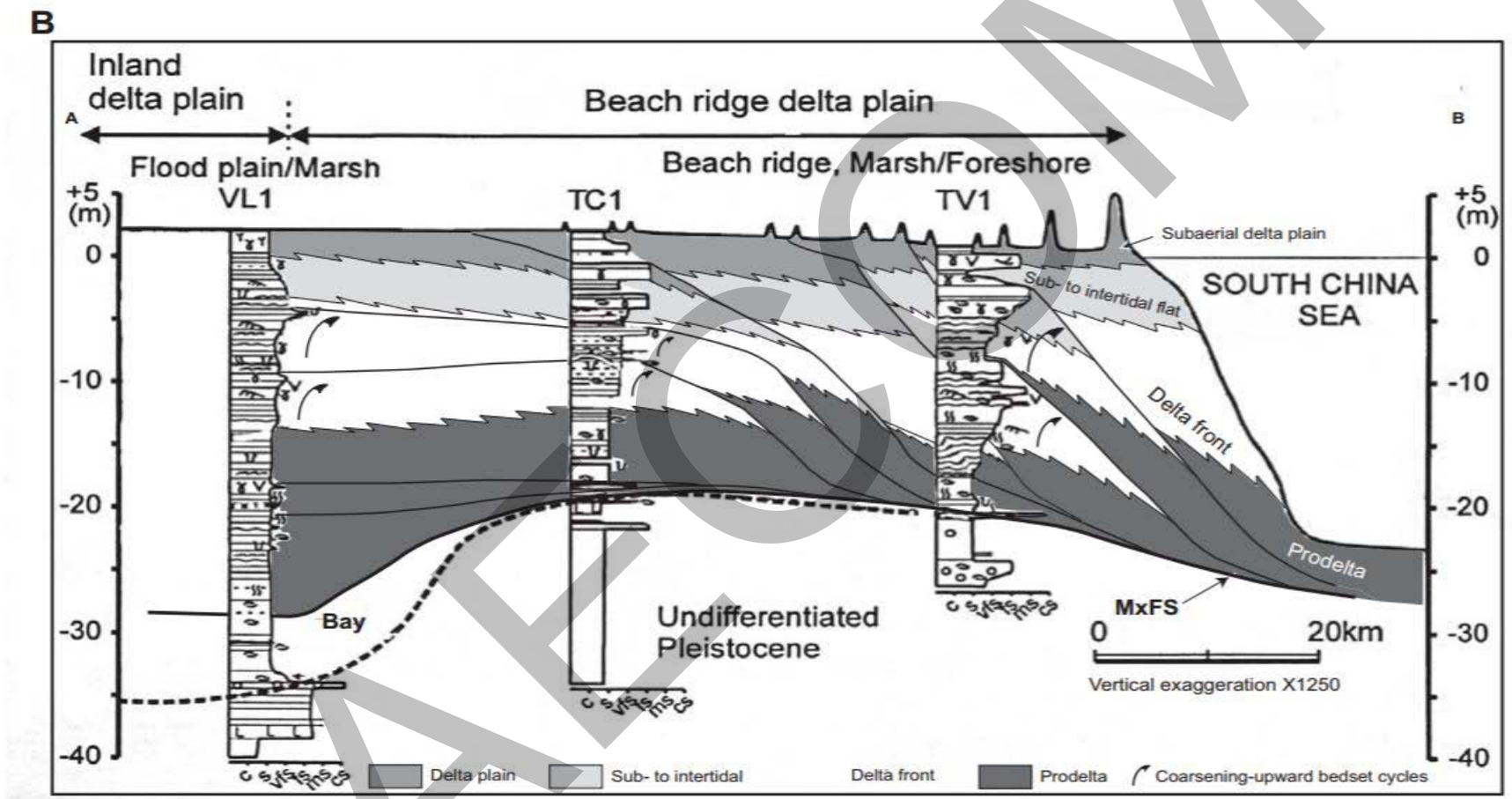
Modern day Mekong Delta

The environmental sector (both academia & industry) has been sluggish in adopting the sequence stratigraphic approach.



Depositional-dip-oriented subsurface correlation of cores through the Mekong River Delta as presented by Ta et al. *Quaternary Science Reviews* (2002)

Sequence Stratigraphy: *Catching Up in the Environmental Sector*



- Reconstruction of the same applying the sequence stratigraphic technique of bedding correlation (Gani & Bhattacharya, 2005)
- Groundwater flow-path changes dramatically!

Key Takeaway:

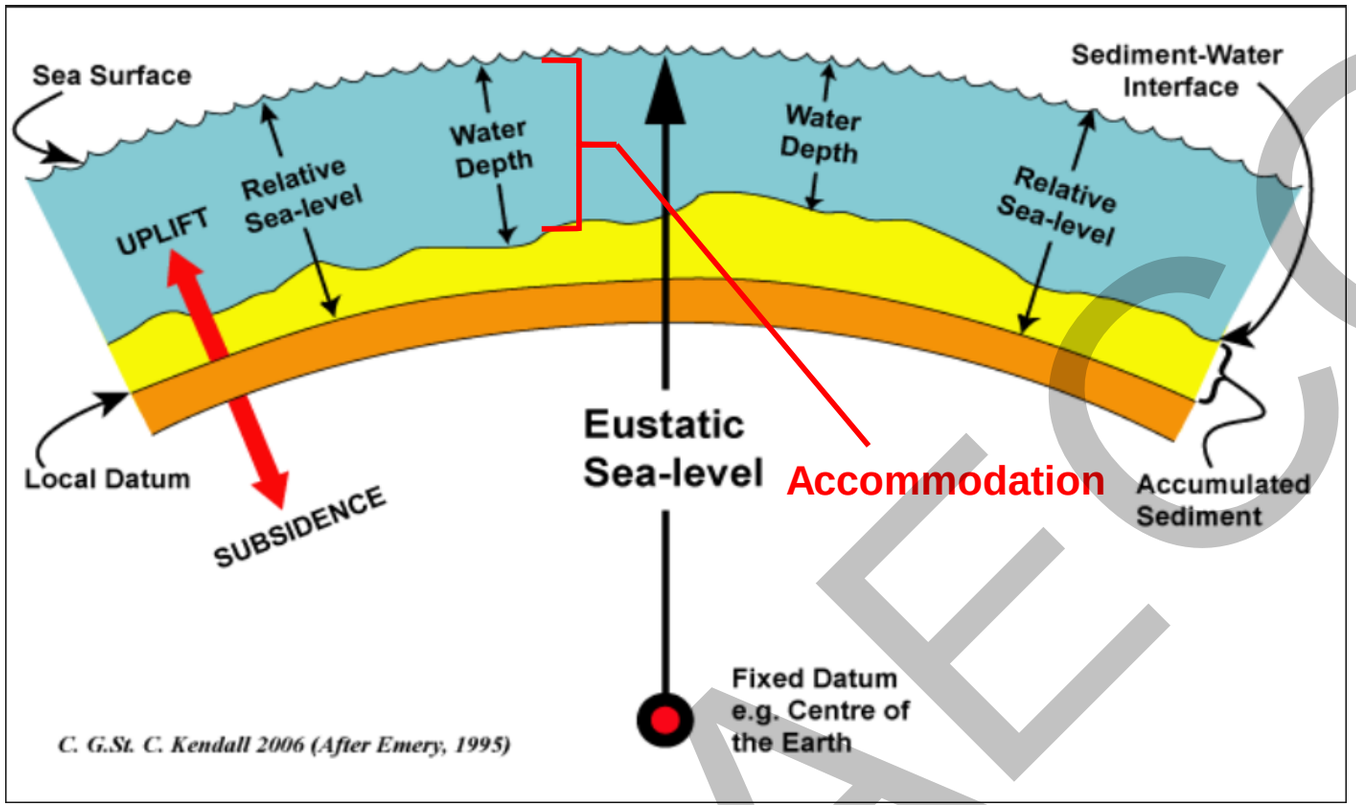
Sequence Stratigraphy is not equal to facies analysis!

- However, facies analysis is an important building block of sequence stratigraphy.

Lecture 2:

The Fundamentals of Sequence Stratigraphy

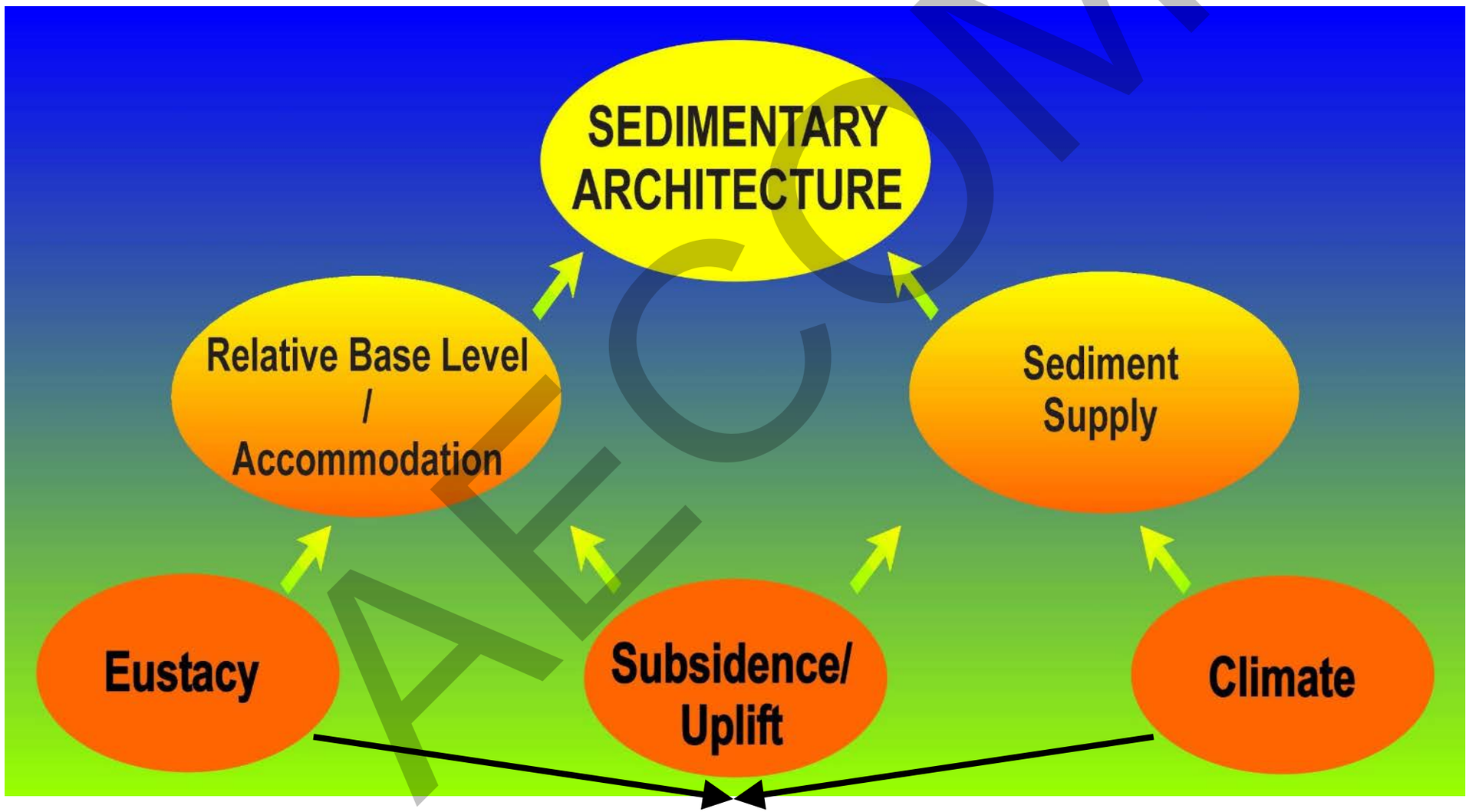
Fundamentals of Sequence Stratigraphy



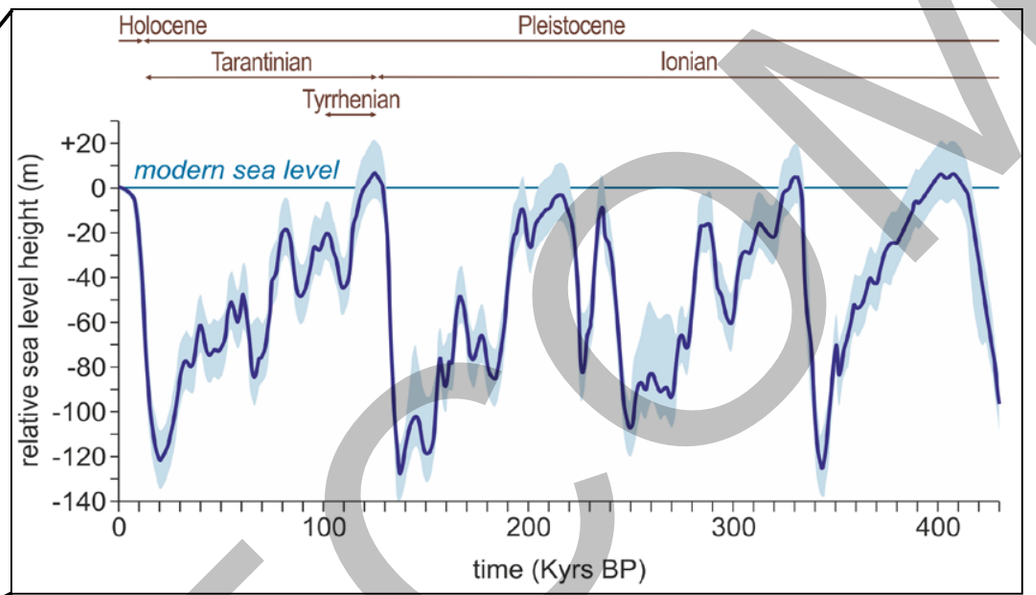
Accommodation vs. Supply

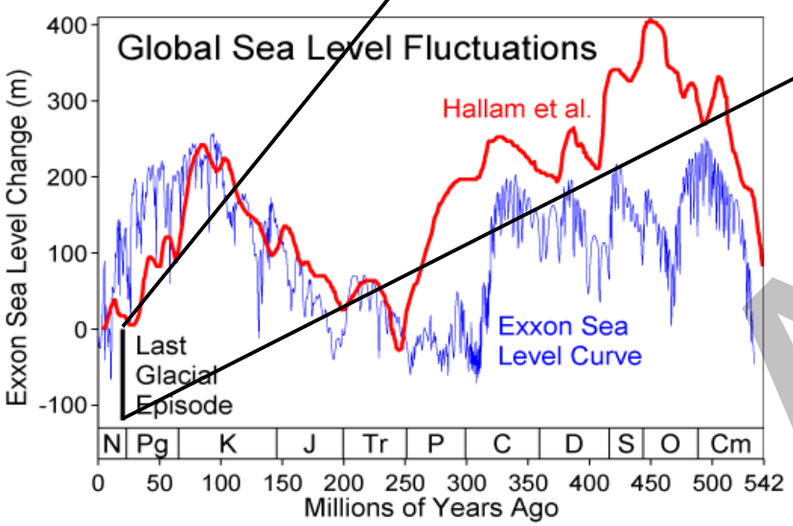
Fundamentals of Sequence Stratigraphy

(and the importance of understanding the system on a regional scale)



Fundamentals of Sequence Stratigraphy

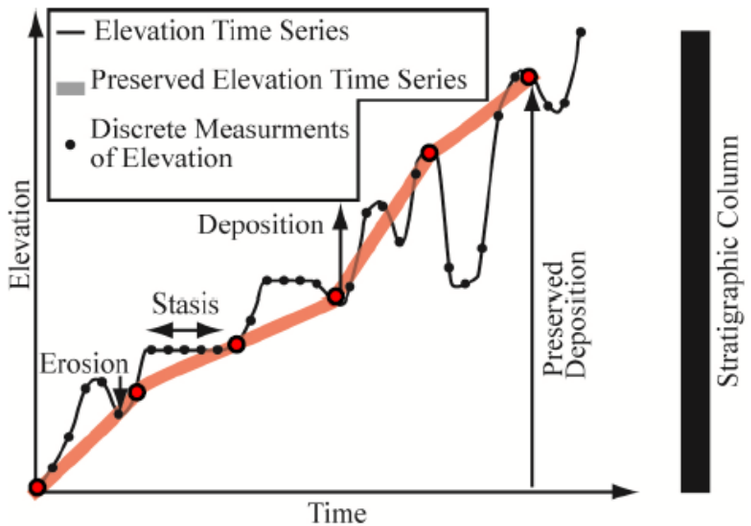




Sea-level over geological time

Sea level cycles occur on different orders of magnitude!

Not all time is preserved in the stratigraphic record!

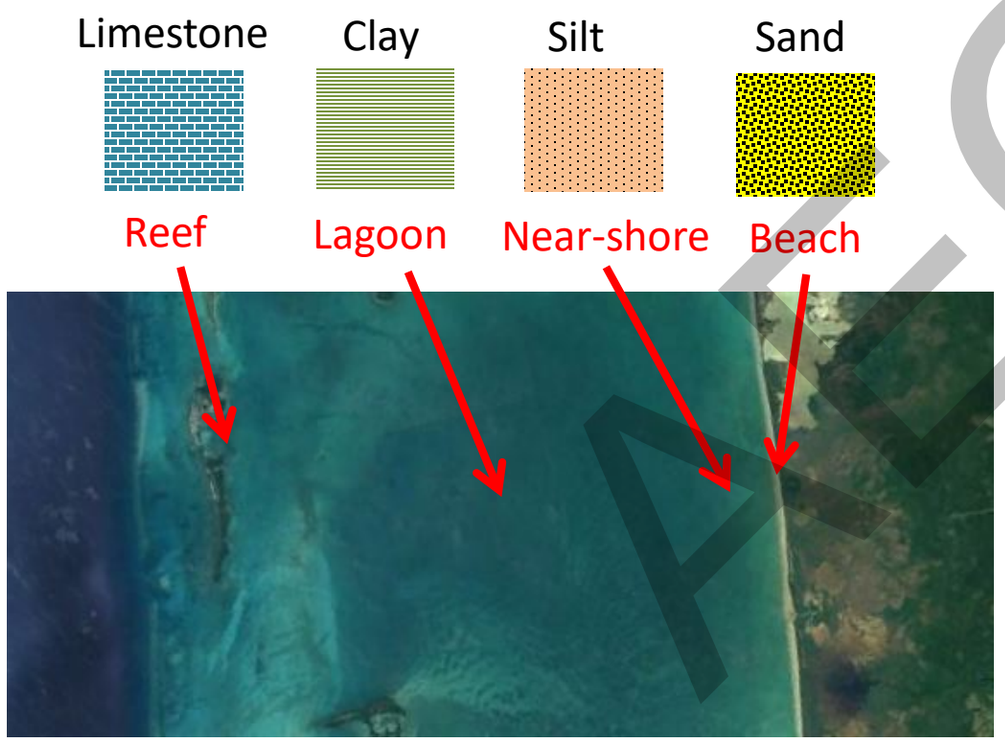


Fundamentals of Sequence Stratigraphy

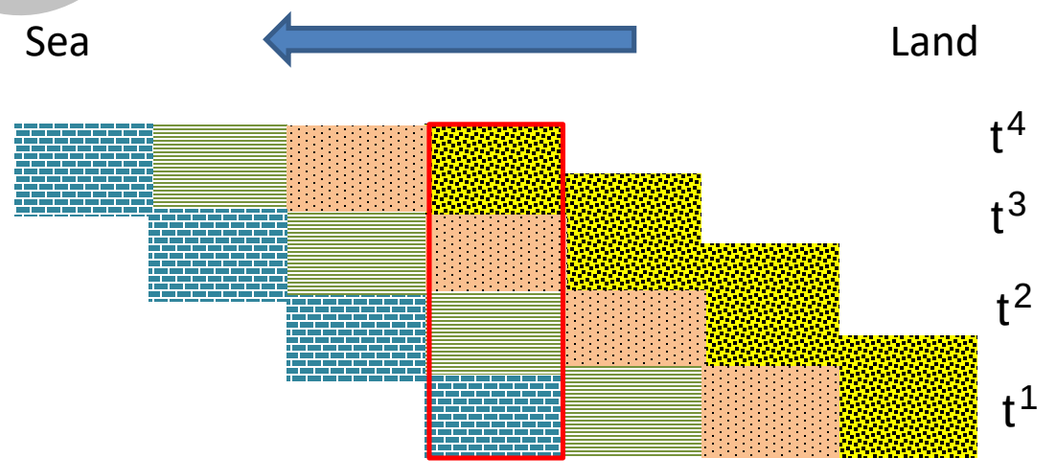
Walther's Law

Sedimentary environments that started side-by-side will end up over lapping one another over time due to progradation and retrogradation.

Note: Walther's Law applies only if there is no unconformity (erosion/non-deposition)



Deposits moving seaward (Coastal Progradation)



Lateral facies change stacked over time ($t^1 + t^2 + t^3 + t^4$)

Coarsening up!

Fundamentals of Sequence Stratigraphy

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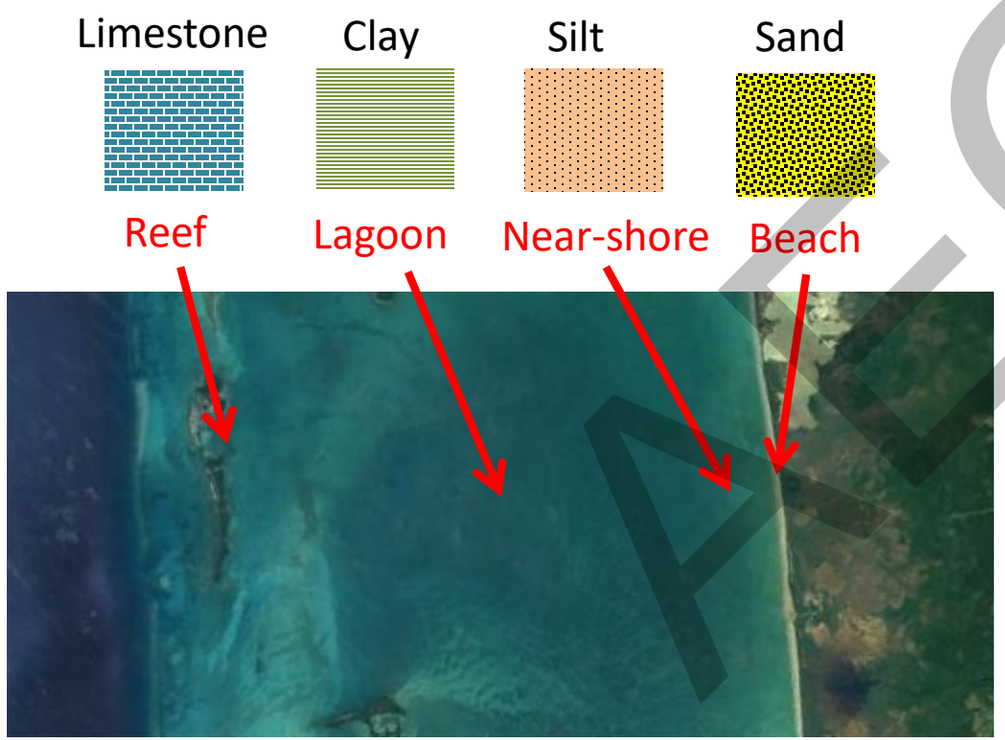
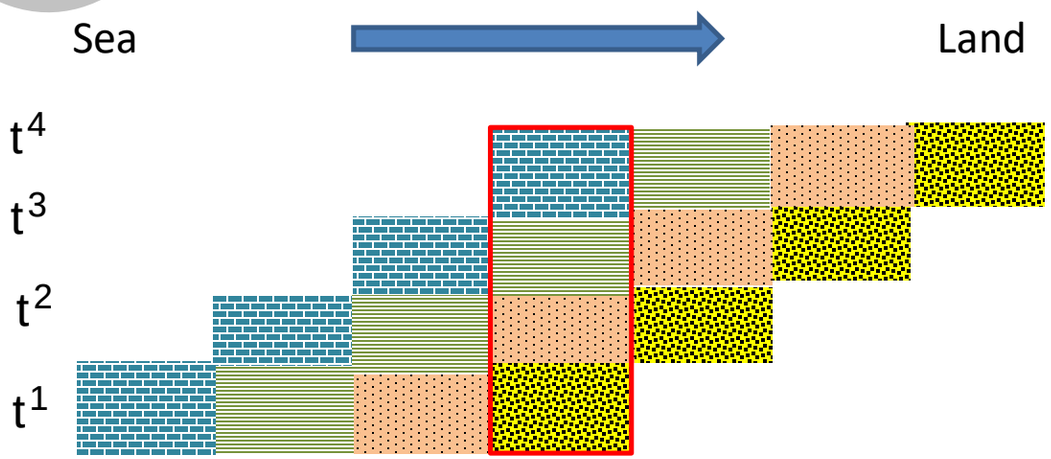


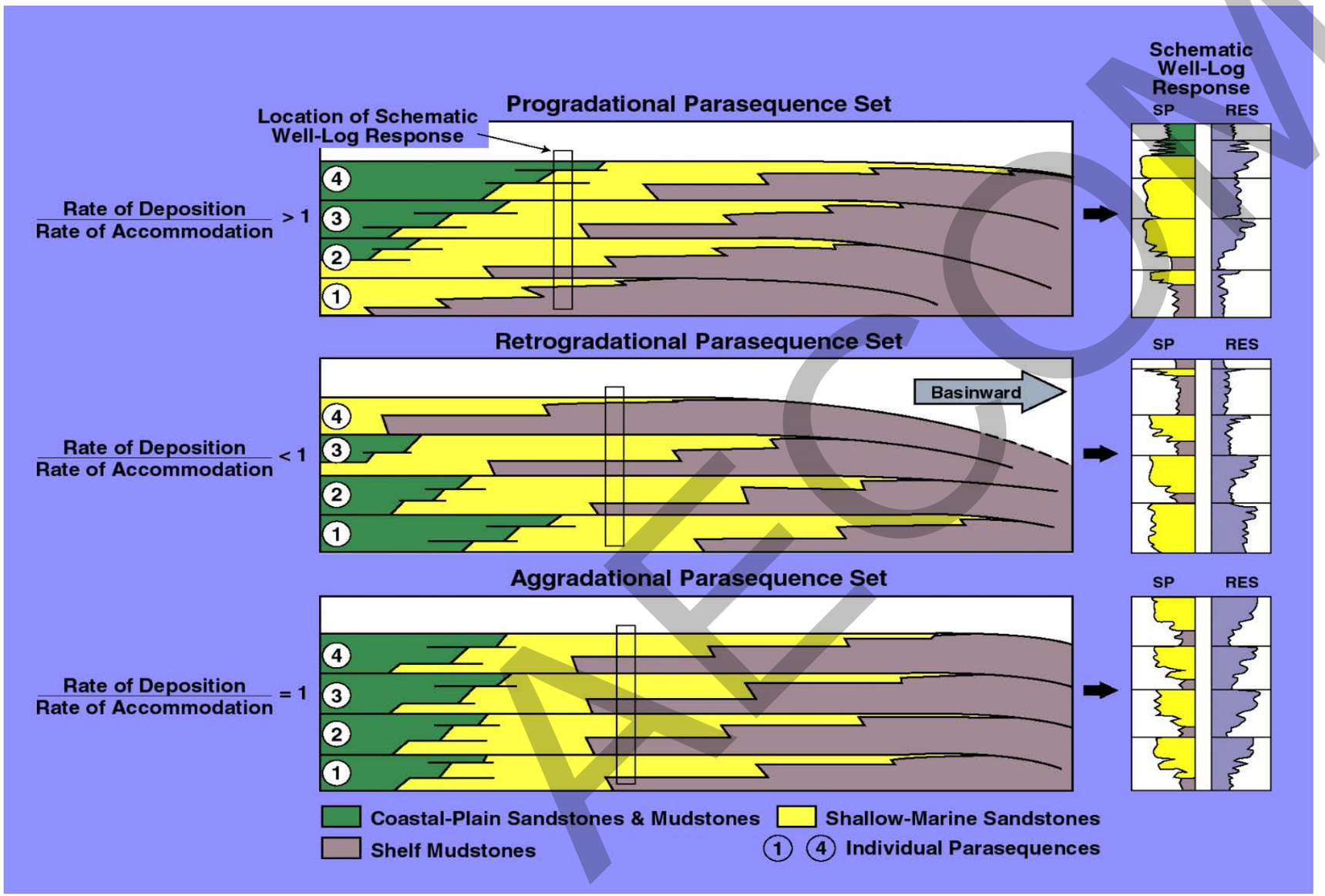
Deposits moving Landward (Retrogradation)

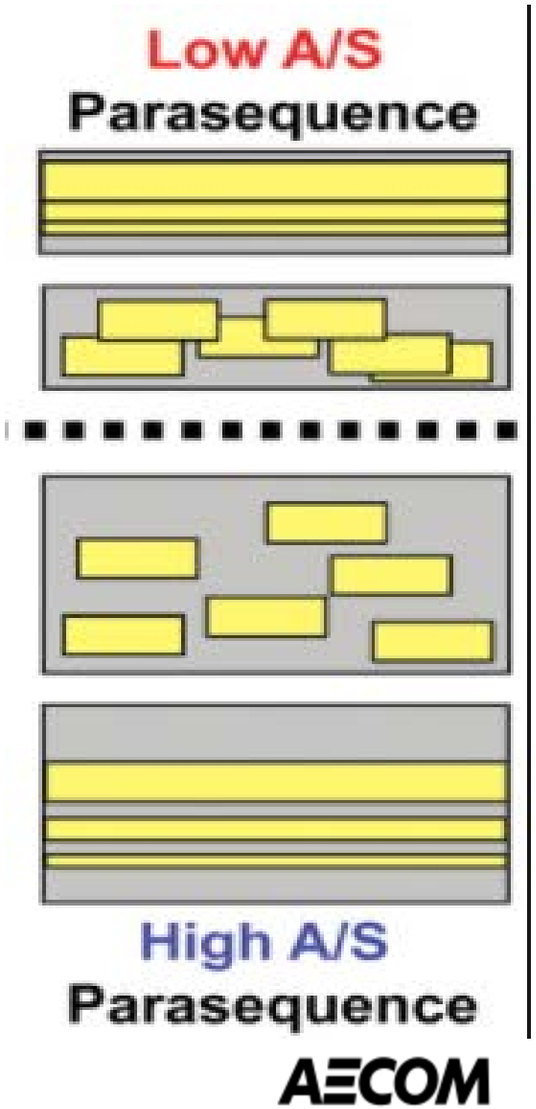


Fining up!

Lateral facies change stacked over time ($t^1 + t^2 + t^3 + t^4$)

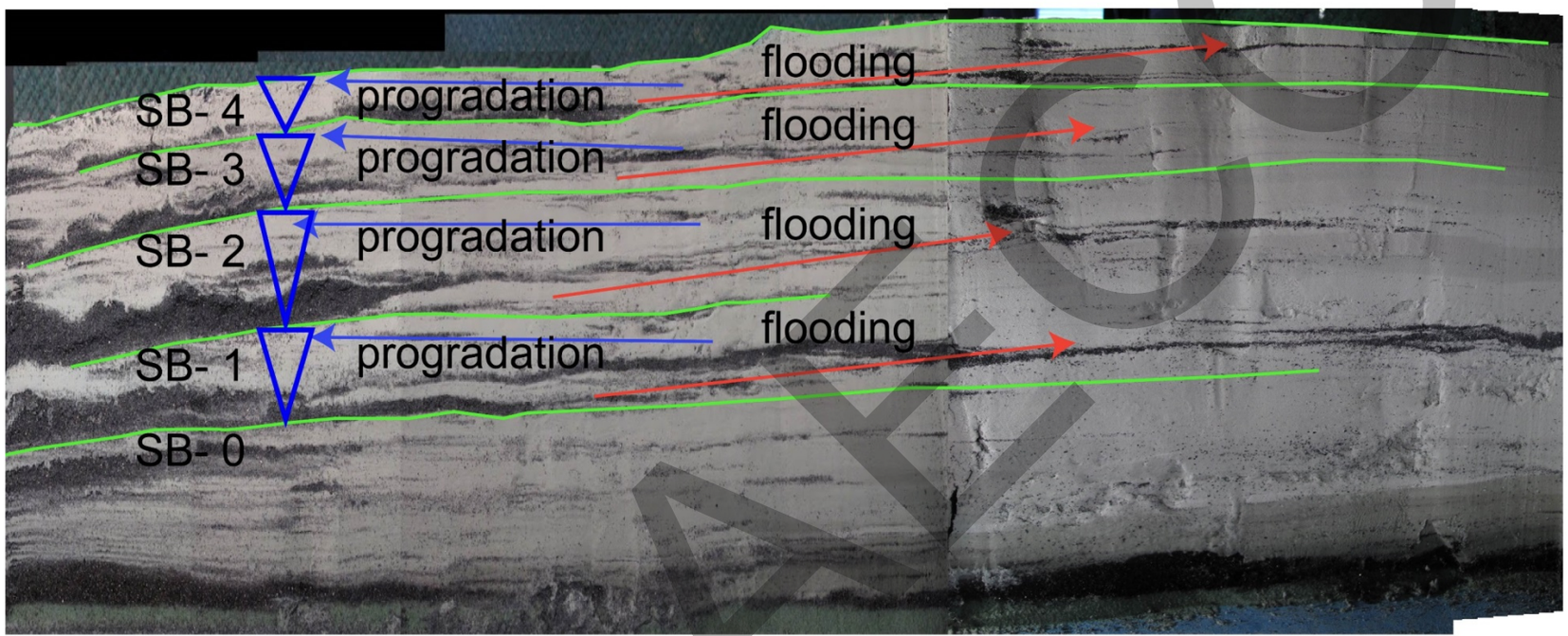
Accommodation vs. Supply

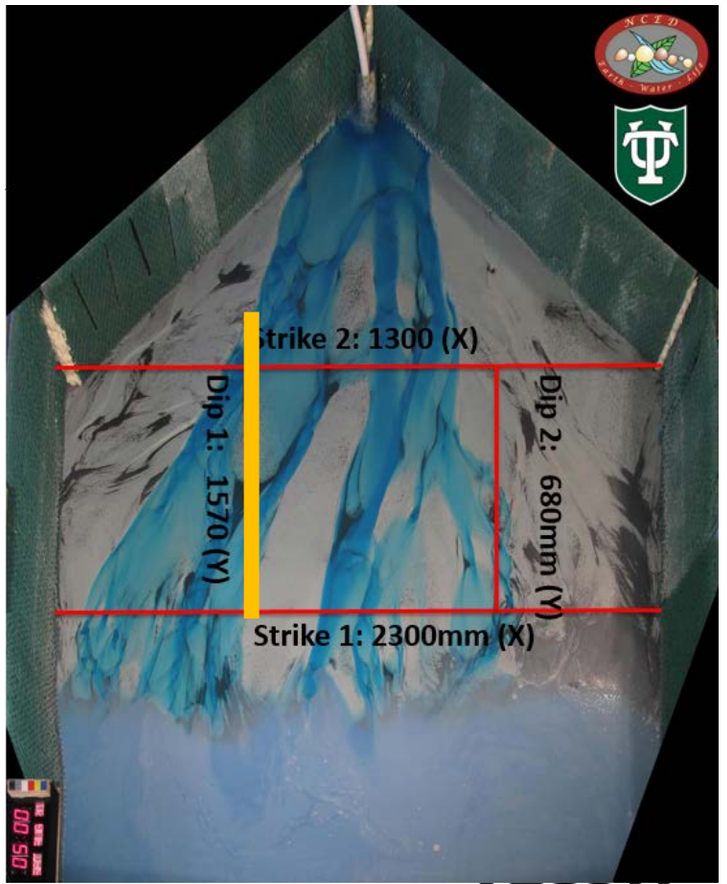




Accommodation vs. Supply

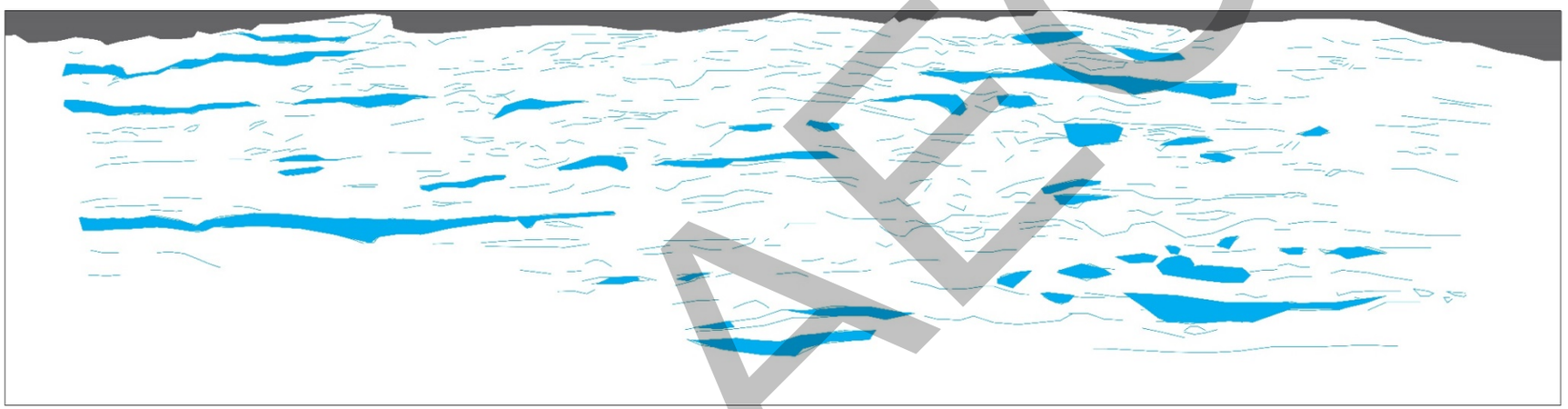
TDB_SIESD_2015_LAN.mov

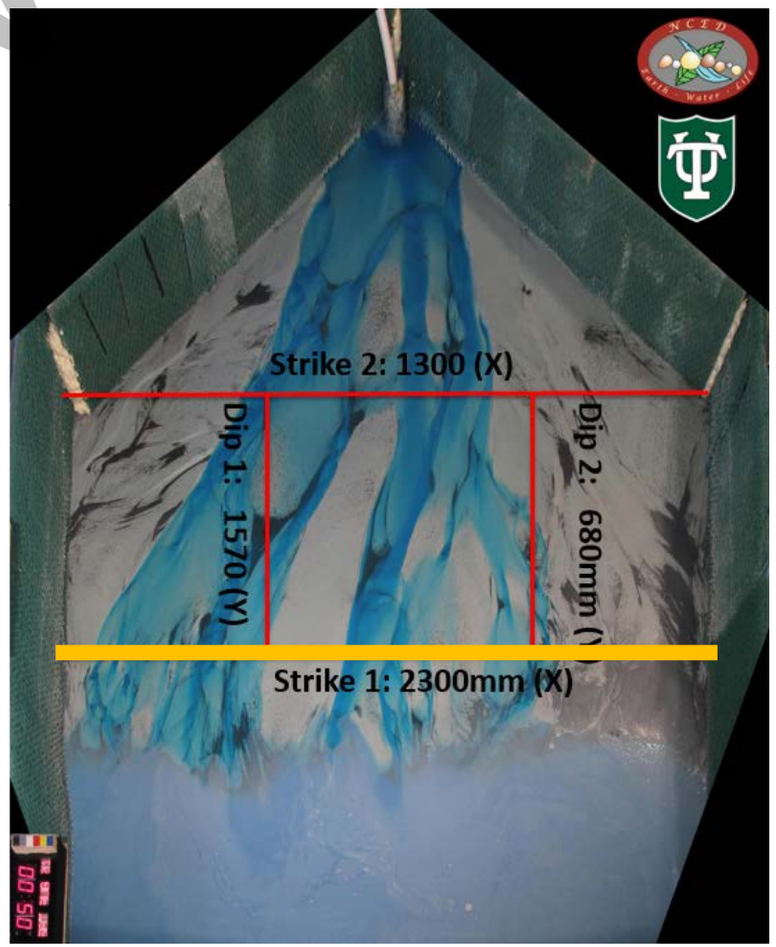




Accommodation vs. Supply

Depositional facies architecture is an interplay of Accommodation and sediment supply

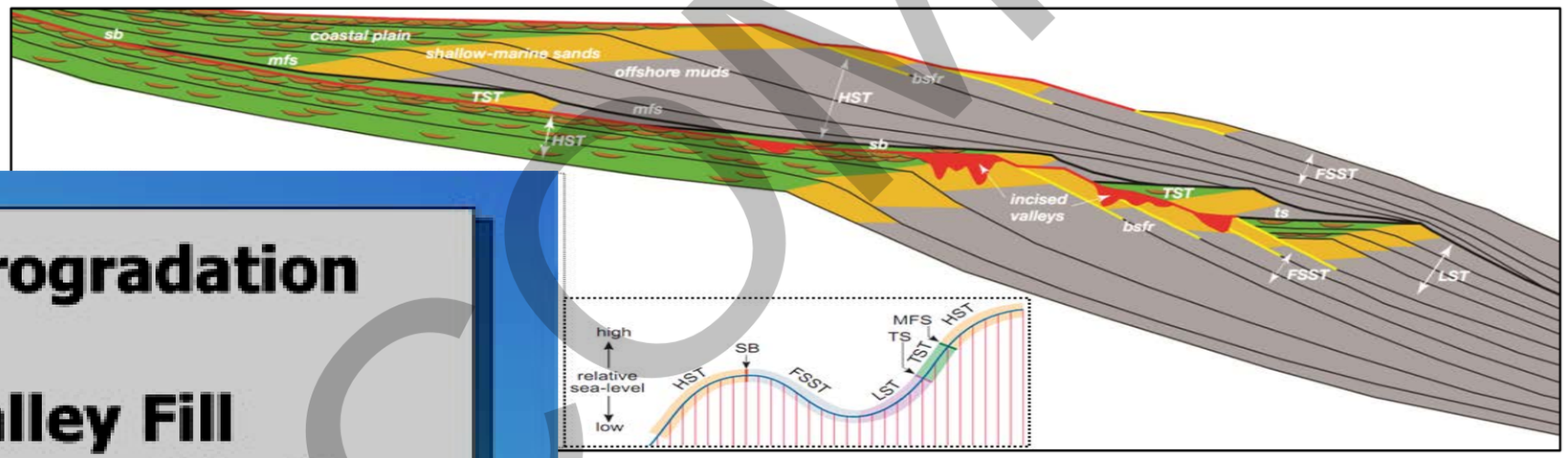




Development of Systems Tract

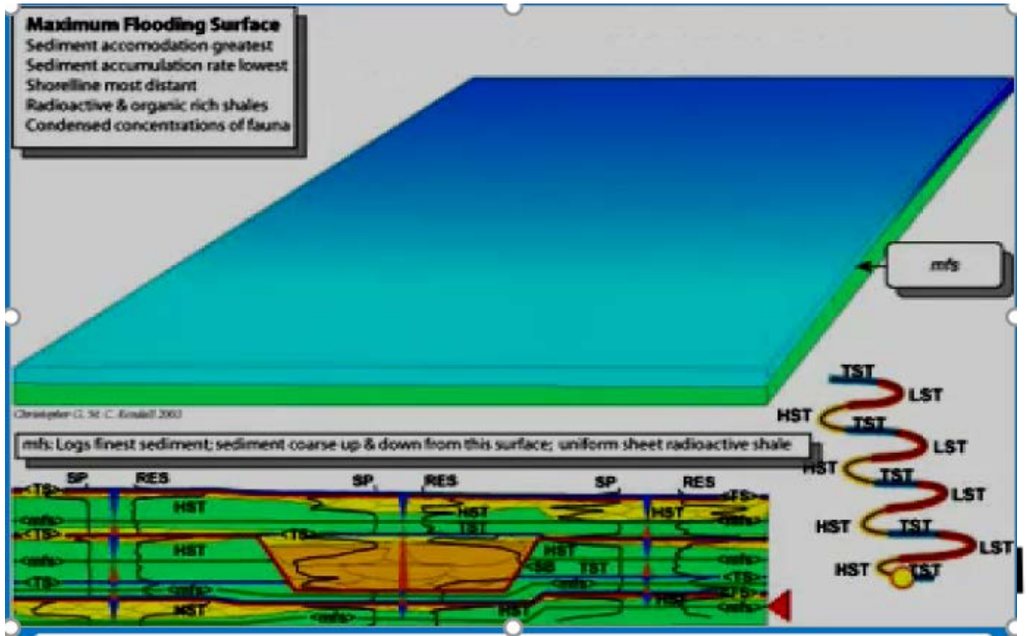
Land

Sea

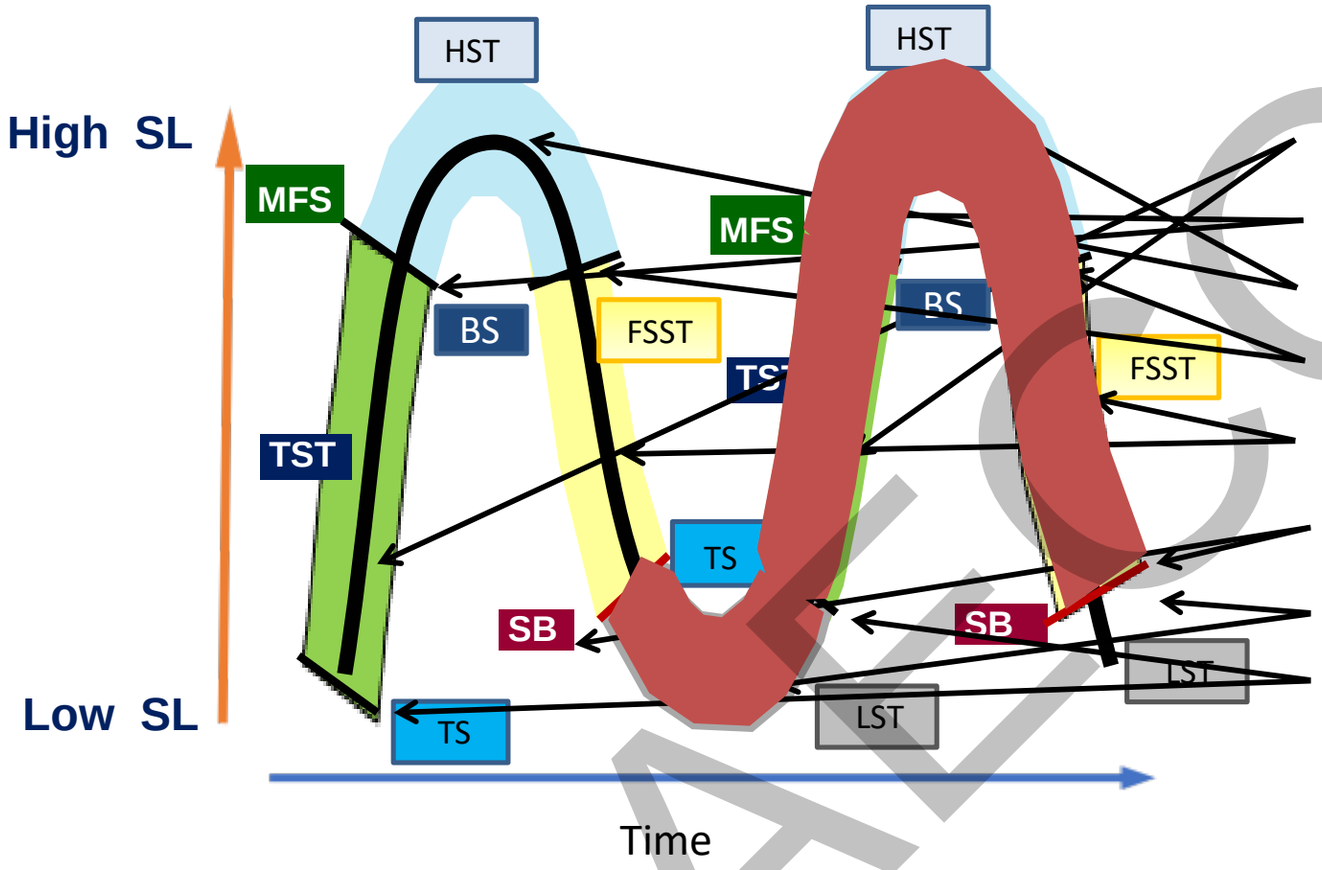


Strandplain Progradation
&
Incised Valley Fill
"La Pascua Formation"
Guarico Sub-Basin - Venezuela

Animation & Annotation
by
Christopher G. St. C. Kendall
August 2003



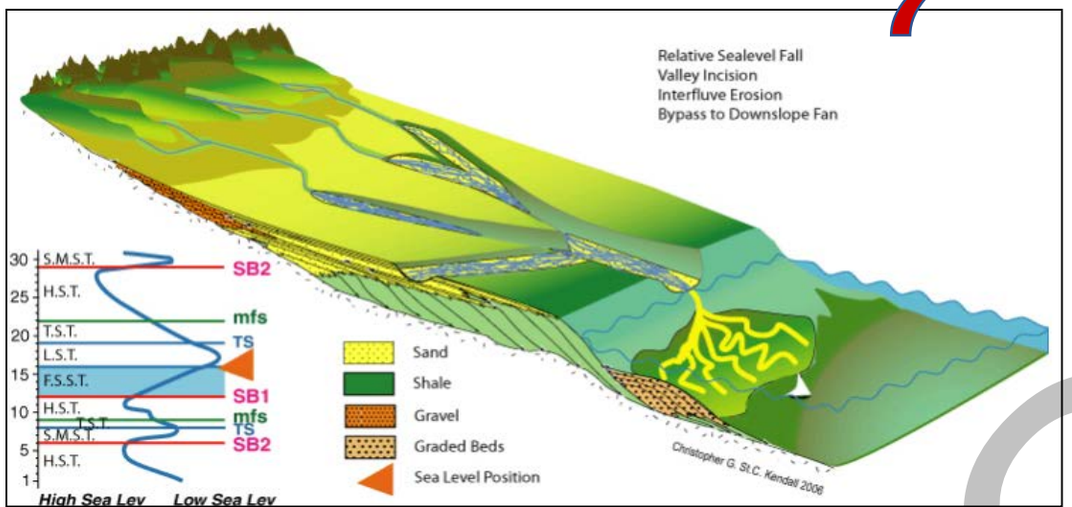
Sea Level Curve…



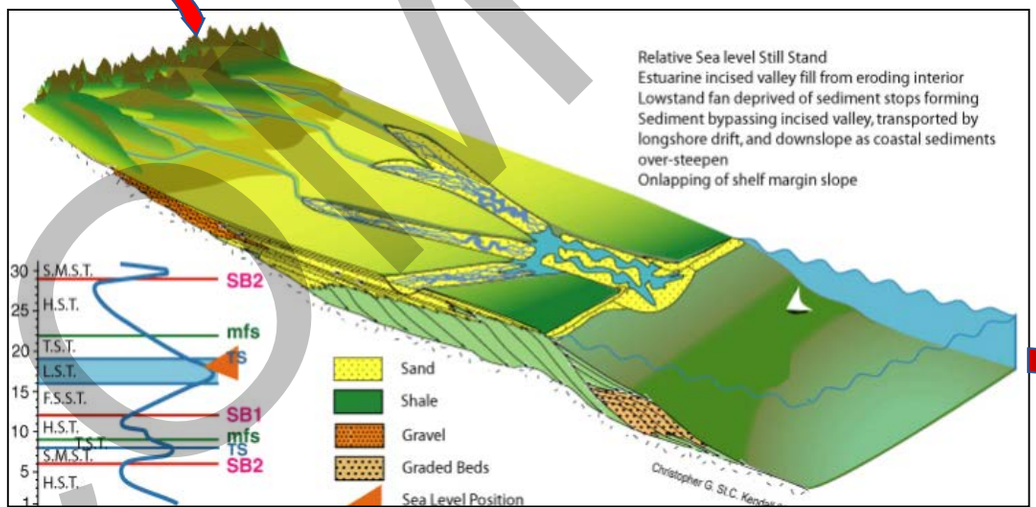
Sequence

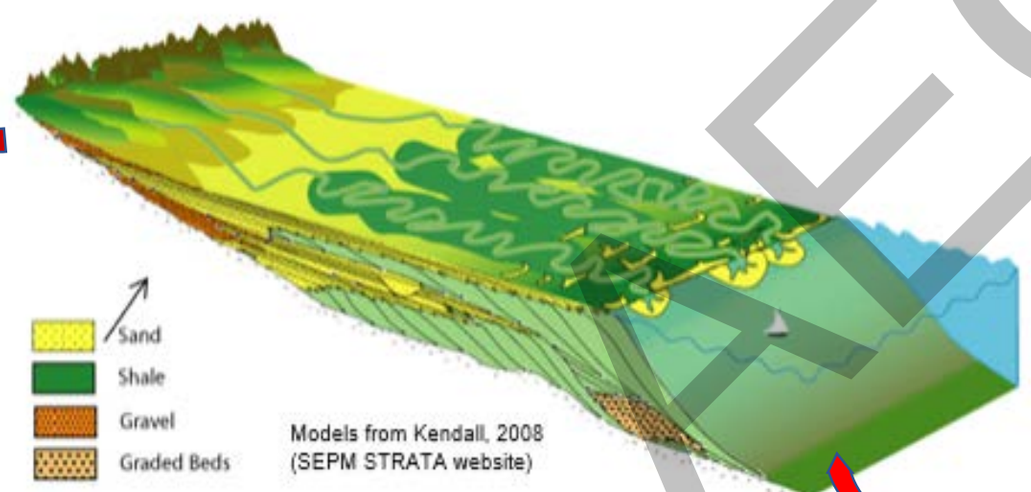
Cycle of Depositional Sequence

FSST

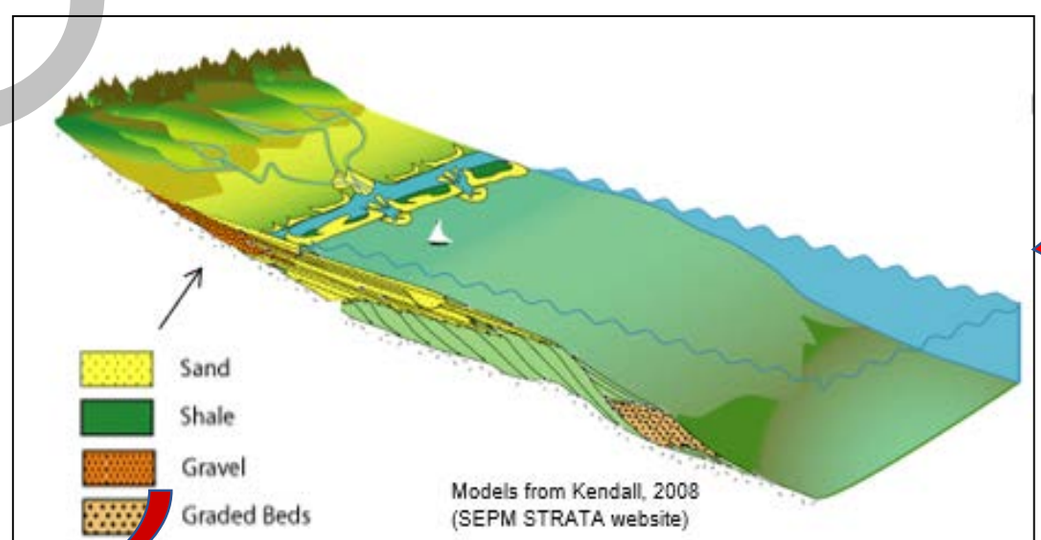


LST



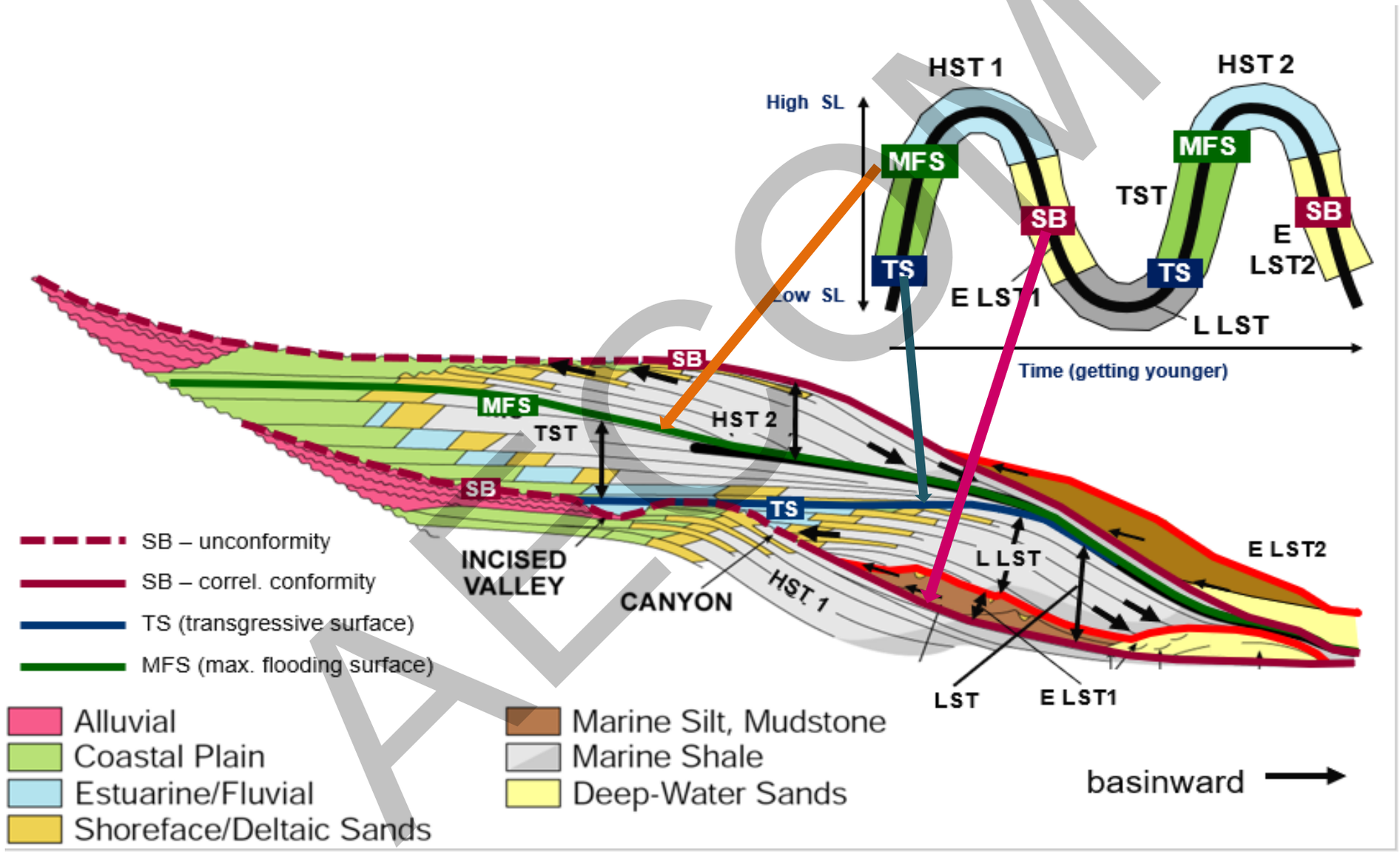


HST

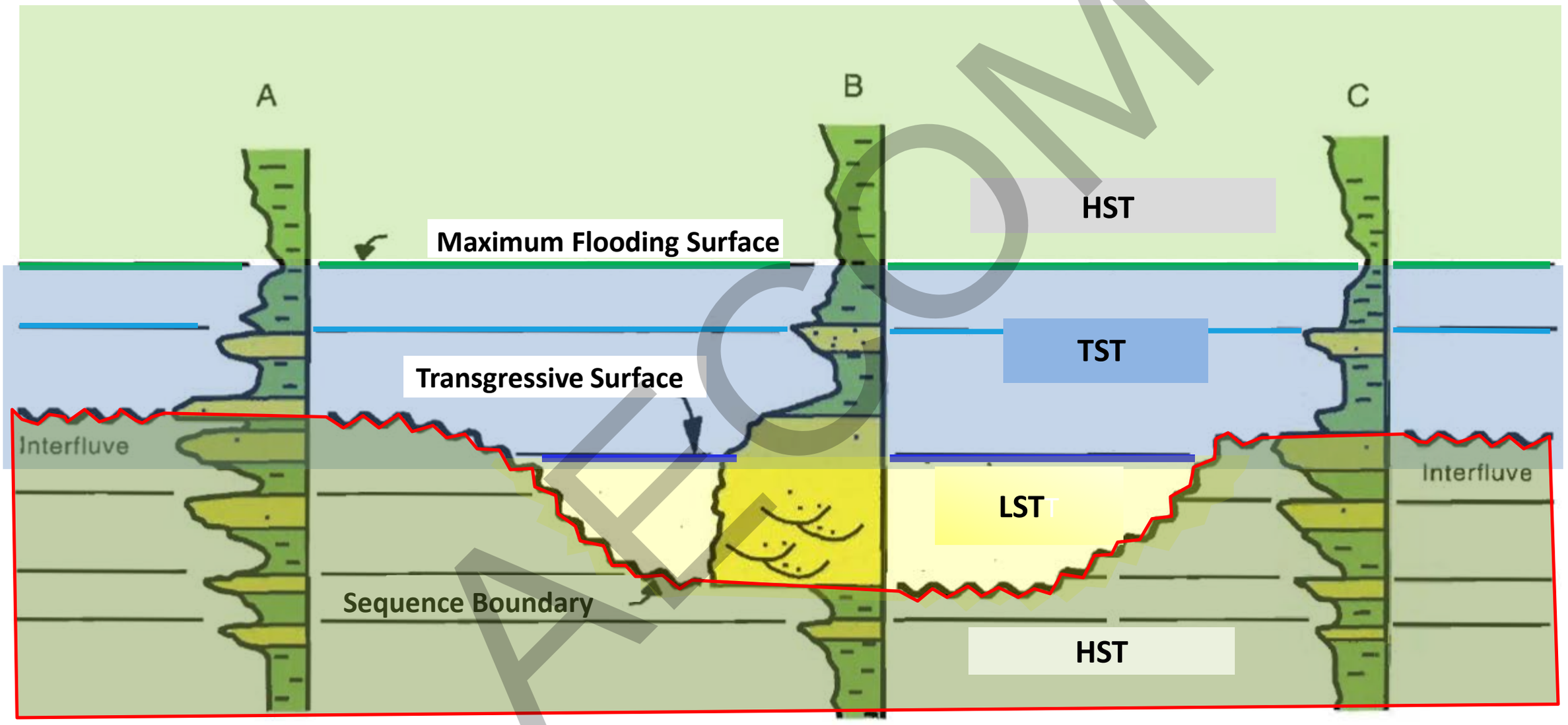


TST

The ‘Slug’ Model

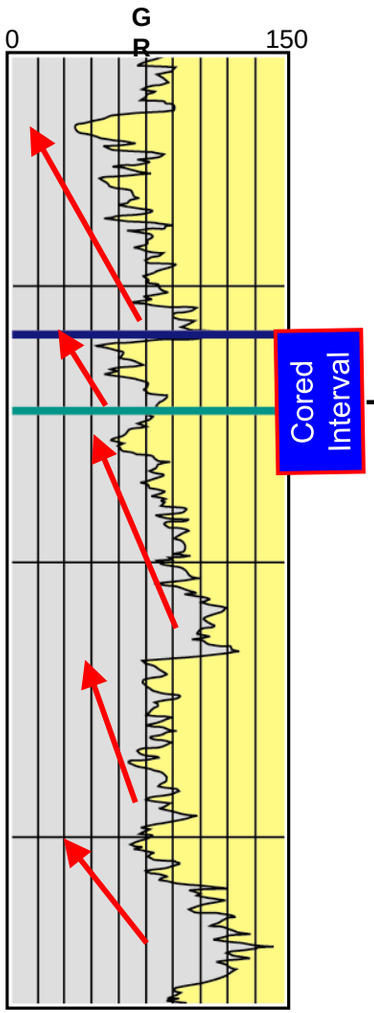


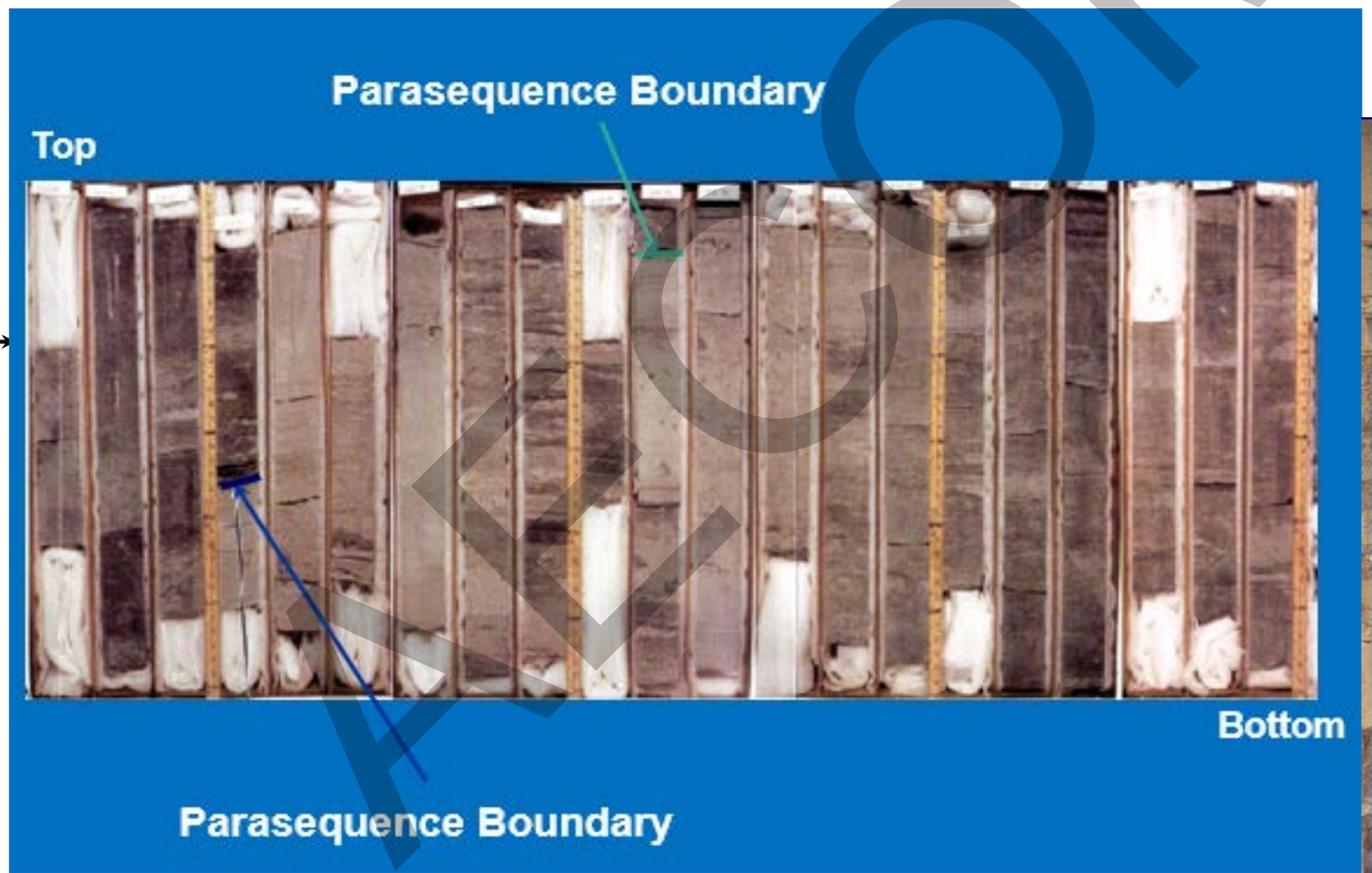
Thought Exercise

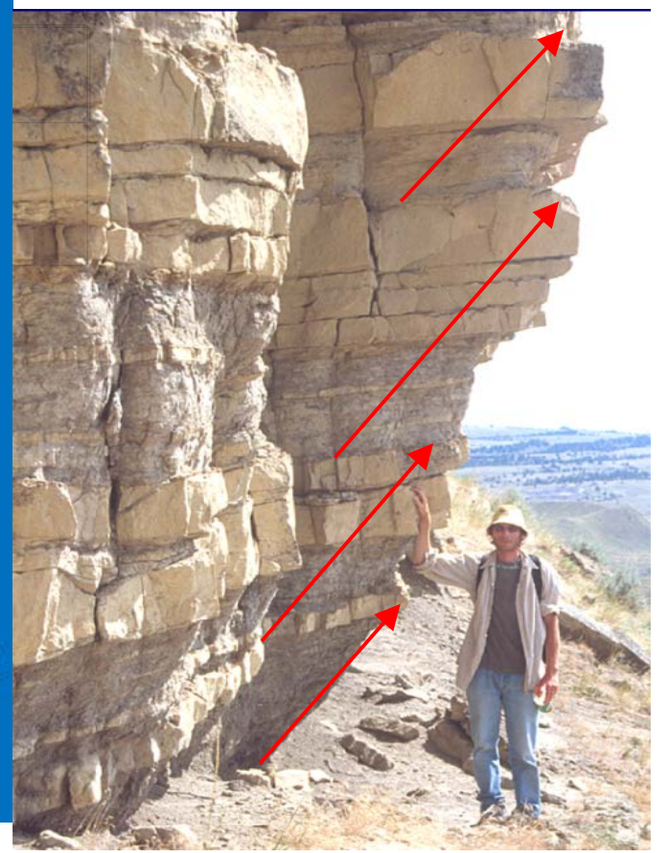


Parasequence Sets in Logs, Core and Outcrop

Parasequence = building block of sequences.

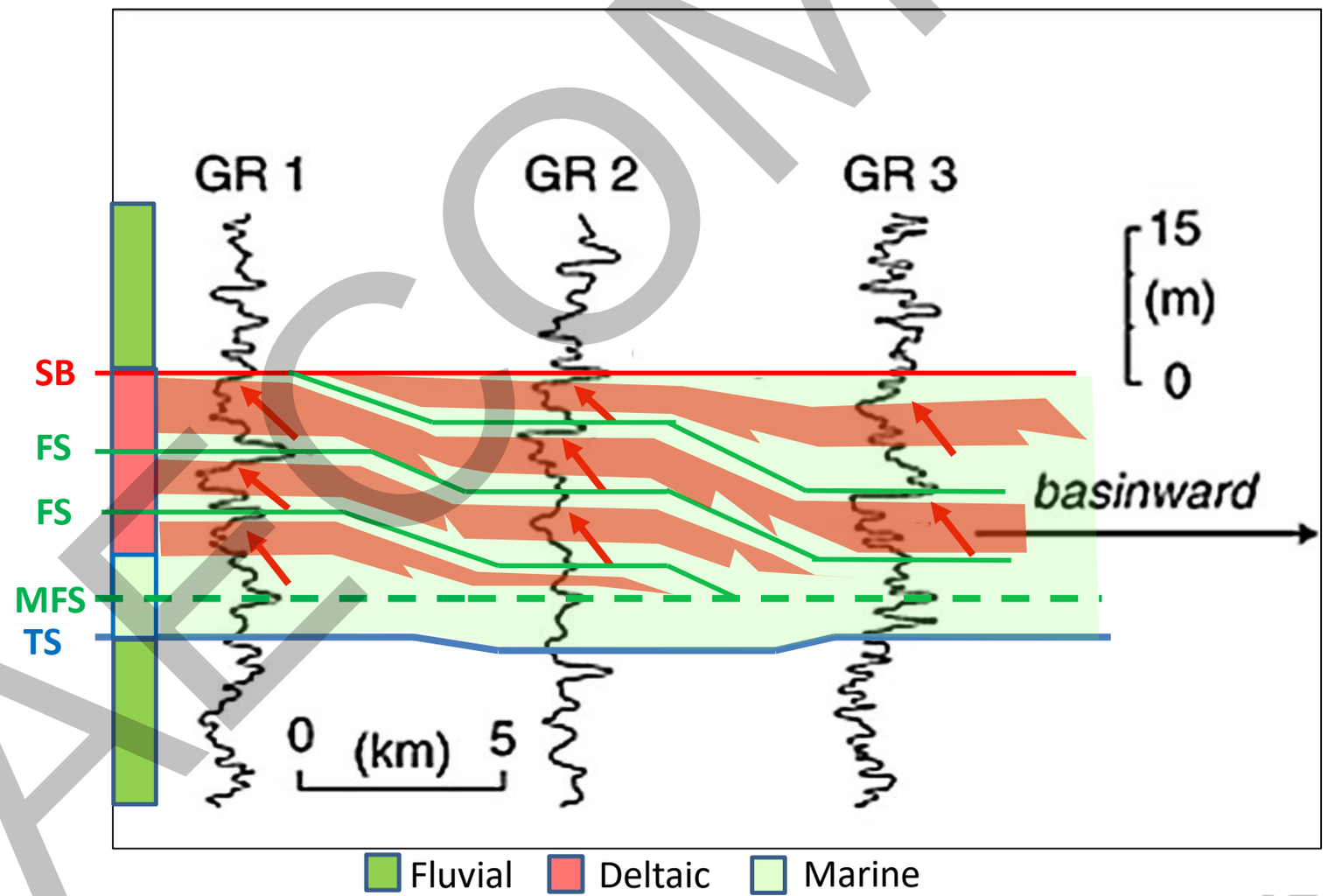






How to Correlate Parasequence Sets

- Note any facies description
- Identify facies vertical trends in logs
- Consider landward to seaward facies transition
- Identify major stratigraphic boundaries for target zone
- Identify all flooding surfaces (shale markers) between sandbodies and correlate them (don't correlate by 'sand tops'!).
- Understand sandbody geometry in context of the framework

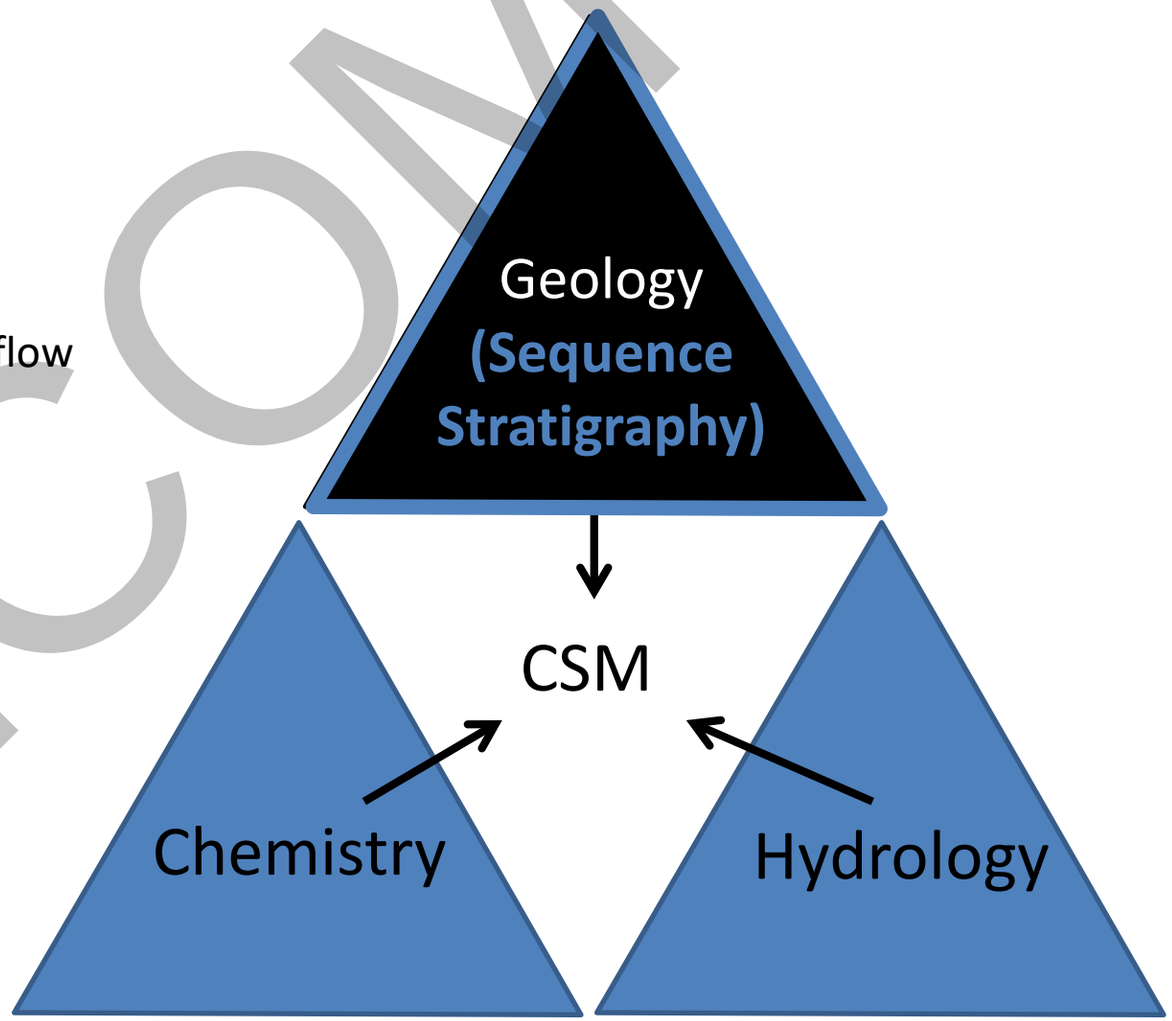


Lecture 3: PRISM® + Case Studies

PRISM® – PRedictive Integrated Stratigraphic Modeling

1. Geology:
   - Background research
   - Analyze site-specific data/local outcrops
   - Develop relevant facies models
   - Sequence stratigraphic correlation
2. Hydrology:
   - Define geologic constraints to groundwater flow
   - Water level elevations
   - Identify local surface water bodies
3. Chemistry:
   - Well screen/trend analysis
   - Define heterogeneity
     - Back-diffusion
     - Emerging contaminants

A fully-integrated CSM for a holistic understanding of the subsurface

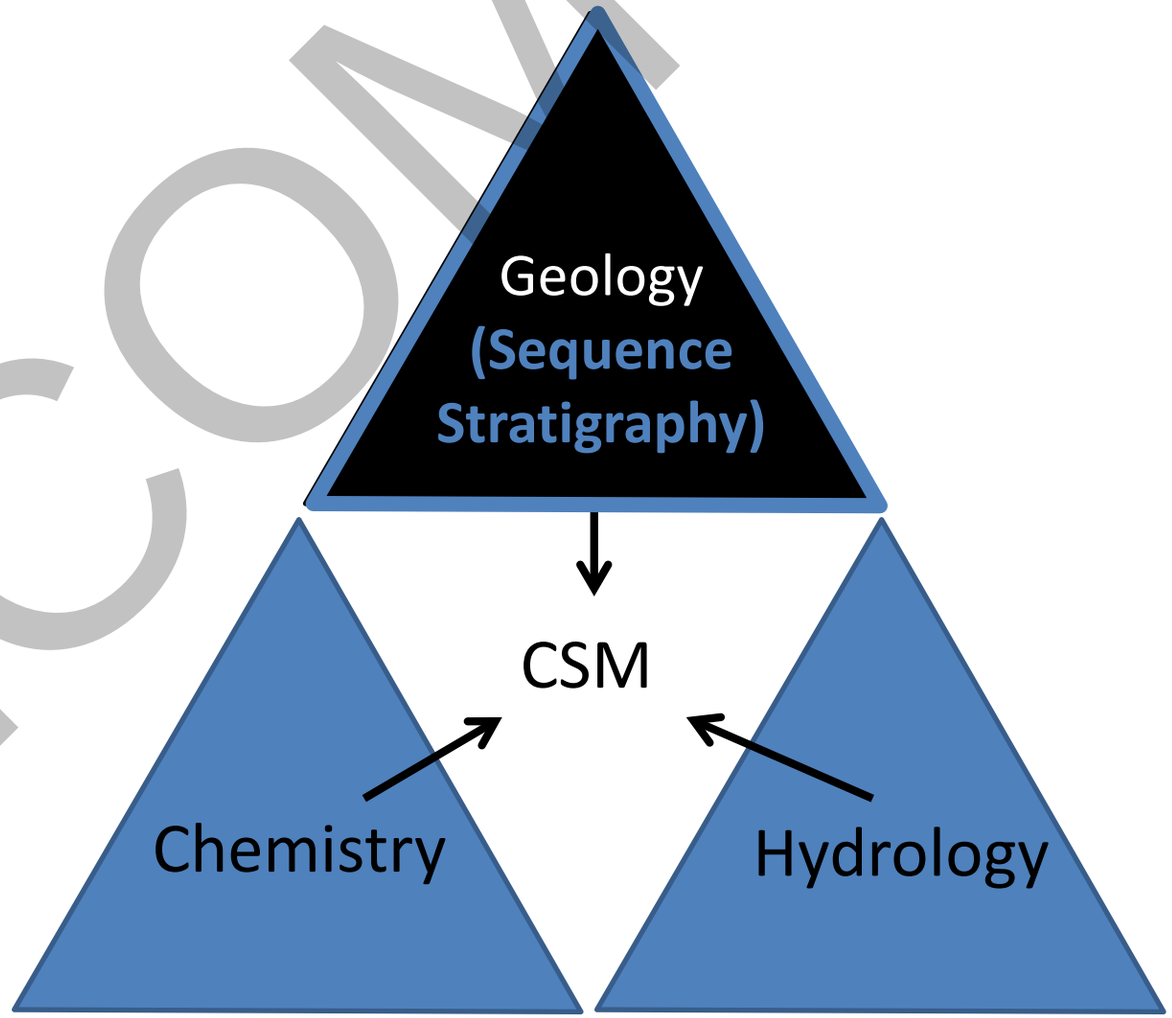


PRISM® – PRedictive Integrated Stratigraphic Modeling

Successful applications include:

- Reduce Life-Cycle Costs:
  - Leverage pre-existing data
  - Streamline investigations
  - Optimize LTM & remediation
- Define and Manage Liability
- Build Stakeholder Trust
- Mass Flux
- Emerging Contaminants

A fully-integrated CSM for a holistic understanding of the subsurface



Case Study 1

PRISM®

PRedictive Integrated Stratigraphic Modeling

Puchack Well Field Superfund Site

Purpose: demonstrate how sequence stratigraphy can be successfully applied at an complex remedial site.

AECOM

The Site

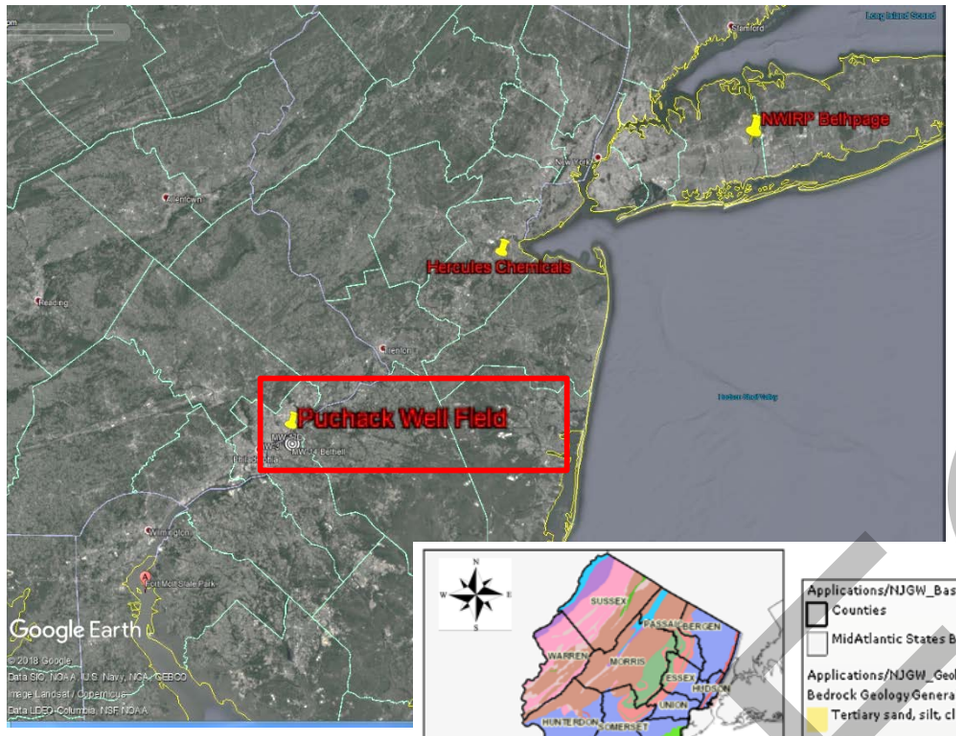
Problem:

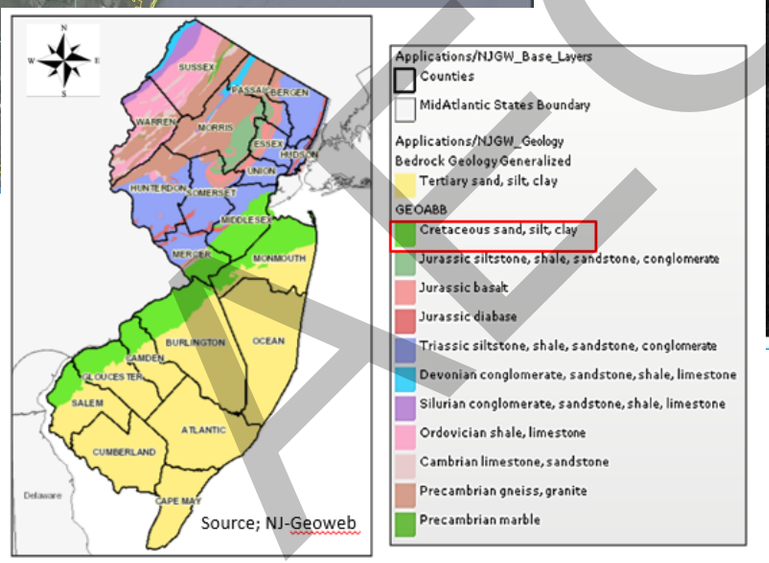
High contamination of hexavalent chromium above 10µg/L is encountered at various depths of the Puchack Well Field Superfund Site in New Jersey. Poor understanding of the subsurface has resulted in uncertainty related to injection strategy for site remediation.

Goals:

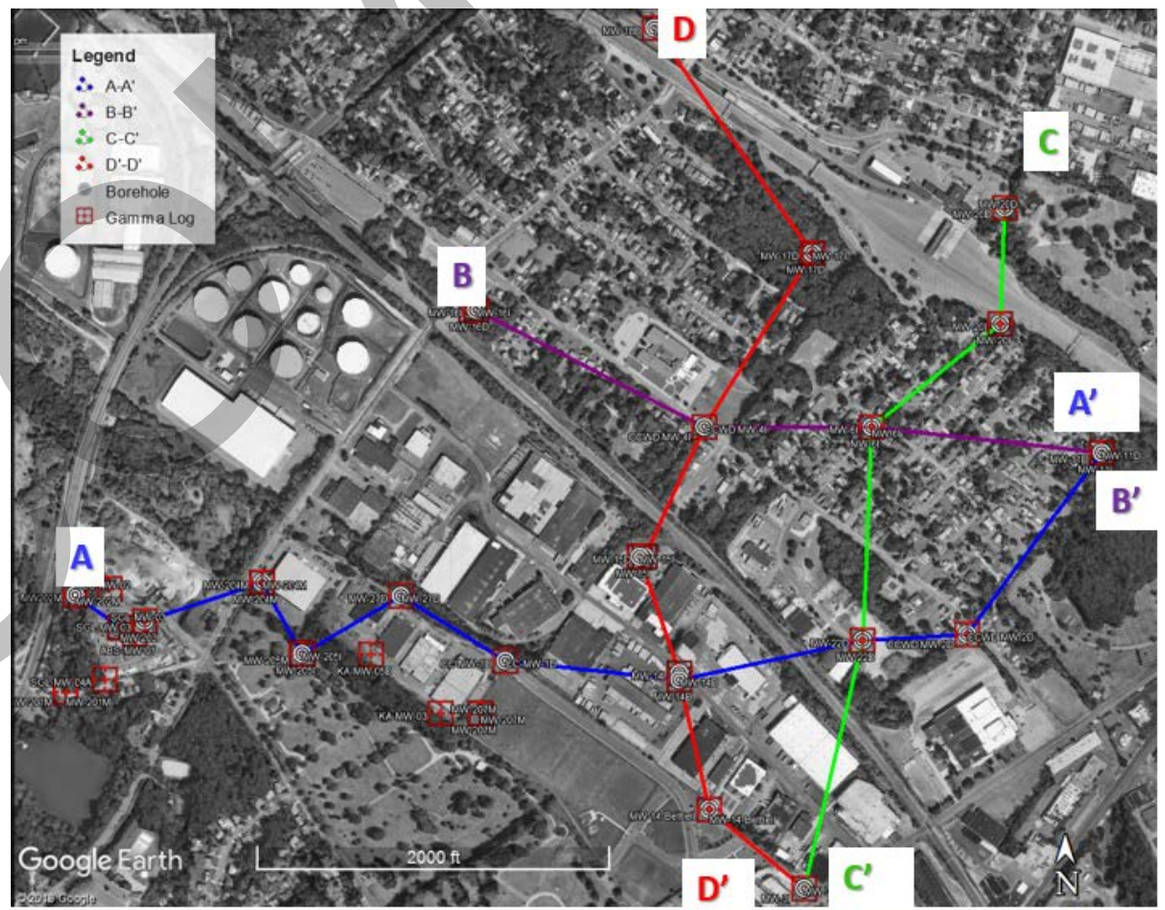
- Understand the subsurface heterogeneity of the Site in order to identify potential flow units and confining units in a predictive way
- Evaluate the impact of present injections in mitigating contamination
- Help develop a predictive remedial strategy based on stratigraphic understanding.

Location & Cross-section Transects





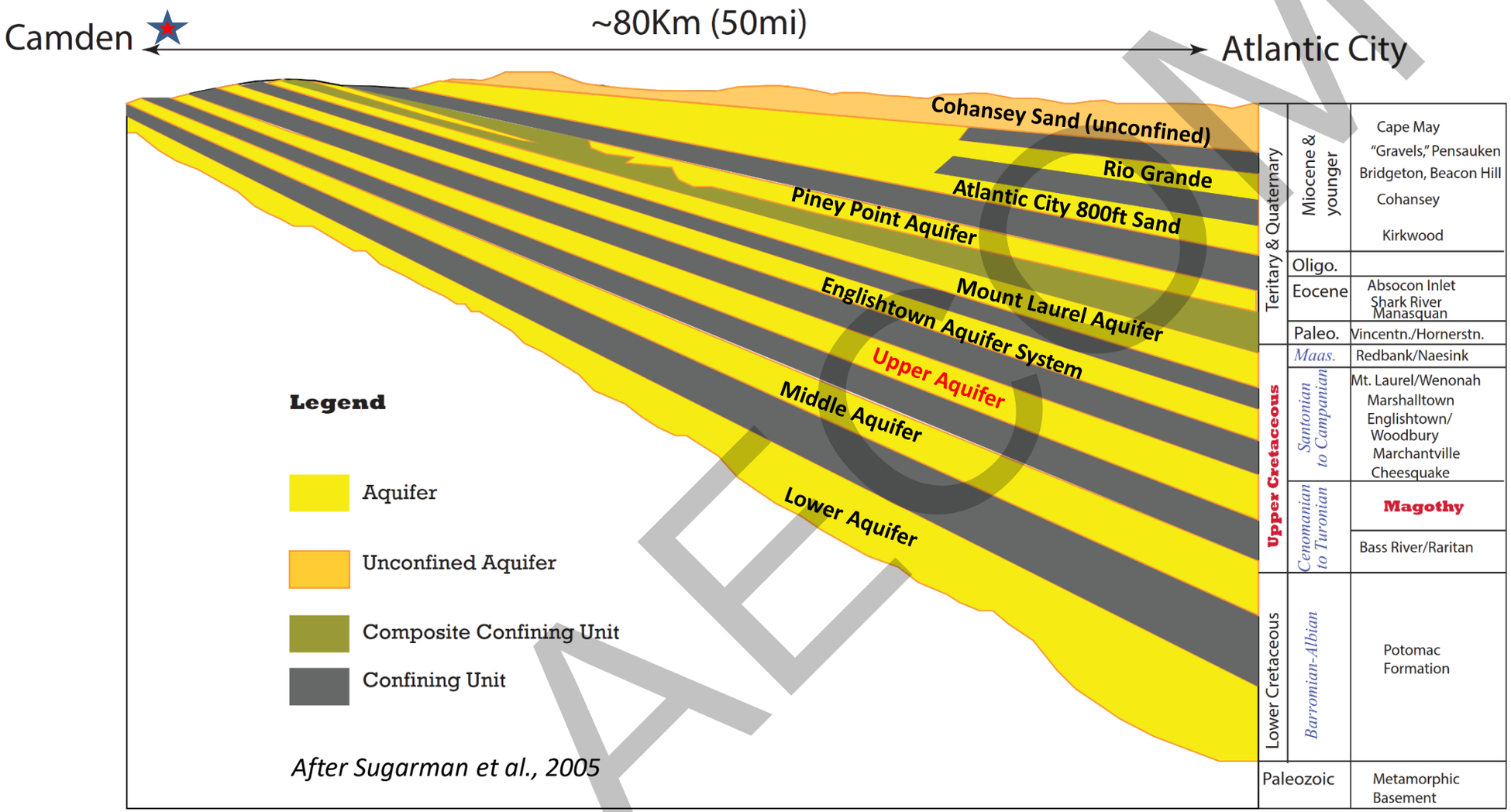
Location

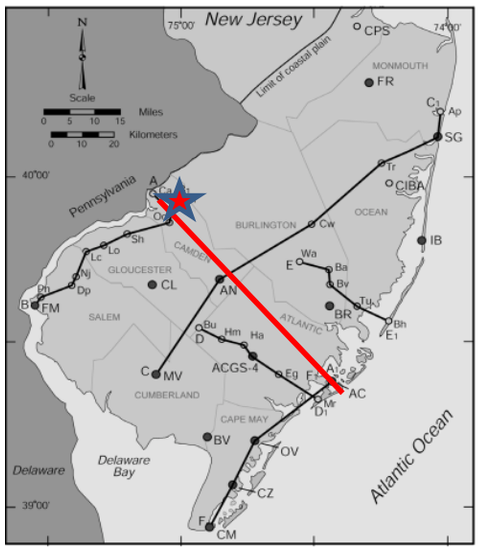


Cross-section transects

AECOM

Hydrogeological Units of Puchack Well Field Superfund Site (Camden, NJ)



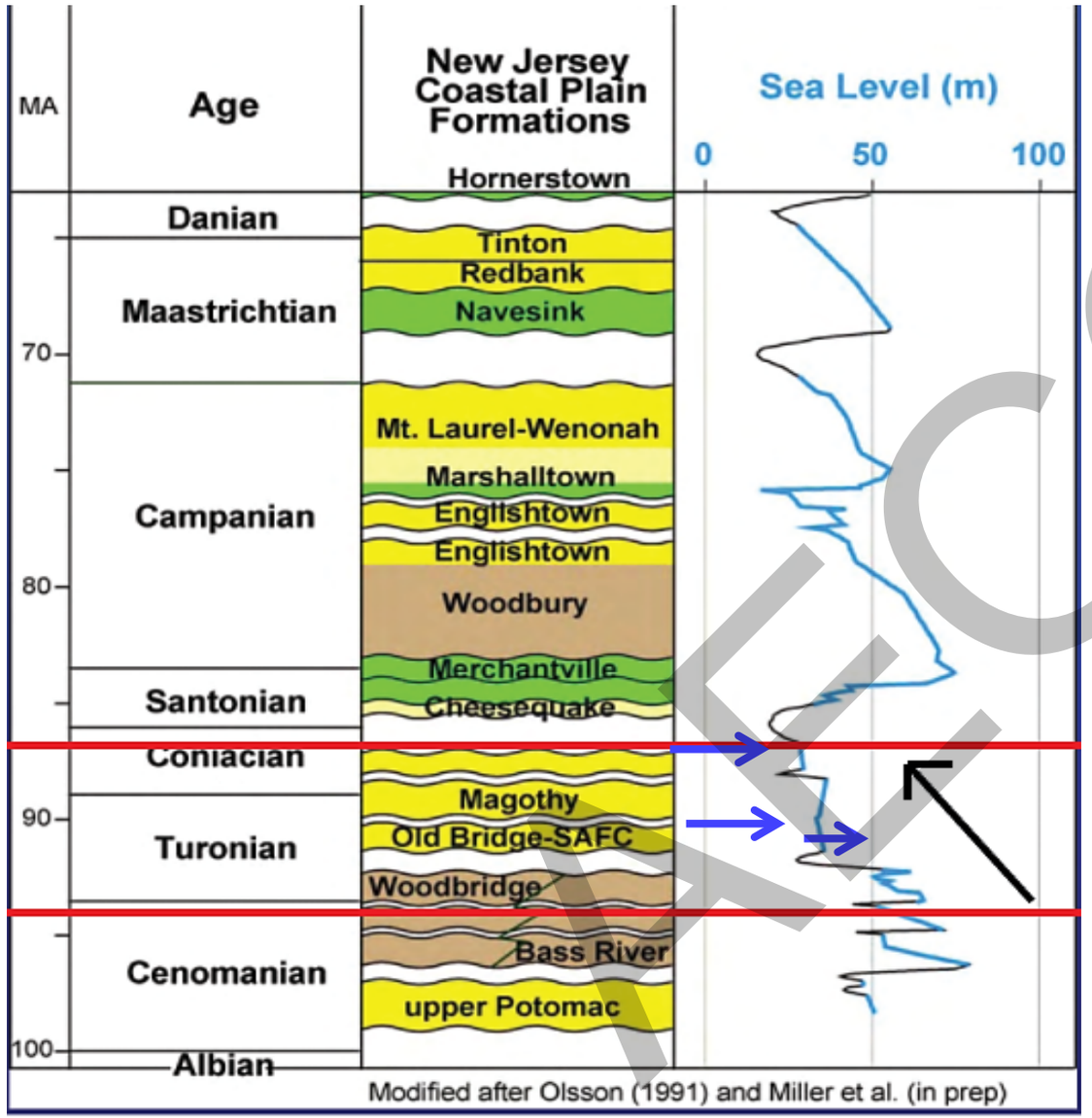


Aquifer sediments at the Site represent the Upper Cretaceous Magothy Formation

★ Approx. site Location

AECOM

Relative Sea-level Changes During the Upper Cretaceous



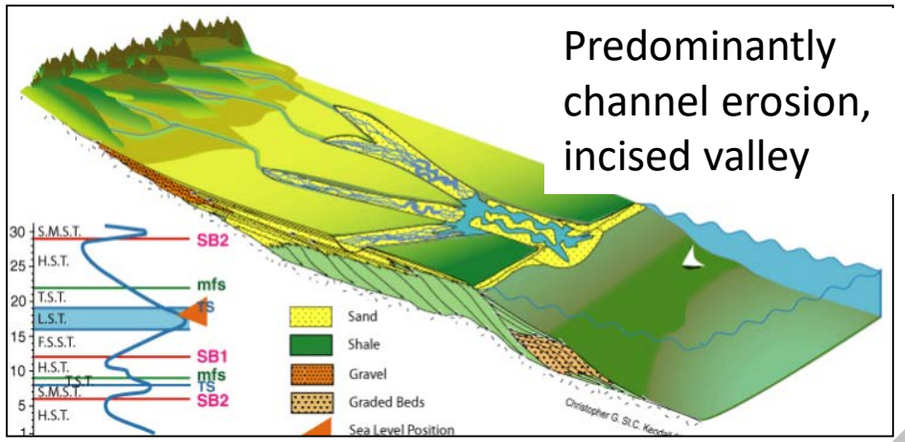
The Upper Cretaceous (Turonian) time is marked by an overall drop in Sea-level with several high resolution rise and fall

→ 3rd order drop in sea level = forced regression (i.e. delta progradation)

→ Probable 4th order drop in sea level = fluvial erosion and channel fill

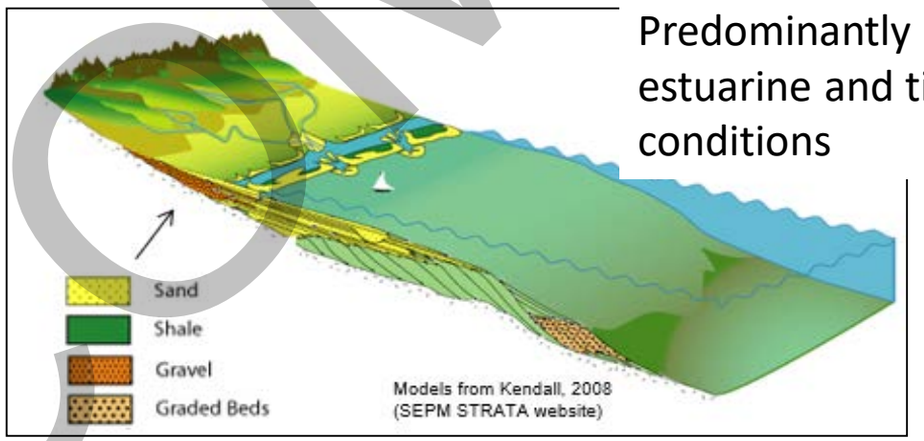
Depositional Cycles Applicable to the Site

Lowstand Systems Tract (LST)



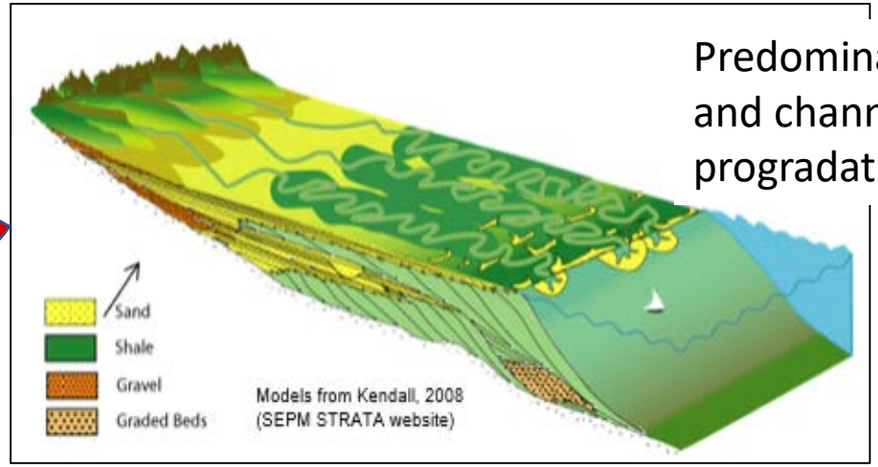
Predominantly channel erosion, incised valley

Transgressive Systems Tract (TST)

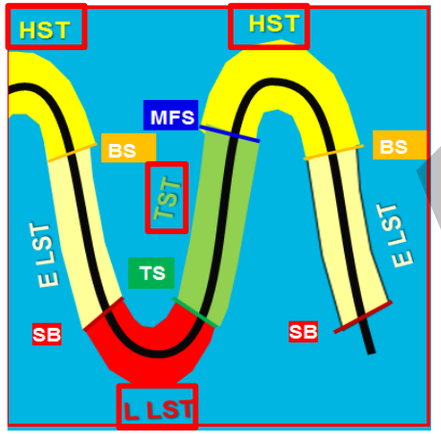


Predominantly estuarine and tidal conditions

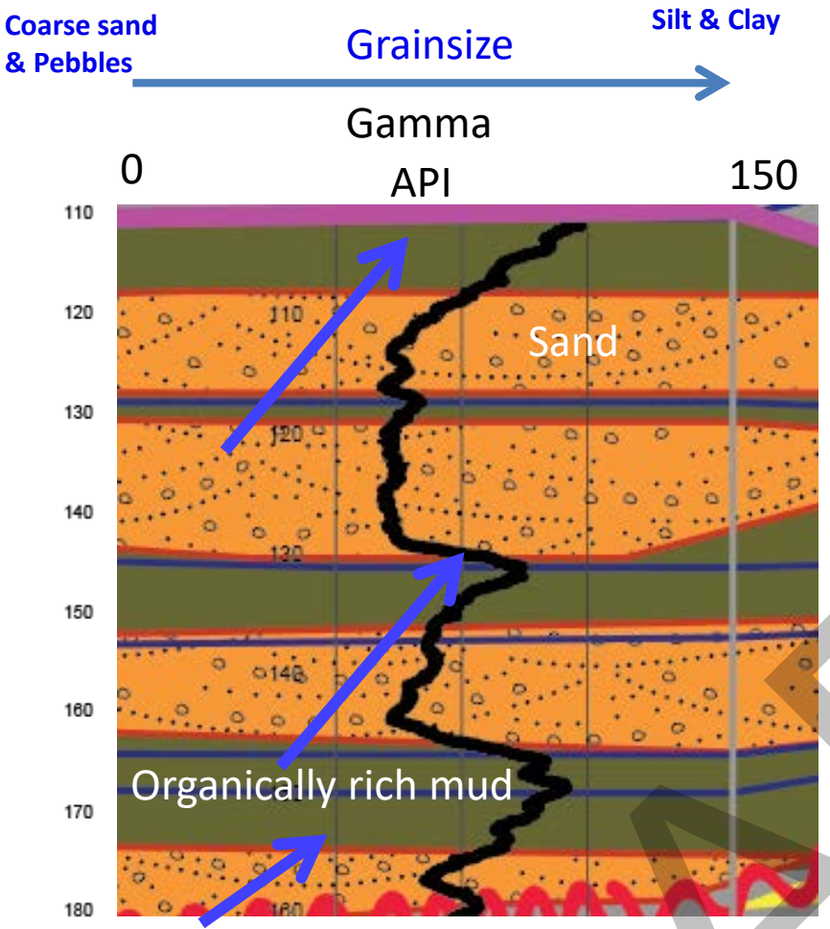
Highstand Systems Tract HST



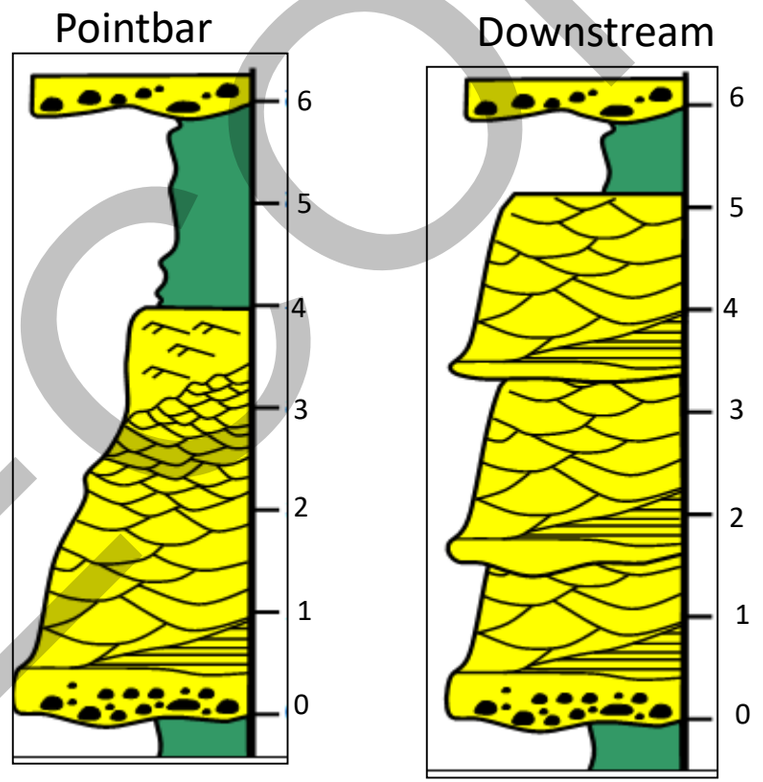
Predominantly delta and channel progradation



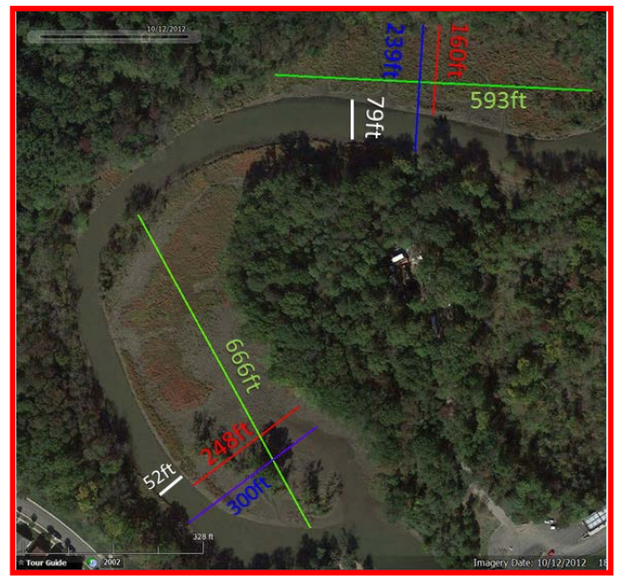
Identifying Depositional Facies: Fluvial Deposits



Example of stacked channel bars Identified in logs



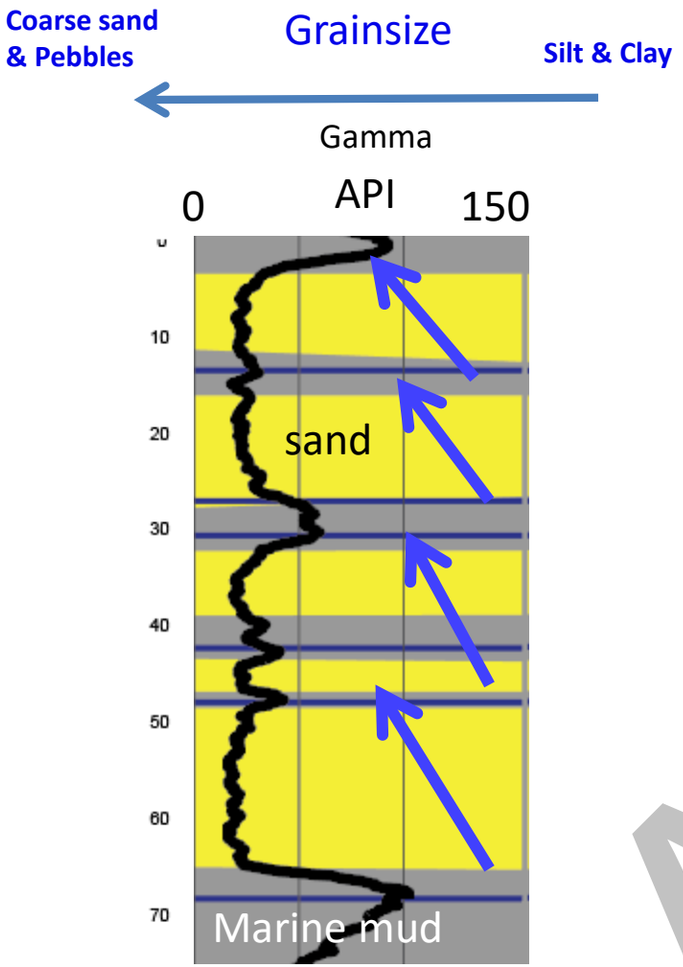
Model vertical profile of channel bar deposits (Miall et al., 1975)



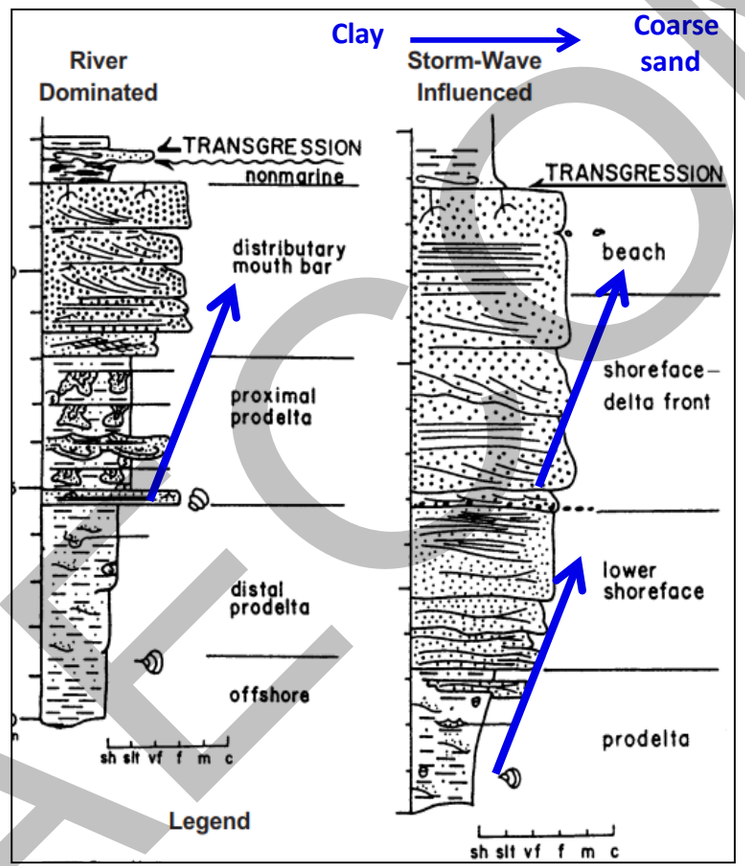
Modern pointbar, Fort Belvoir

AECOM

Identifying Depositional Facies: Deltaic Deposits



Example of stacked mouthbars identified in logs (Parasequences)



Vertical model of delta mouthbars (after Bhattachariya, 1991)

Modern analog of delta moutbars

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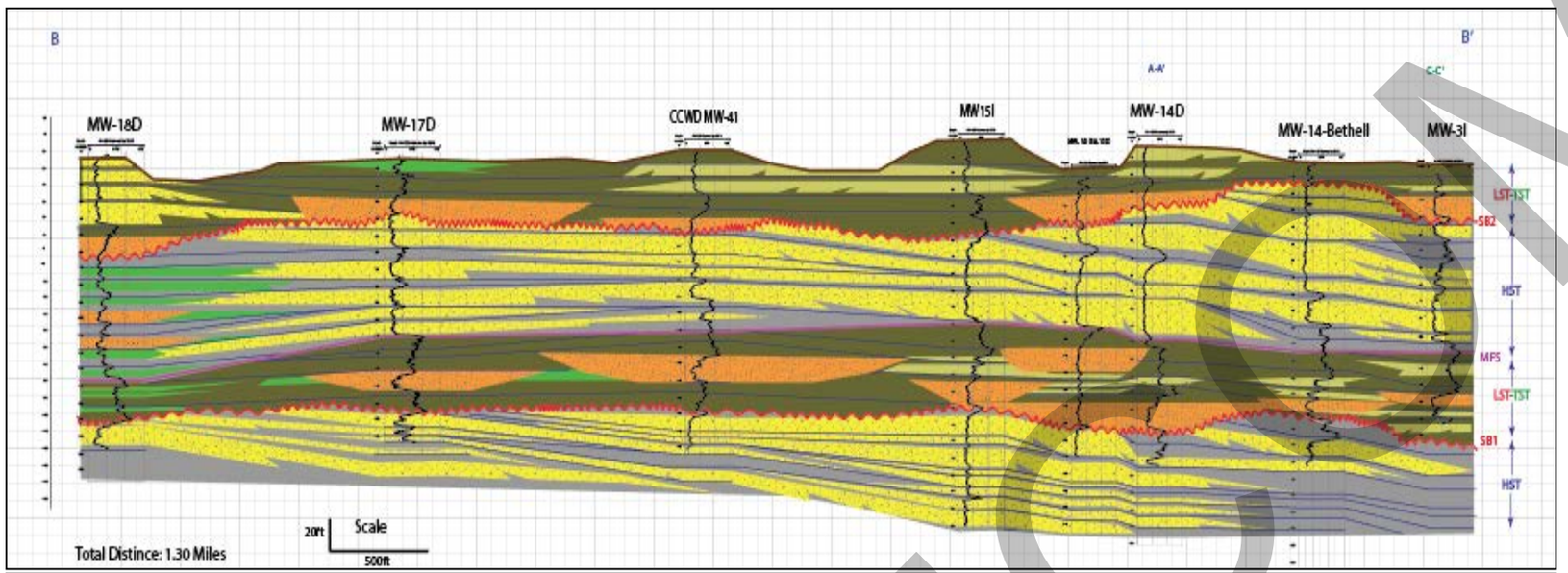
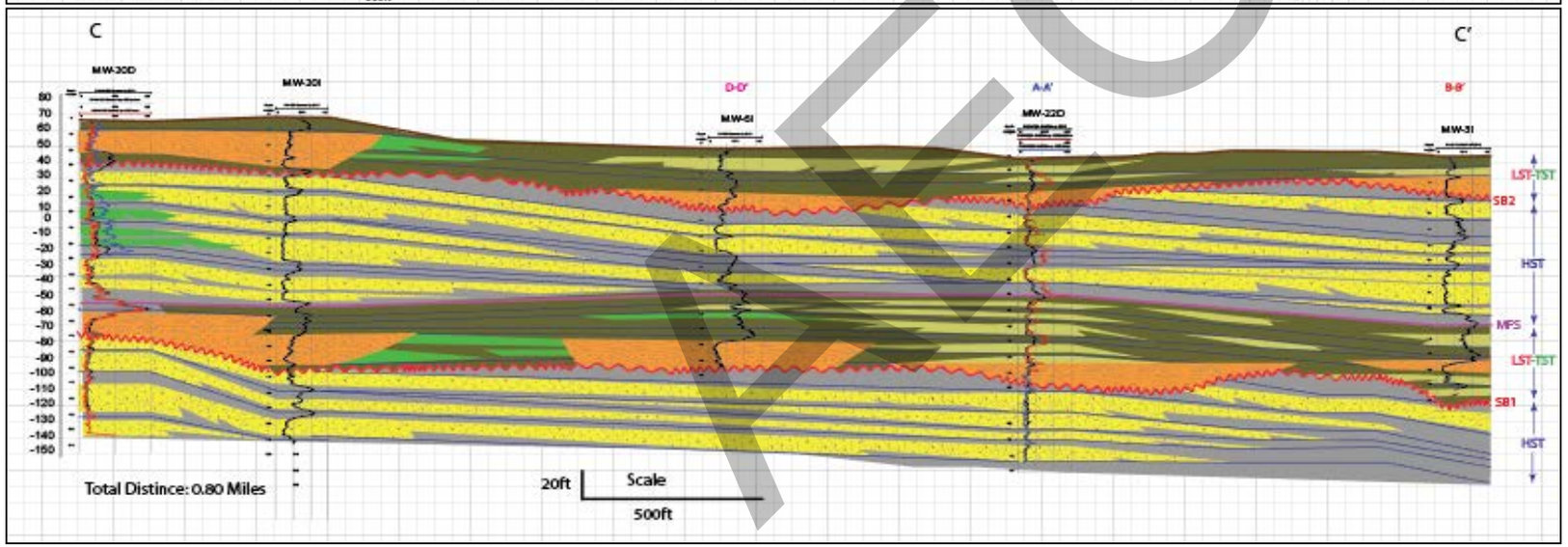
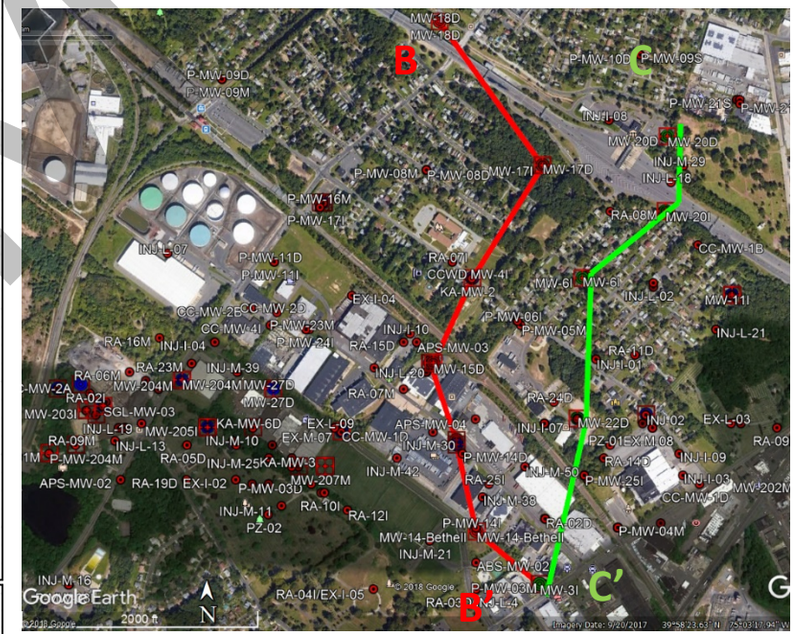
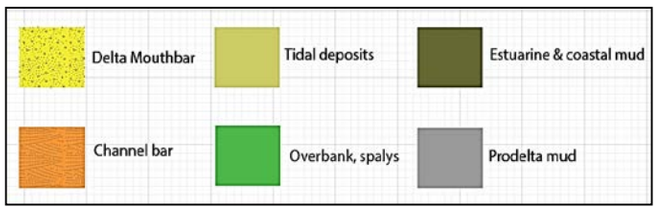
Dip Sections

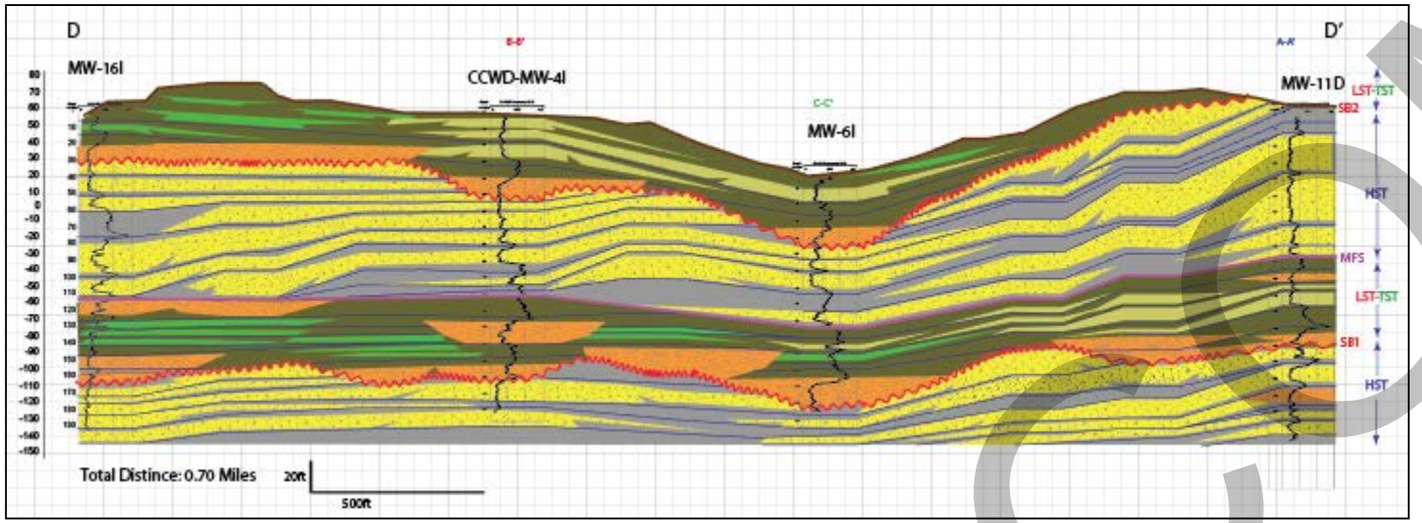


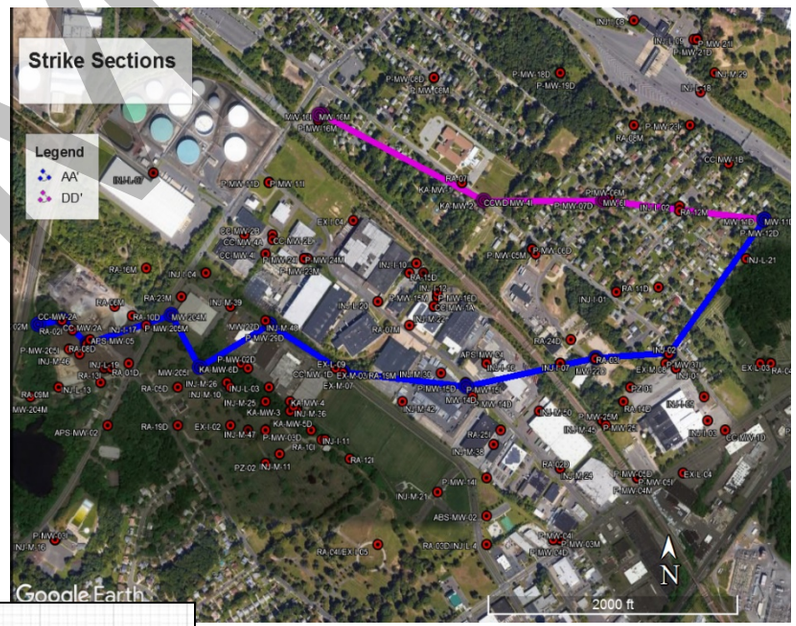


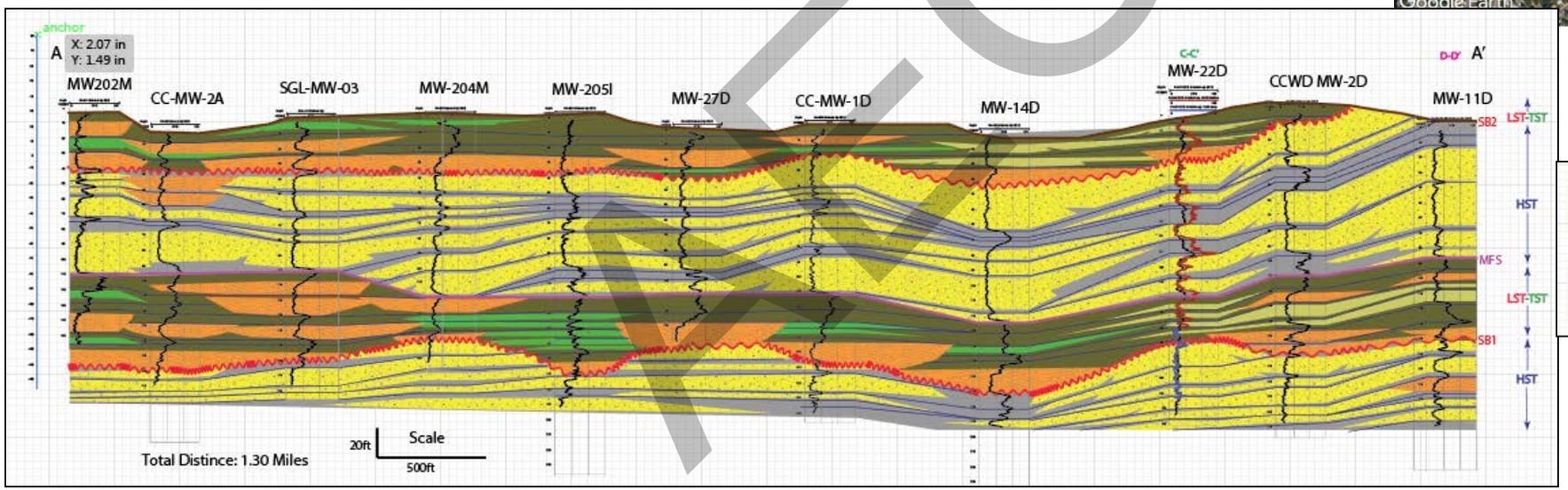


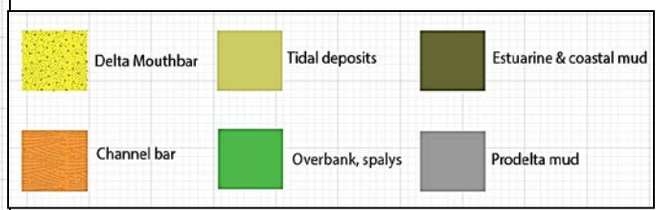


Strike Sections

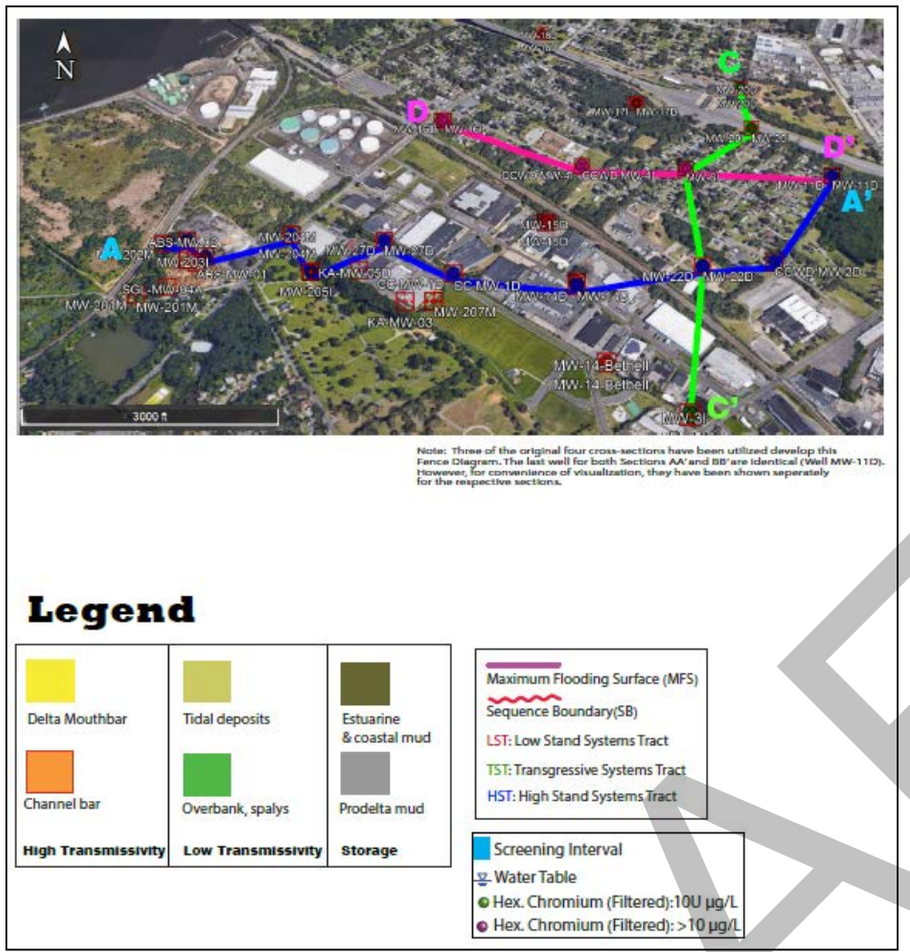


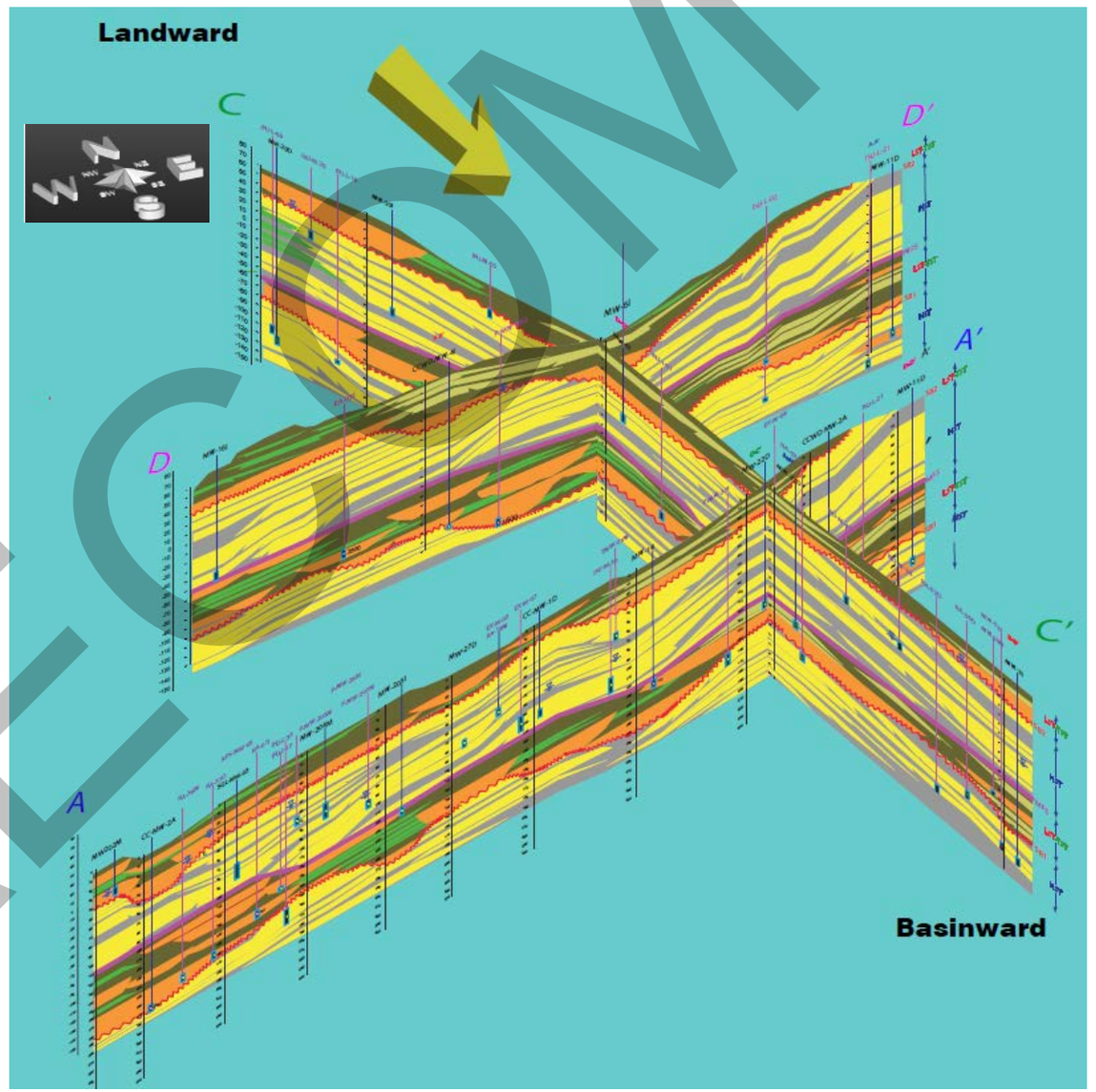




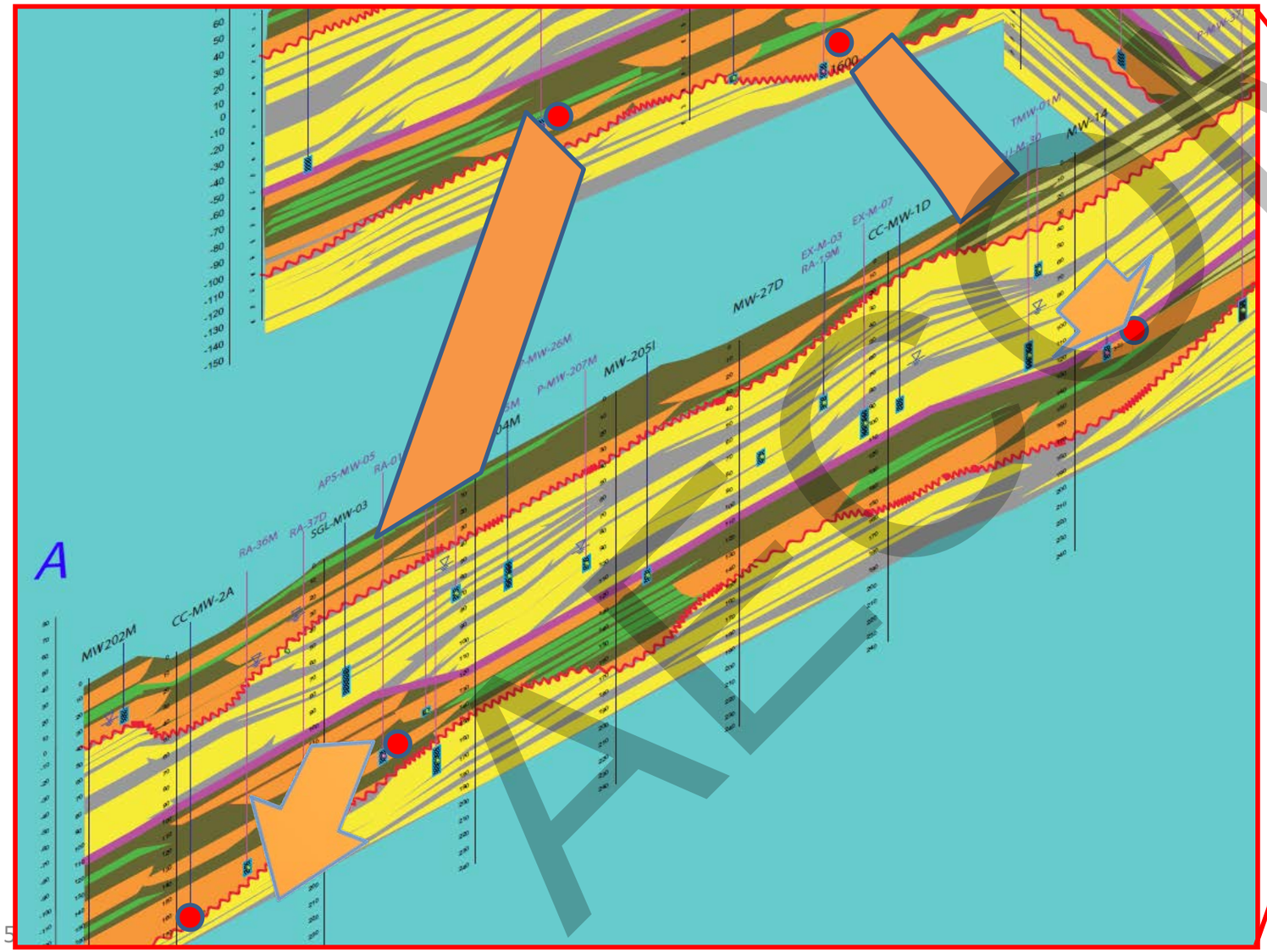


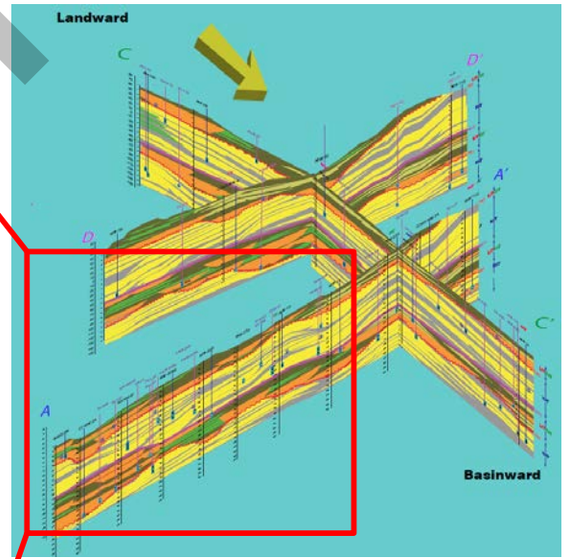
Fence Diagram: Sections ADC





High Contamination Flow-Paths



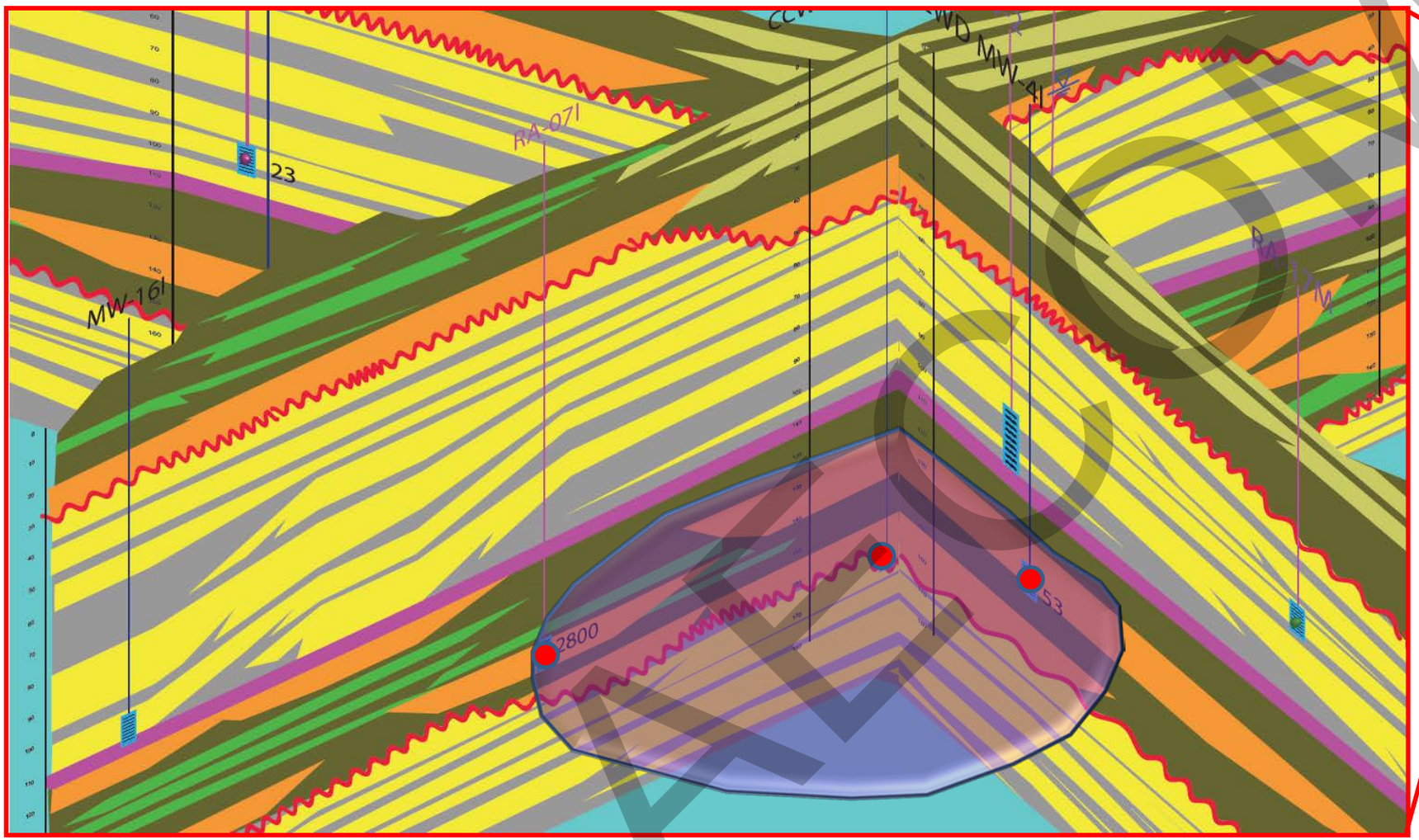


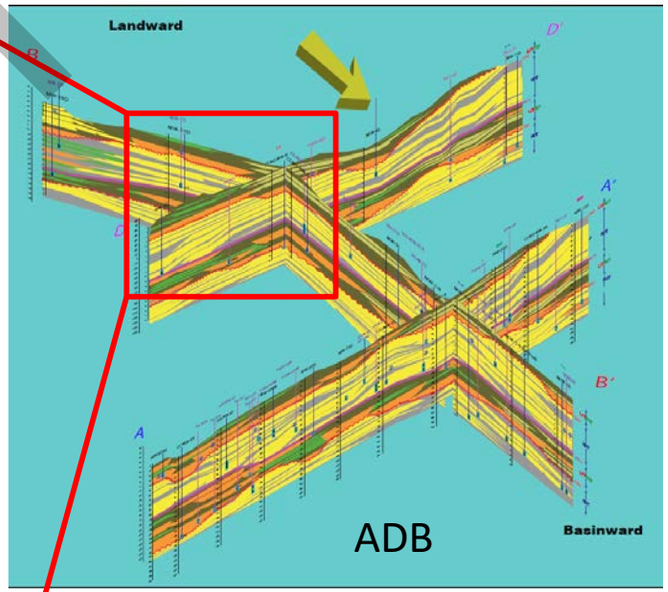
High concentration of contamination predominantly moving through the channel bars of LST/TST1

- Concentrations above MCL

AECOM

High Contamination Flow-Paths





High concentration of contamination predominantly moving through the channel bars of LST/TST1

● Concentrations above MCL

AECOM

Summary of Transmissivity & Connectivity

Facies Symbol	Depositional Environment	Transmissivity	Connectivity
	Fluvial Point Bar	High	Low
	Delta Mouthbar	Moderate to high	High
	Tidal Bar	Low to moderate	Low to moderate
	Overbank Fines	Very low	Moderate
	Prodelta Mud	Very low	Very High
	Estuarine Mud	Non-transmissive	Very High

Connectivity	Lateral Cor. Distance
Very High	>5000ft
High	1700ft-5000ft
Moderate	1500-1700ft
Low	300-1500ft

- Amalgamated channel bar thickness:~5-20ft (individual channel bars ~5-10 ft.)
- Delta mouthbars are ~10ft. to >30ft (amalgamated)
- Each systems tracts (HST & LST/TST units) are 40-70ft. thick

Implications for Effective Remedial Design

- Hexavalent chromium above 10µg/L is predominantly present in the channel sand bars above SB1.
  - Channel sand bars tend to be isolated with lower lateral continuity, therefore previous injections may not have influenced these zones.

- Delta mouth bar deposits above the channelized estuarine unit are below the reporting limit (10µg/L), with rare exceptions.
  - Previous remedial efforts in these highly connected delta mouth bars were likely more effective.

- No contamination data is recorded in the shallowest channel bar deposits above SB2.
  - Focus remedial efforts in deeper units.

Case Study 2

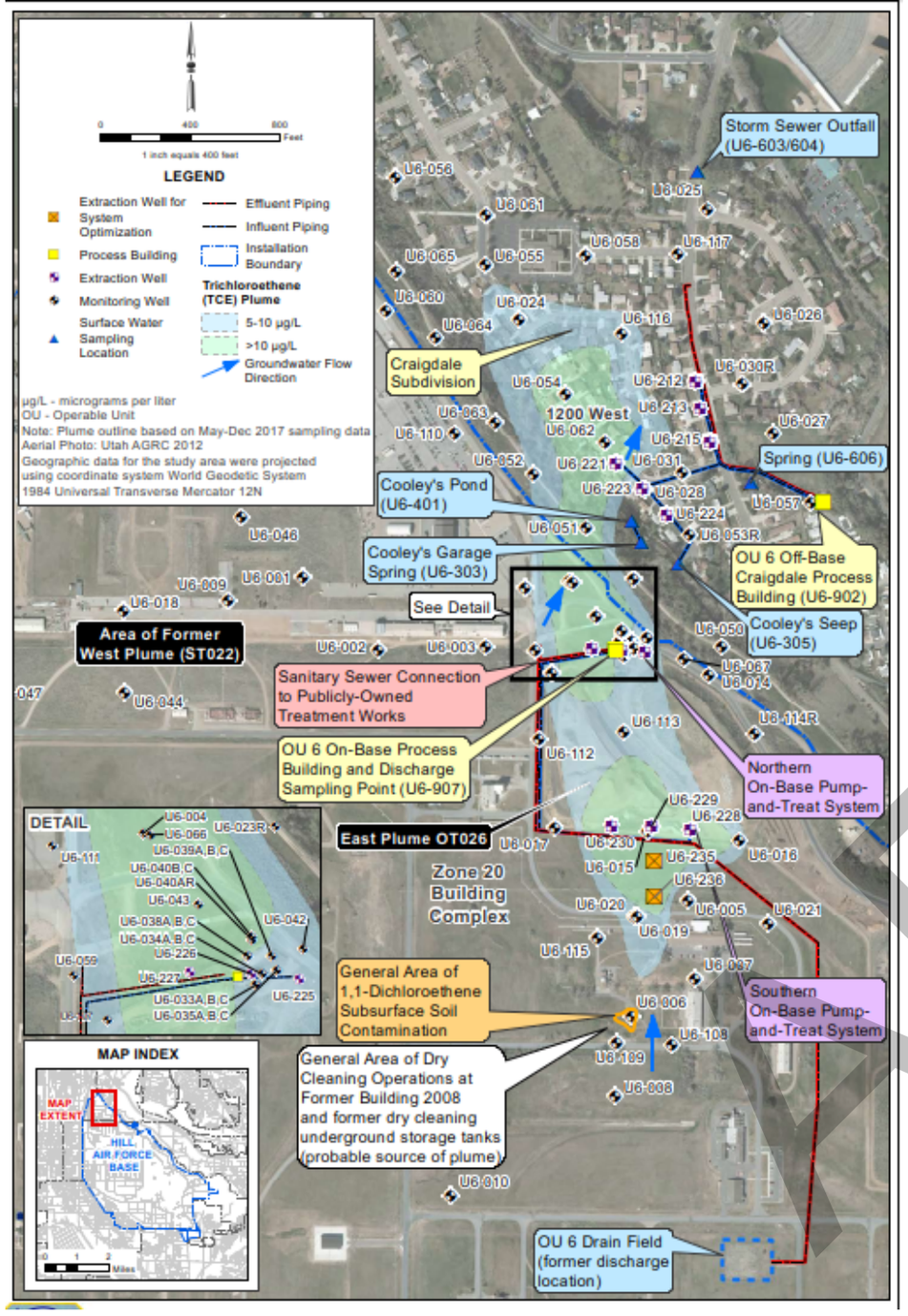
PRISM®

PRedictive Integrated Stratigraphic Modeling

Hill AFB – OU6

Purpose: demonstrate how sequence stratigraphy can be used to develop an effective remedial strategy

AECOM



The Site

Problem:

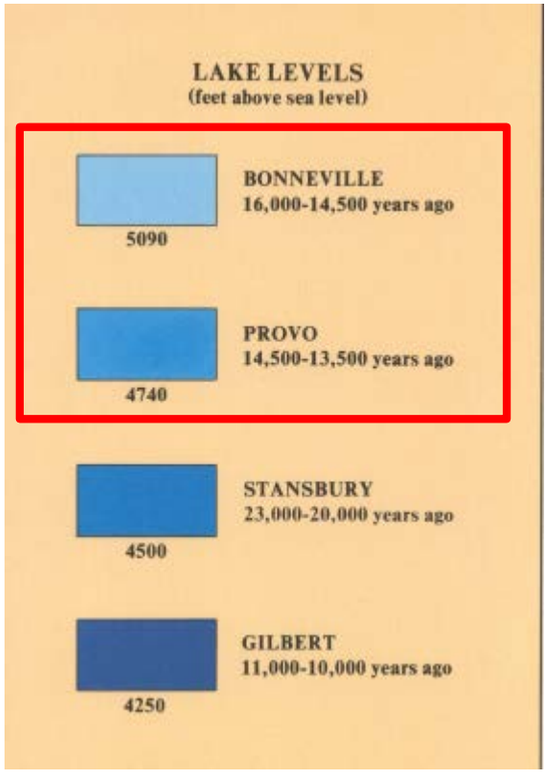
- Off-base system is not treating northern lobe of plume and is not meeting ROD required RTF.

Goals:

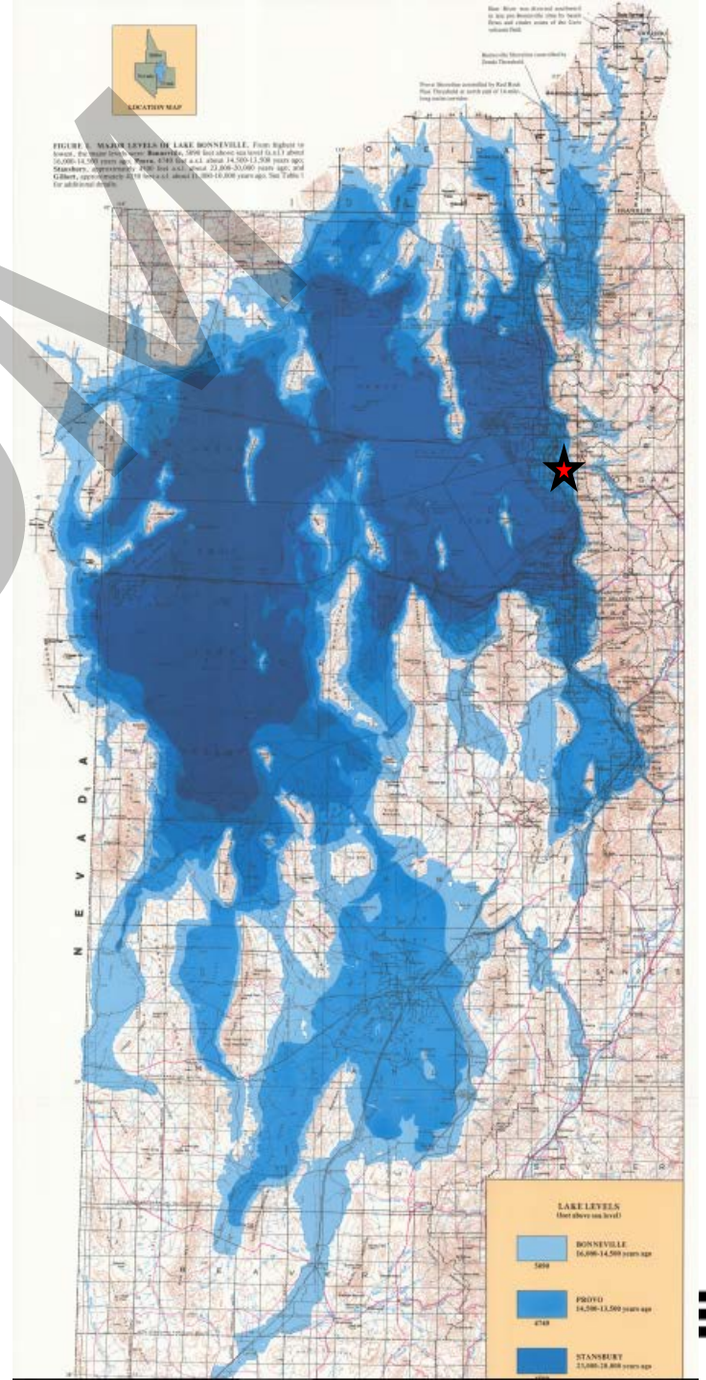
- Evaluate the effectiveness, efficacy, and adequacy of the existing remedy and treatability studies.
- Use the above information to augment, modify, and/or replace the existing remedy.

Paleo-extent of Lake Bonneville

http://www.aero-graphics.com/lake-bonneville-flood-animation/

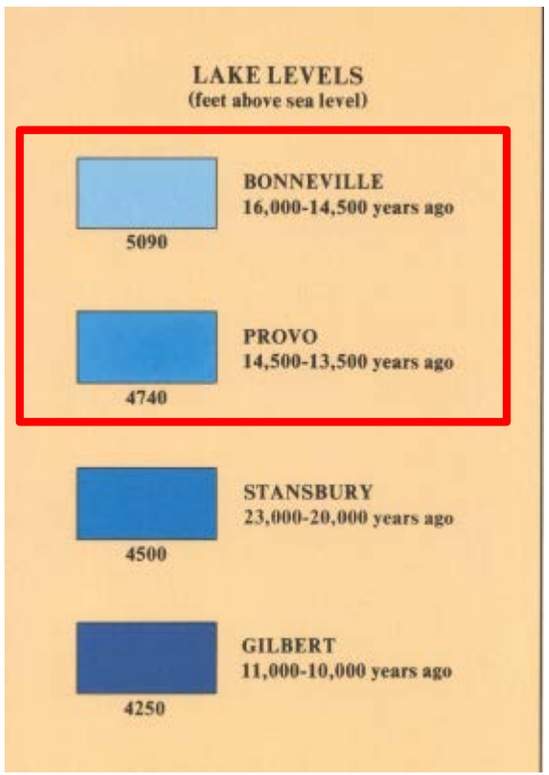


★ Hill AFB

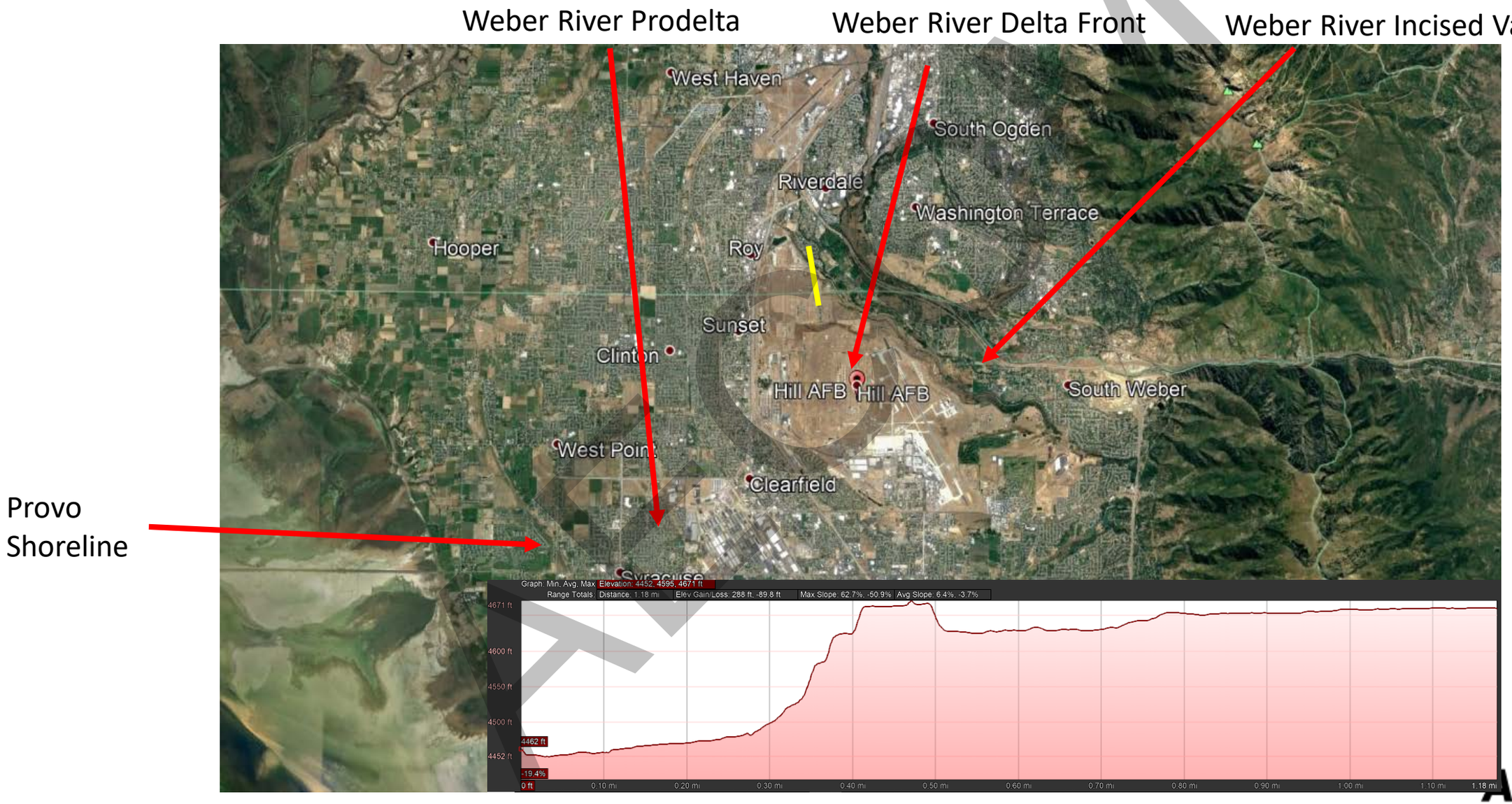


Site Area

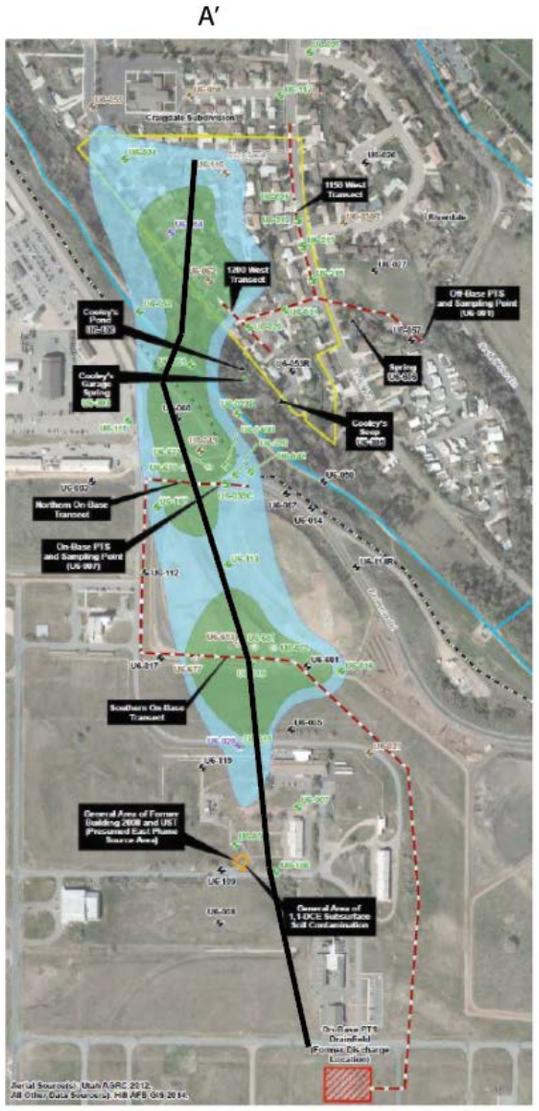
★ Hill AFB

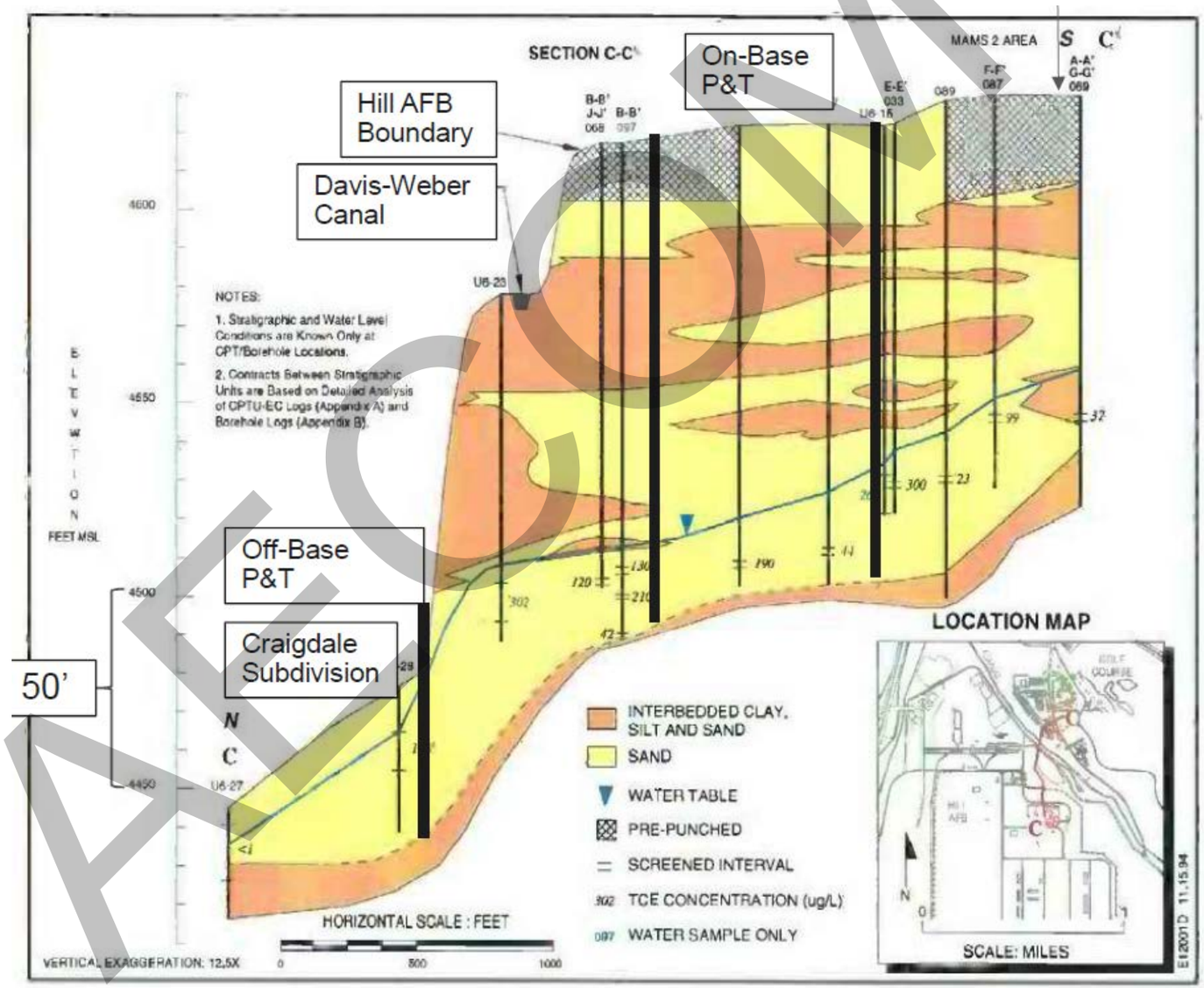


Leveraging Google Earth Imagery

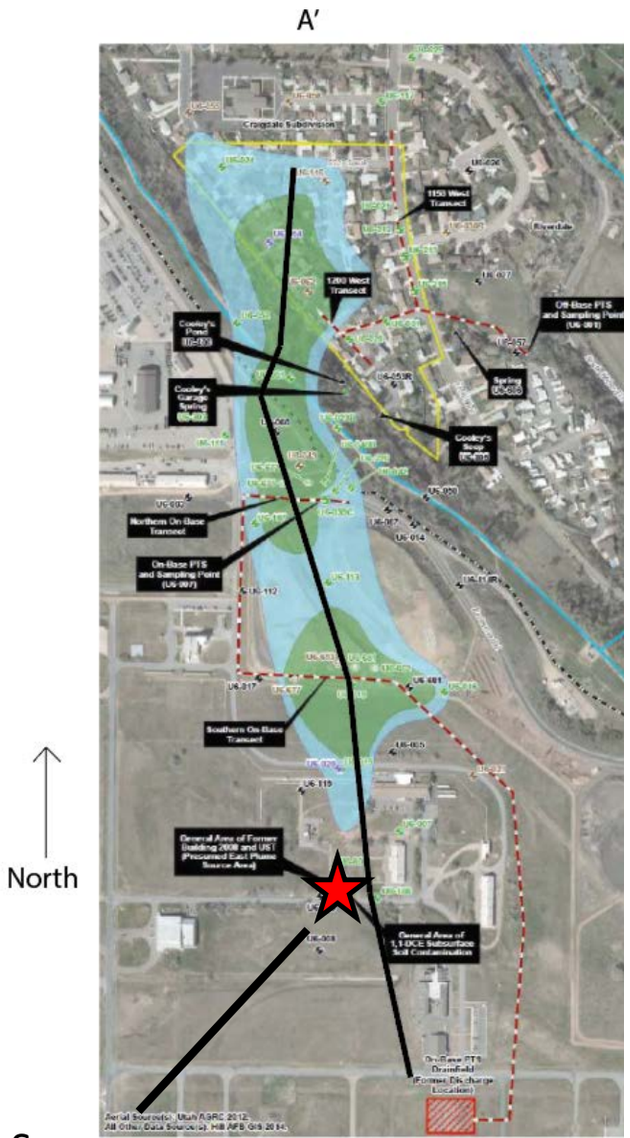


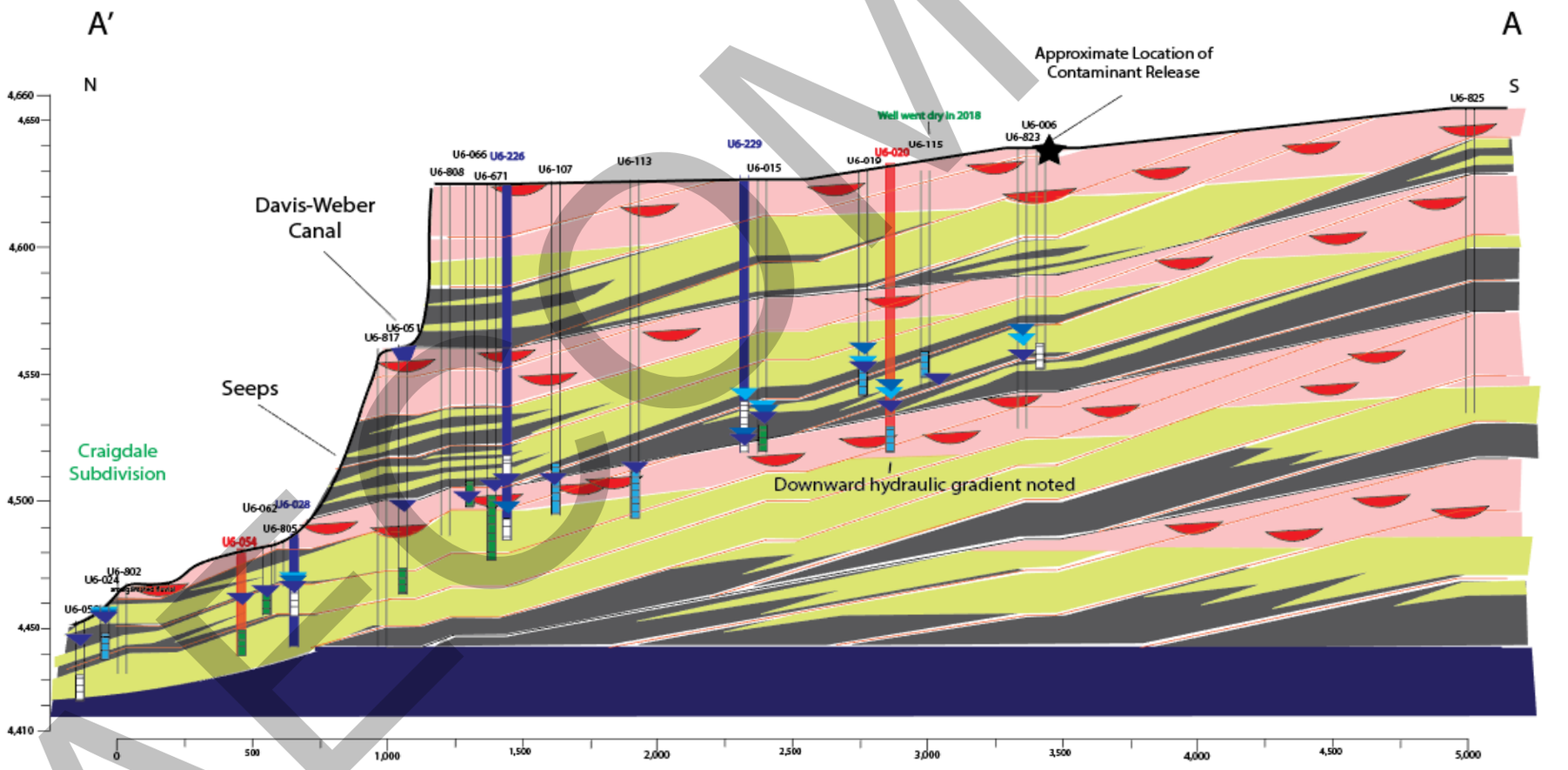
Previous Interpretation





Re-evaluation of Well Network in Light of New Understanding





Transmissivity

High
- Channel deposits - Coarse Sand and Gravels
- Delta Mouthbar - Fine to Medium Sand
- Overbank - Fine Sand and Silt

Low
- Prodelta - Silt and Clay

Projected Well Network

Wells with increasing Trends

Extraction Wells

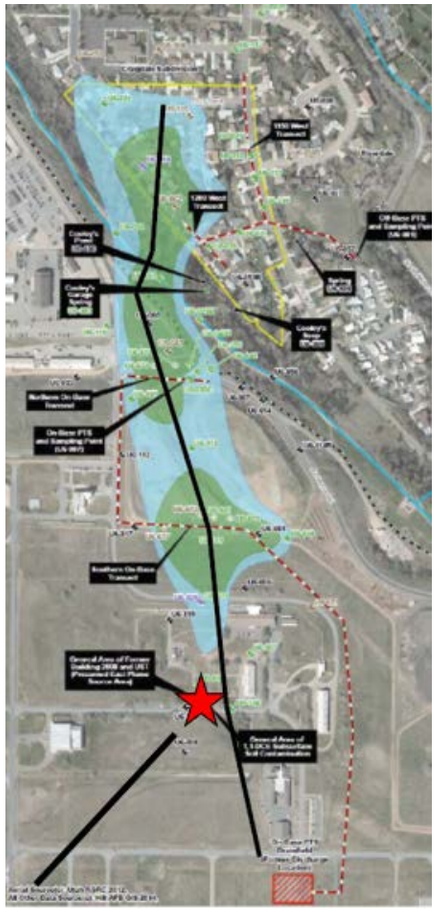
Concentration Data (June 2017)

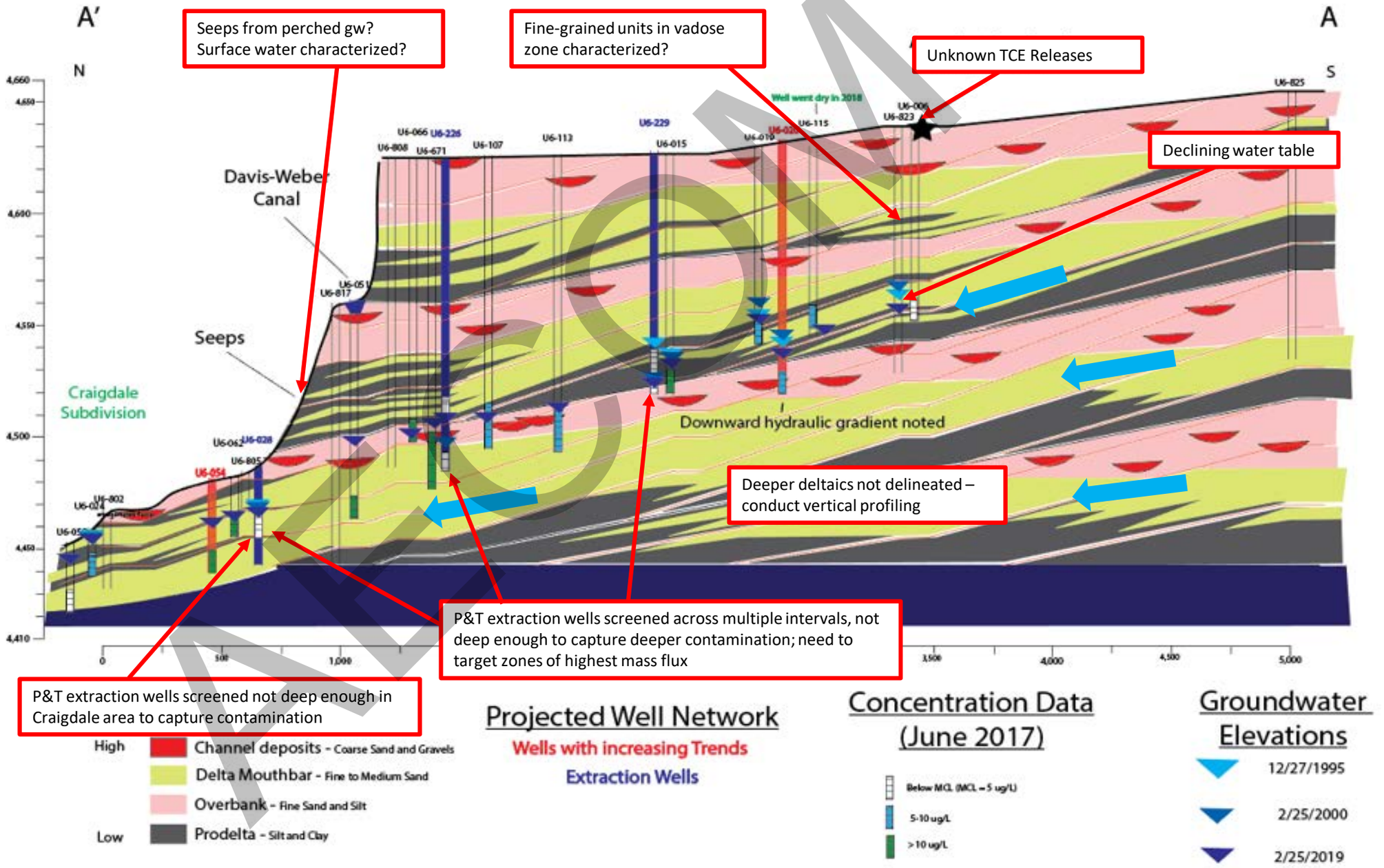
- Below MCL (MCL = 5 ug/L)
- 5-10 ug/L
- > 10 ug/L

Groundwater Elevations

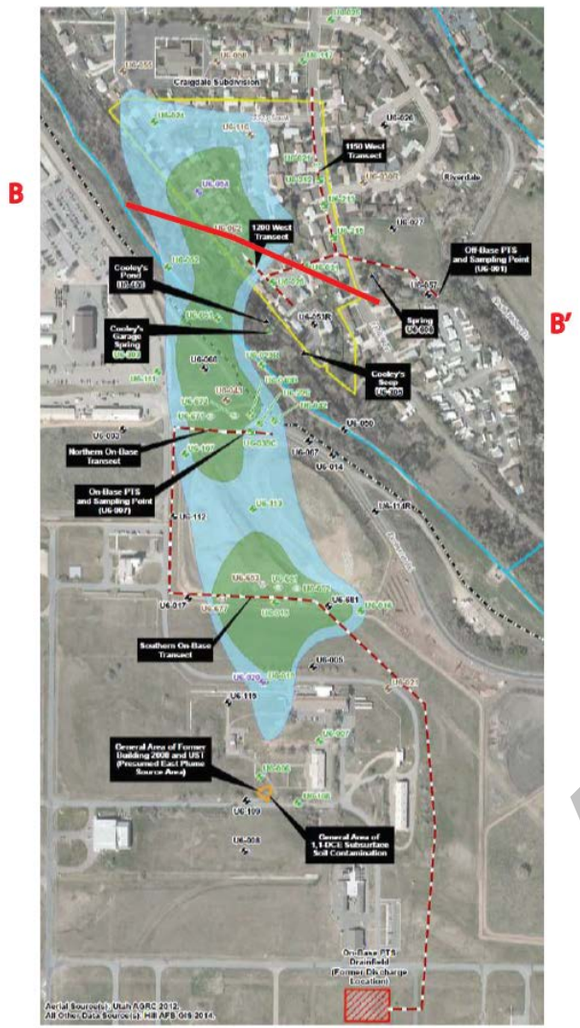
- 12/27/1995
- 2/25/2000
- 2/25/2019

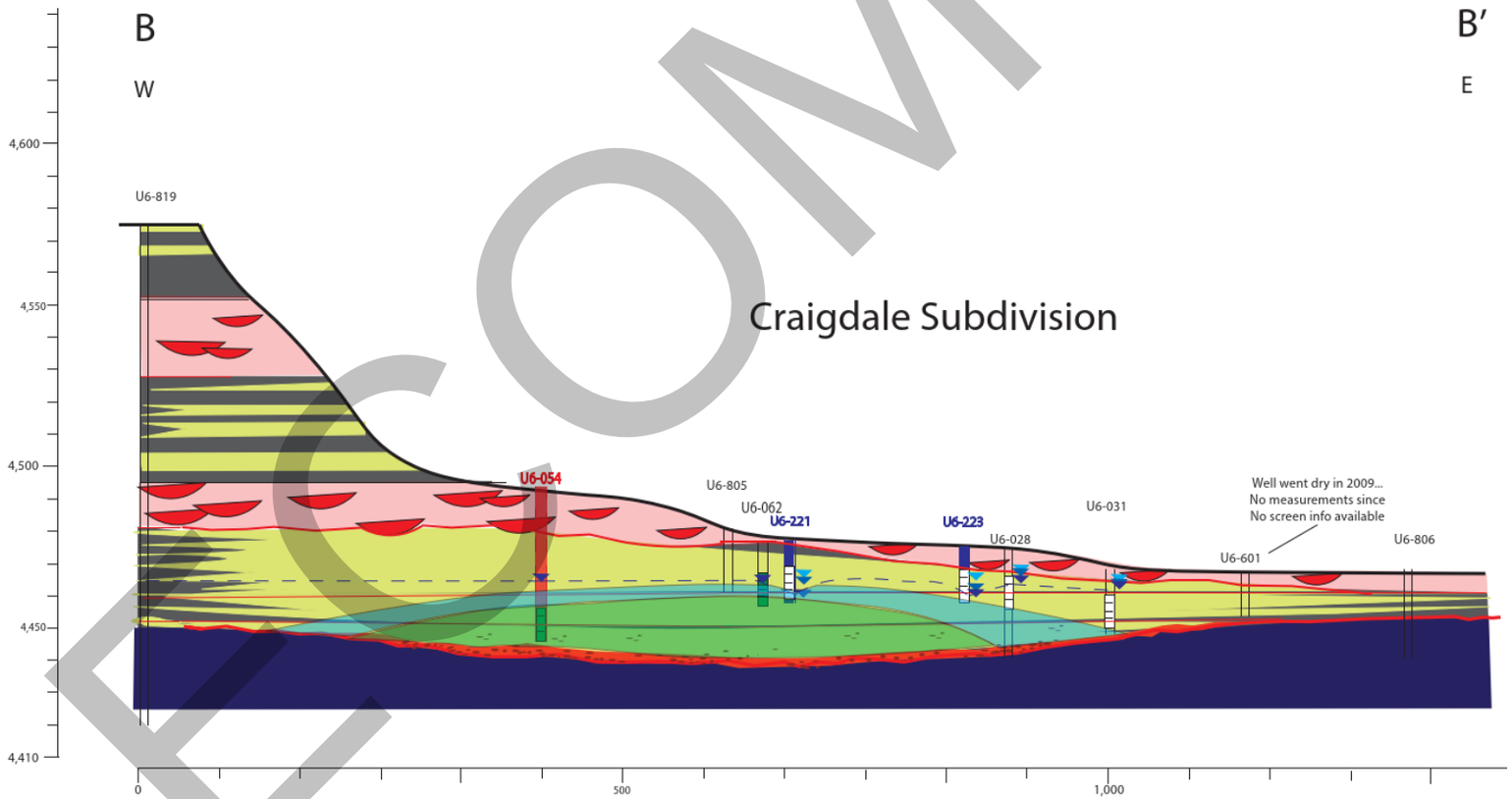
Data Gap Assessment in light of new understanding





Evaluating the Craigdale Subdivision





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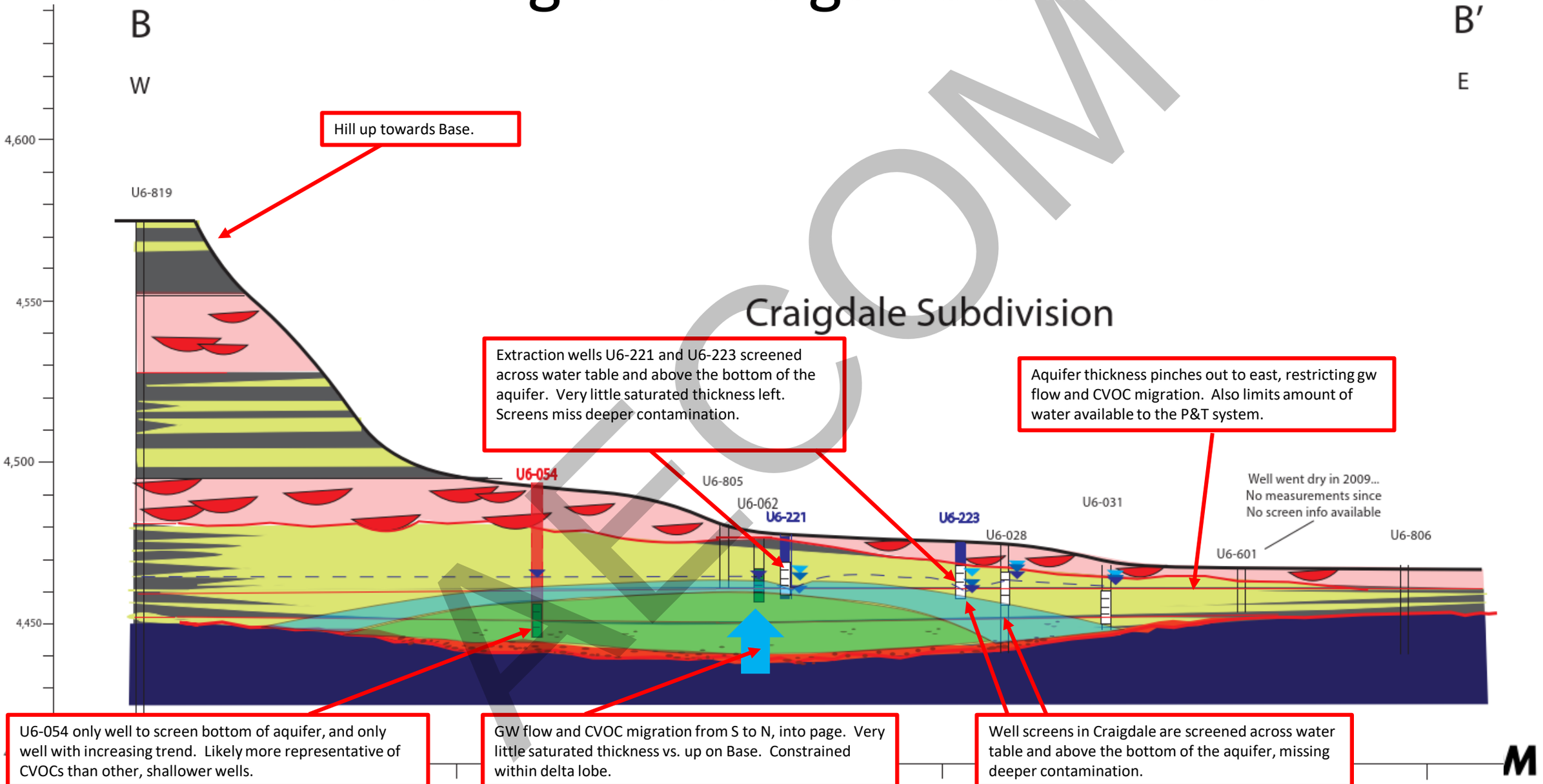
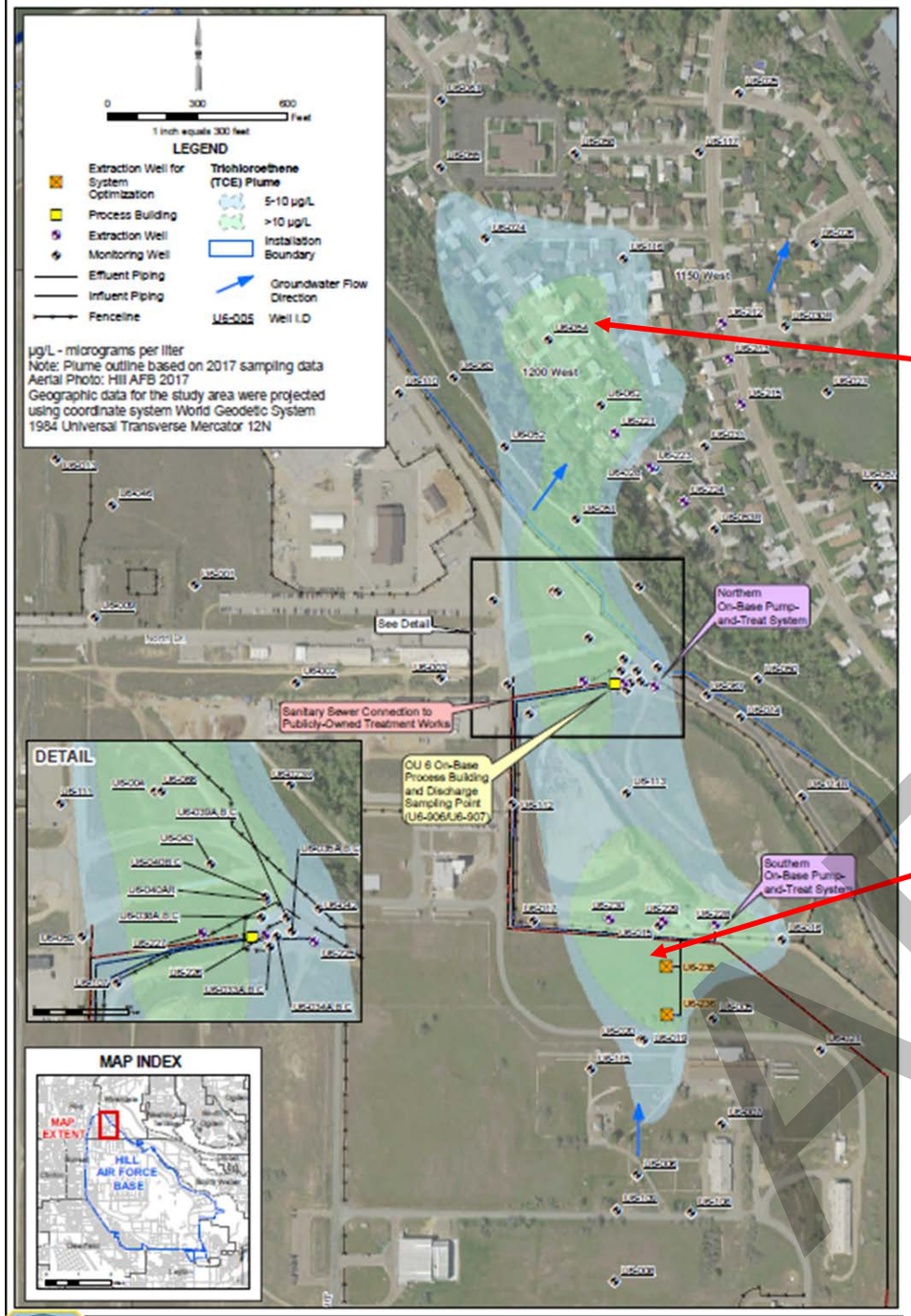
AECOM

Evaluating the Craigdale Subdivision



Proposed Approach



Evaluation of Existing Remedy Effectiveness, Efficacy, Adequacy

Hydraulics Evaluation

Plume Stability Assessment

MNA Assessment

Supplemental Site Investigation

Source Strength/On Base Plume Evaluation

Off Base Plume Evaluation

Case Study 3

PRISM®

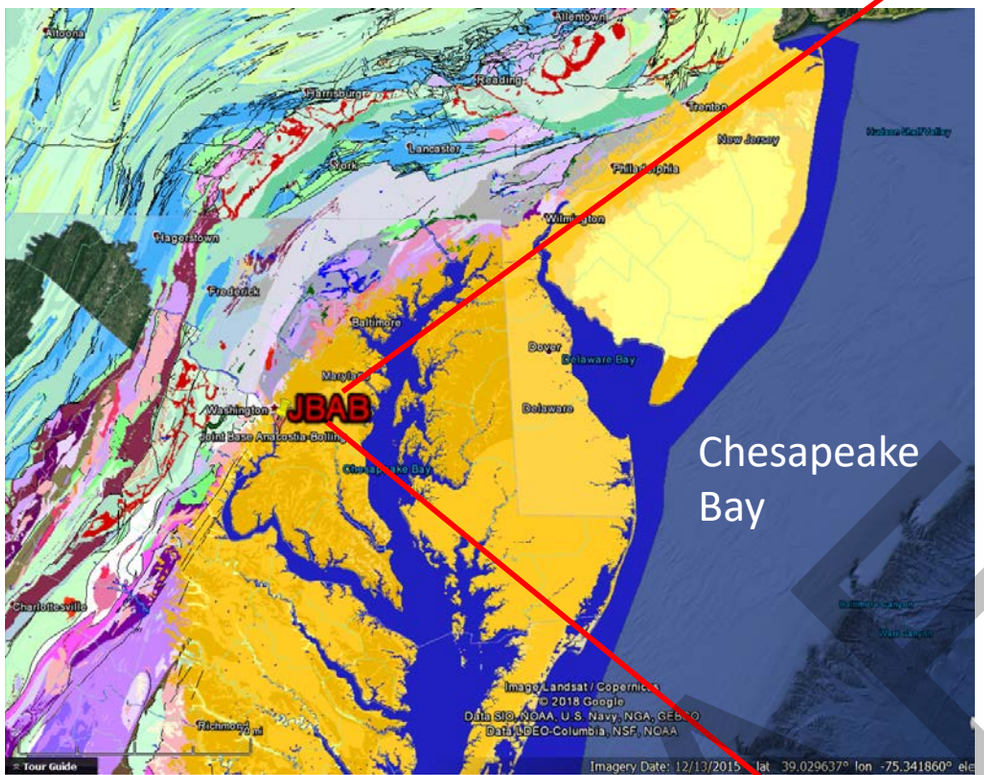
PRedictive Integrated Stratigraphic Modeling

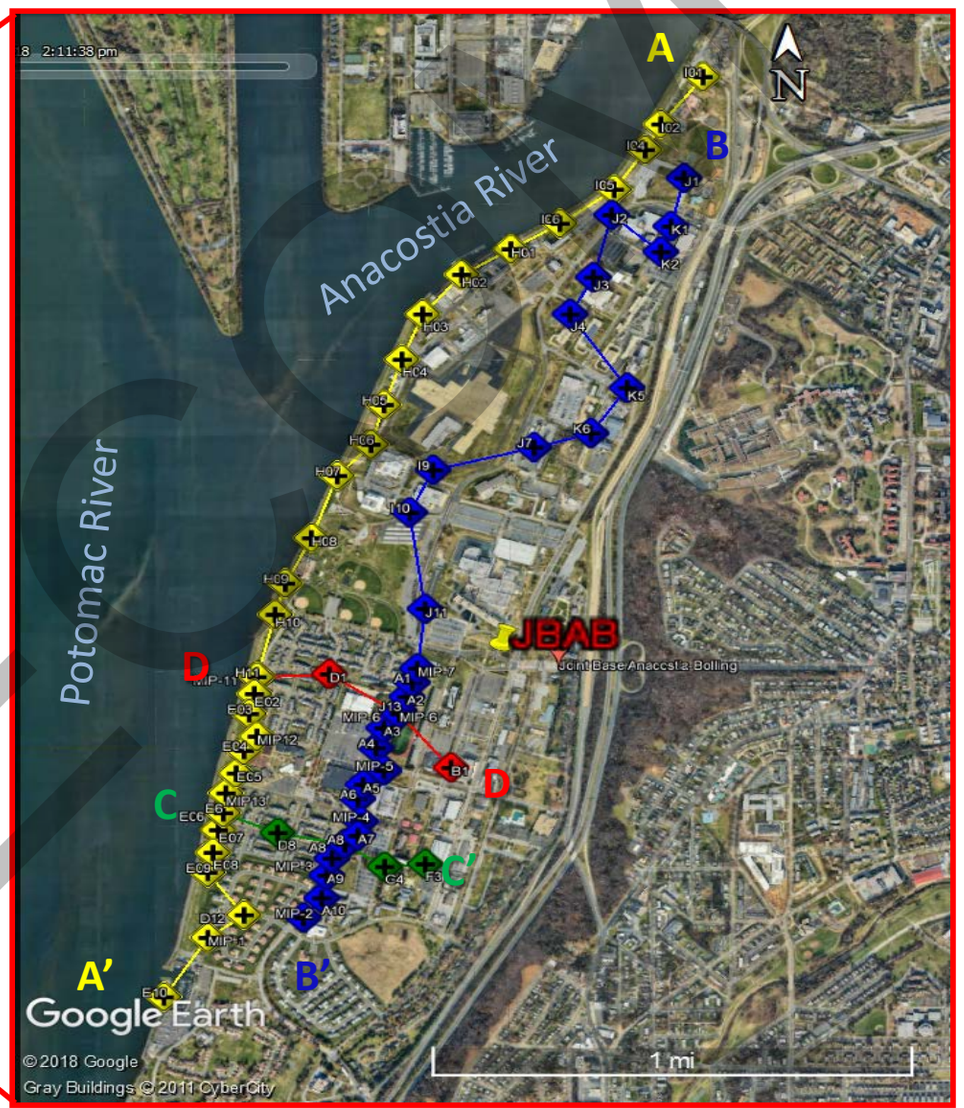
Joint Base Anacostia – Bolling (JBAB)

Purpose: demonstrate 3-D visualization techniques and benefits to stakeholders.

AECOM

JBAB - Site Location & Data



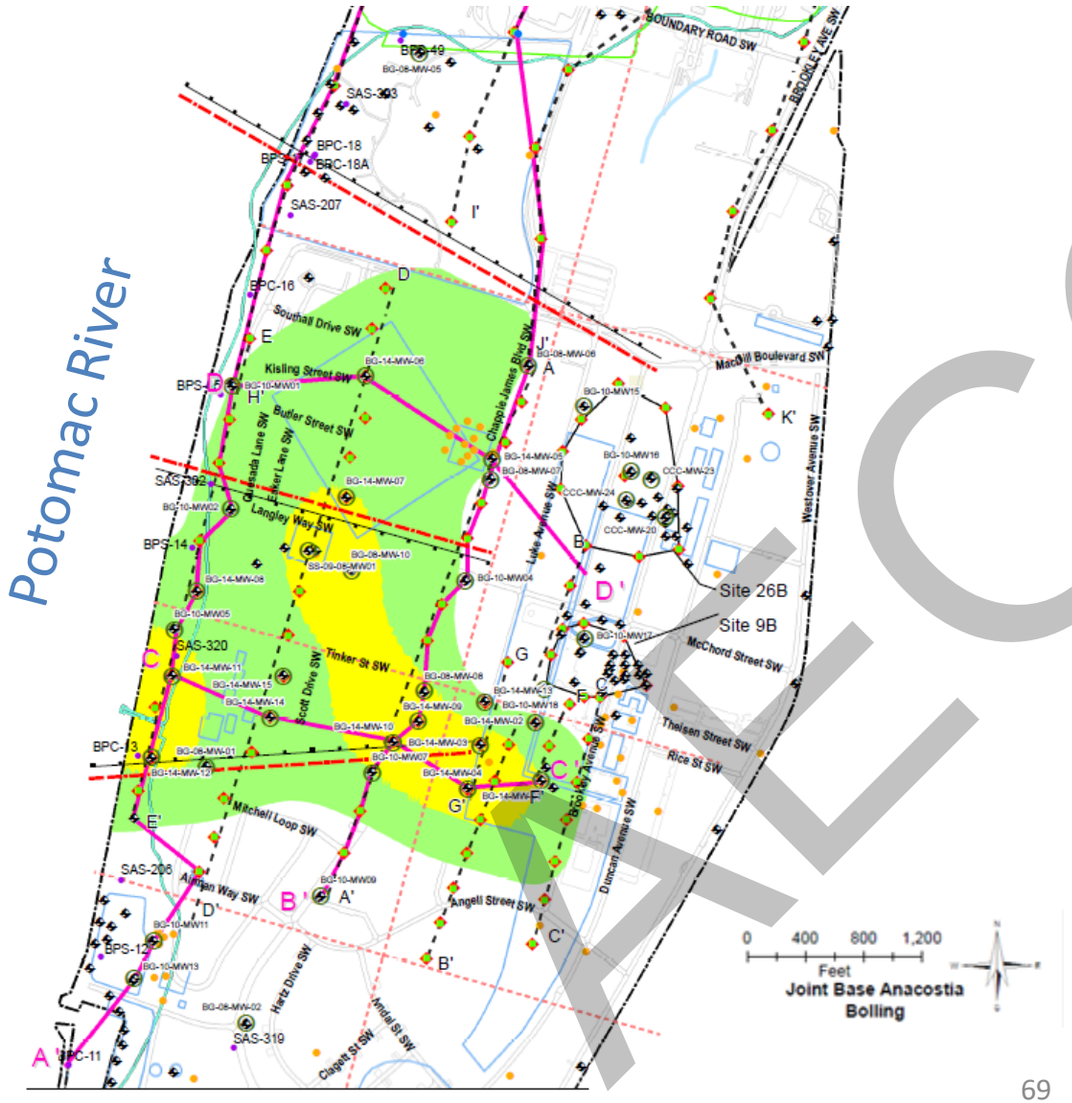


Purpose: to better understand and predict the contamination plume's flow-path at the site

Data use:

- HPT logs from 67 wells in 4 cross-section transacts
- Boring logs from Water Division
- 3-D CSM derived from EVS model without geological input

The Site



Problem

- How much contaminant mass is being discharged into the river?
- Plume migrating towards the north?

Goals

- Refine an existing EVS model to design a targeted investigative approach.

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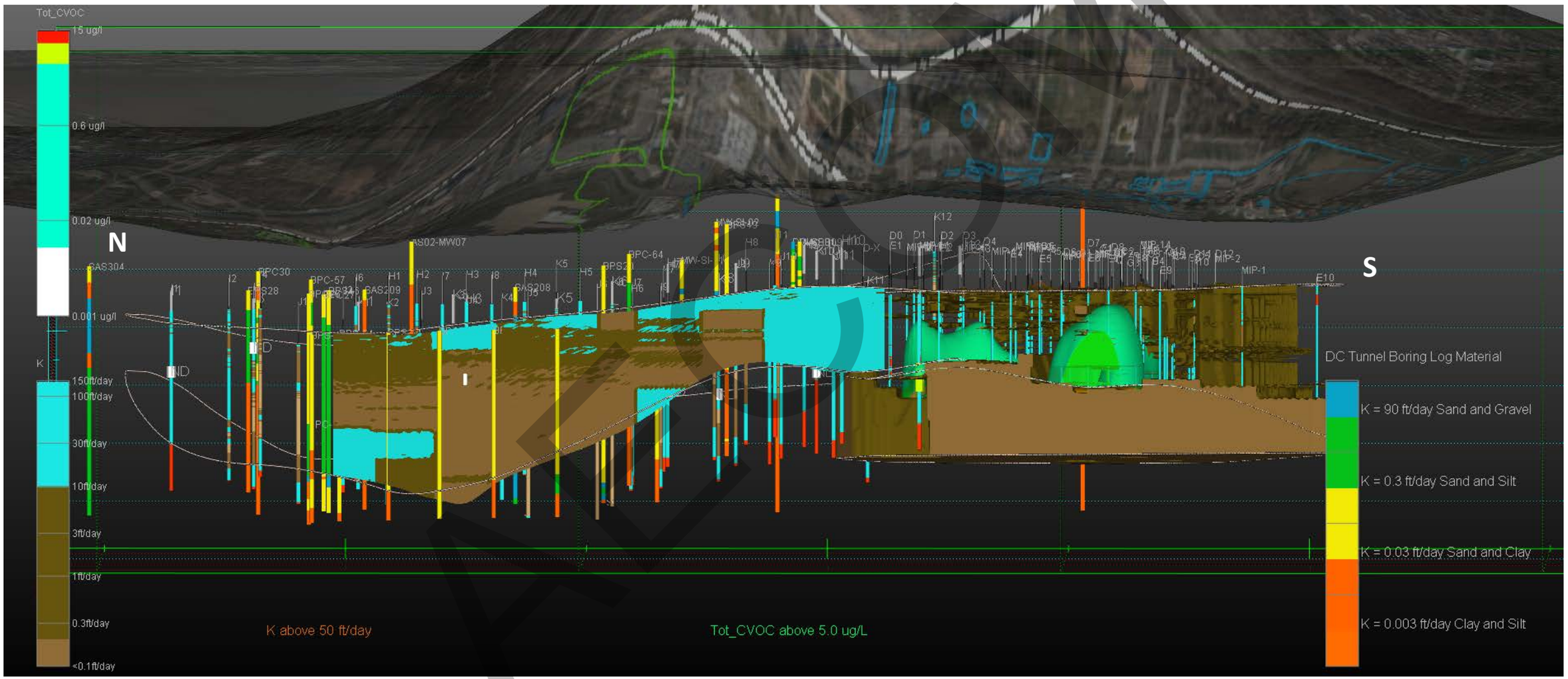
EVS Model (*K>50ft/Day*) -No Stratigraphic Input)



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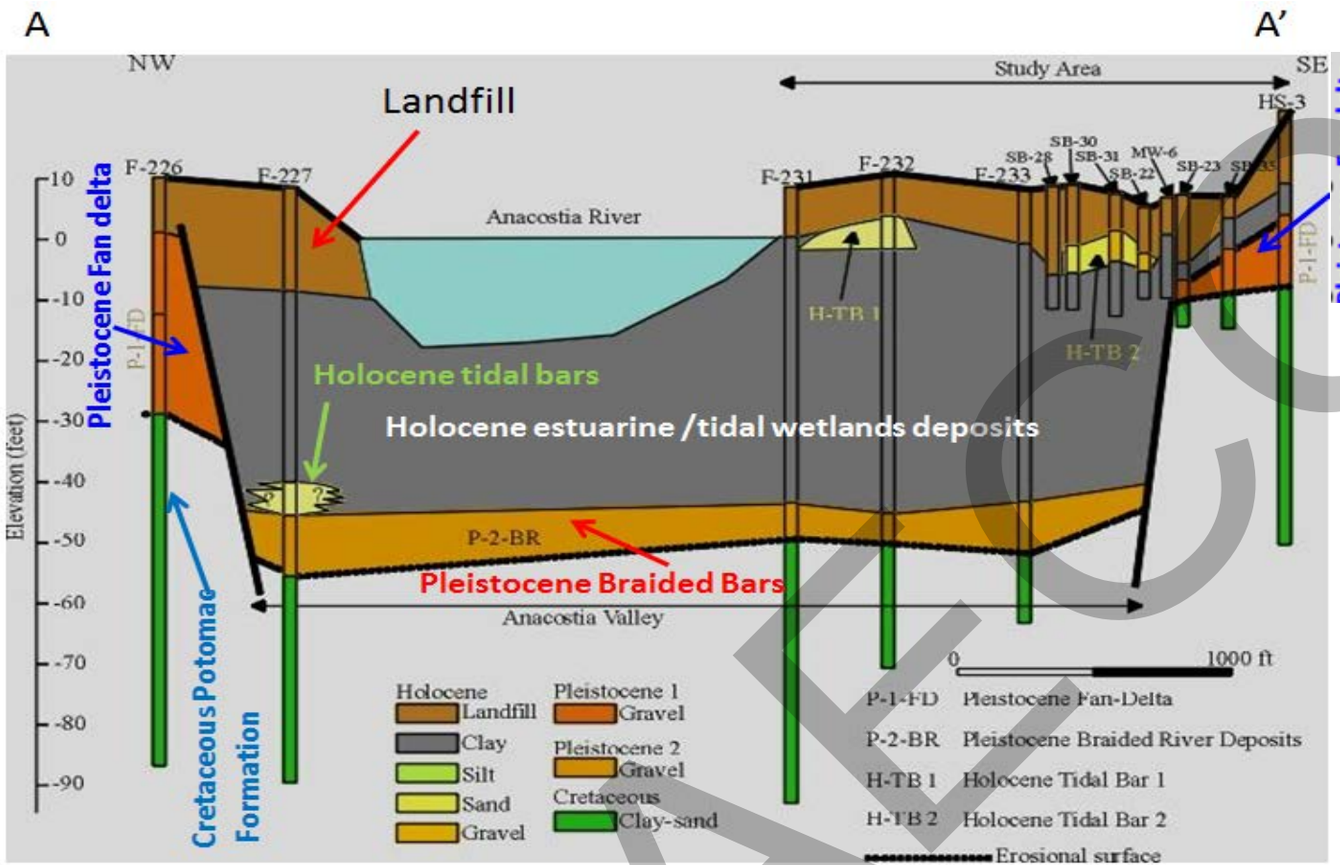
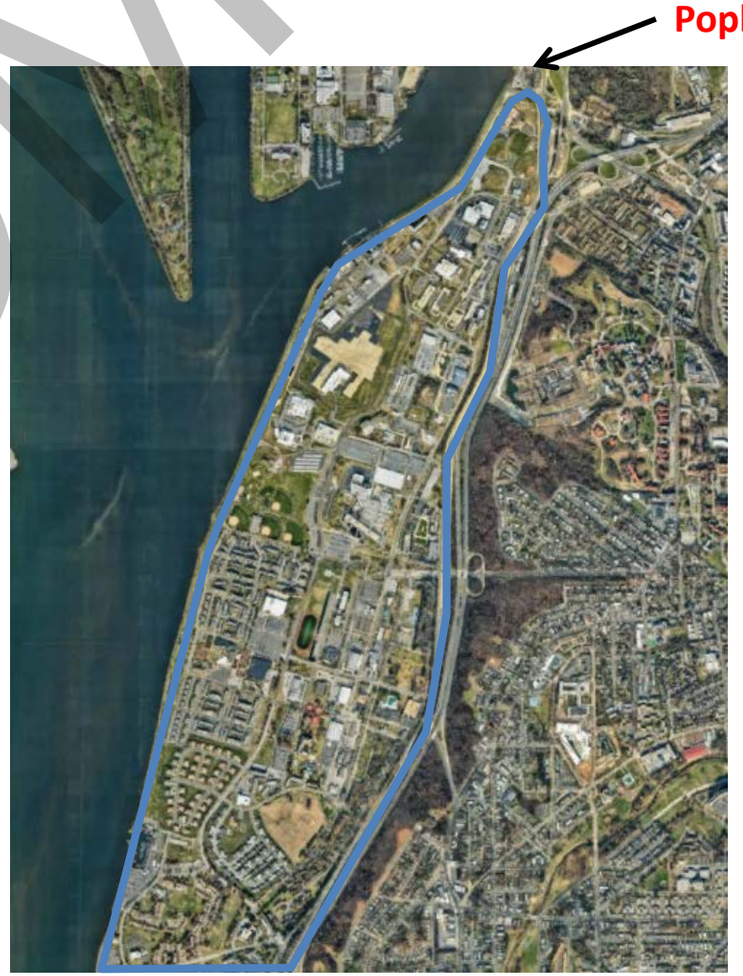
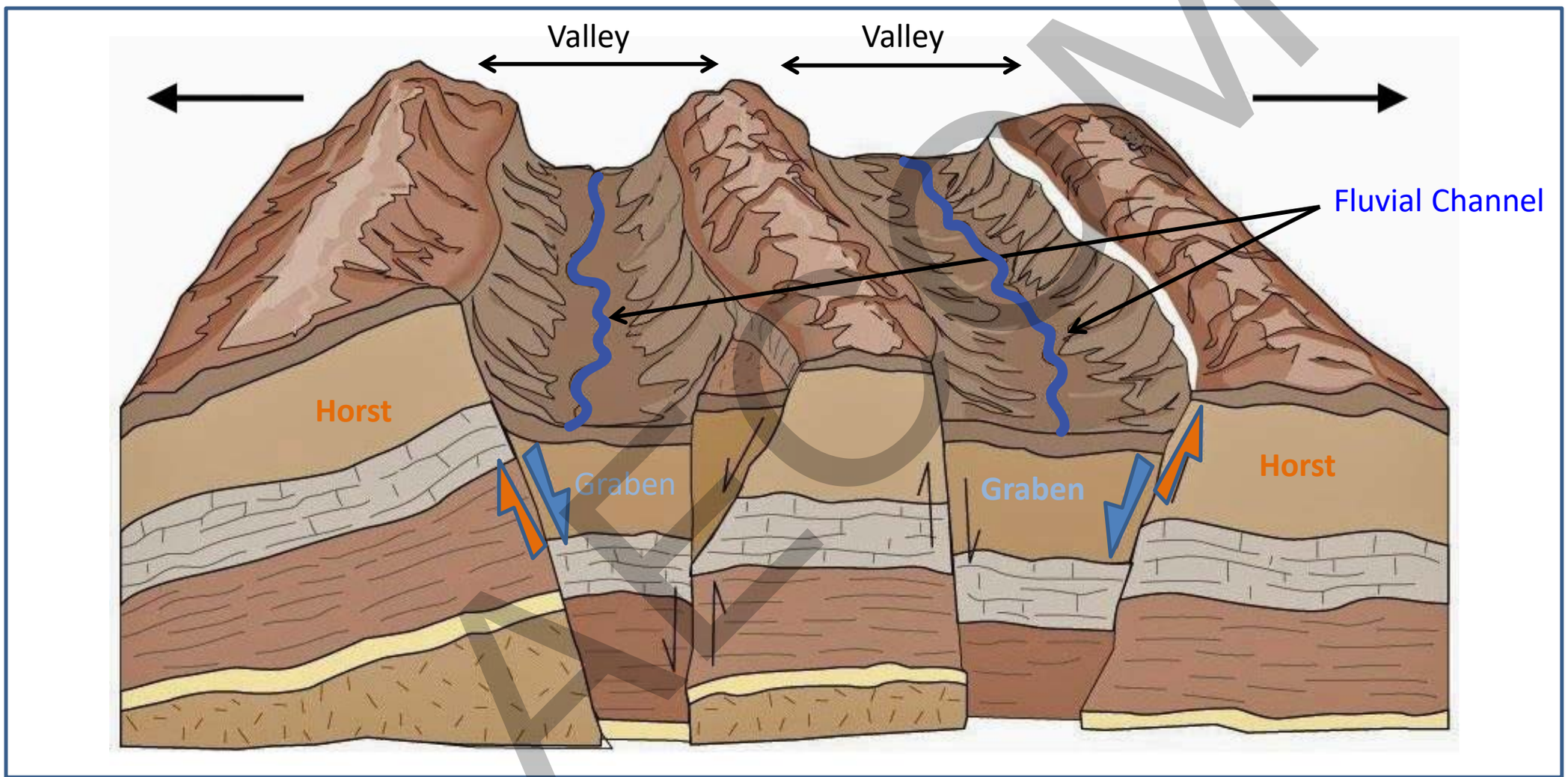
Regional Geological Background



Stratigraphic Characterization and Ground Water Flow in the Poplar Point Area, Anacostia River Basin, Washington, D.C.
Csato et al. 2013



The Horst & Graben Model in Extensional Tectonics

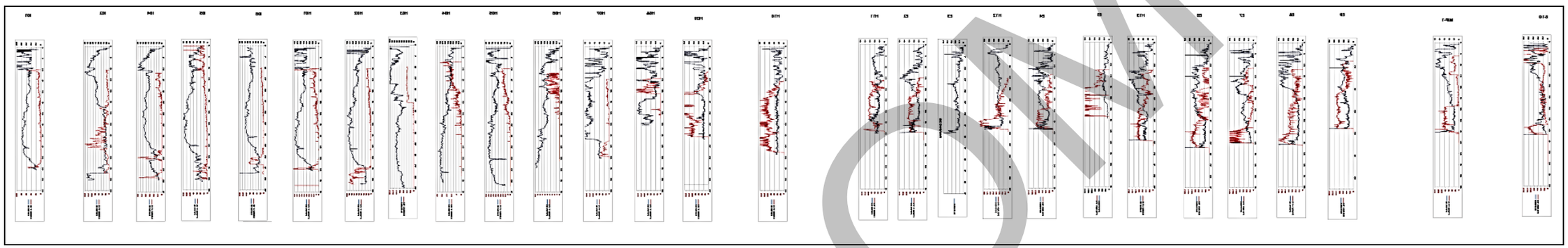


- Modified from geoscience.wisc.edu

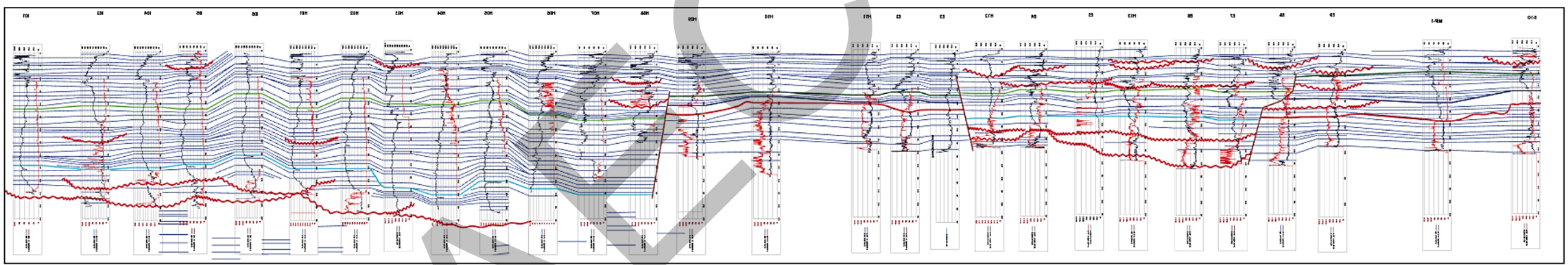
Correlation Technique

S

N



Organize Data : Develop cross-section transect based on EC & K information from HPT logs

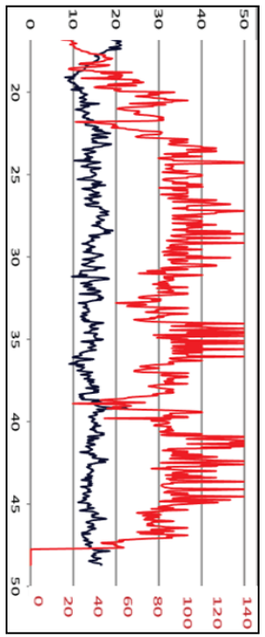


Interpretation:

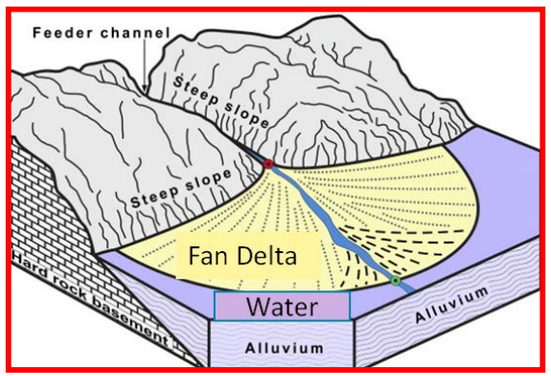
- Identify Continuous shale markers
- Identify discontinuous channel markers
- Determine sequences

Depositional Facies of JBAB

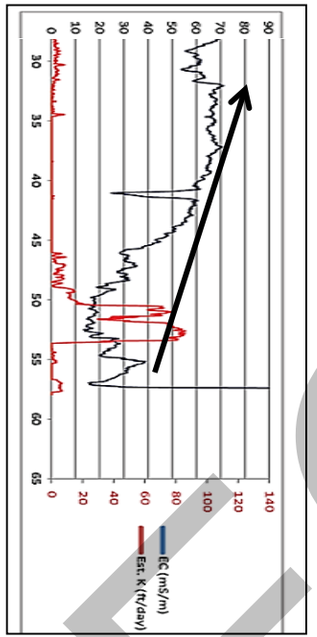
Fan Delta



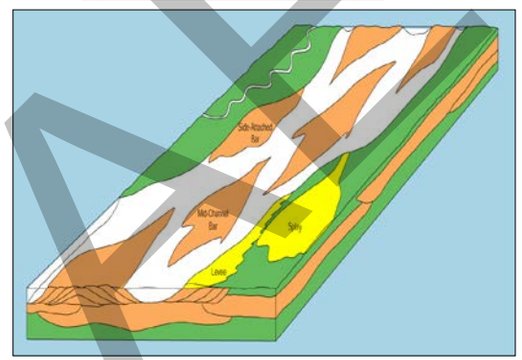
K value high (generally >80)



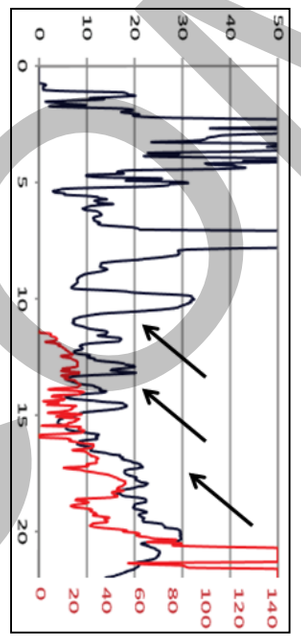
Channel Bar



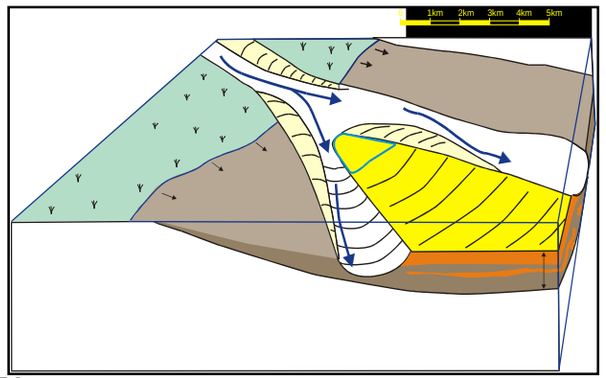
K value decreases upwards



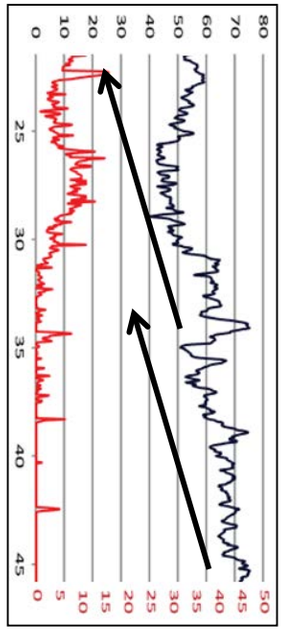
Bay-head Delta Mouthbar



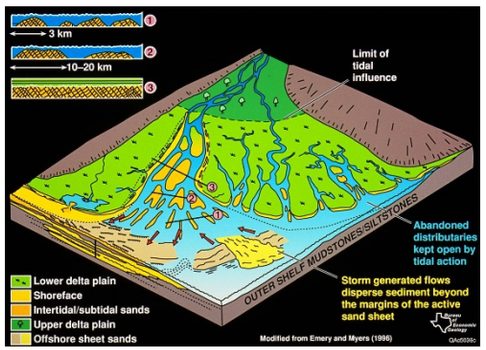
K value variable (~140 to <10), EC fining up



Tidal Bar



K value increases upwards within very low values



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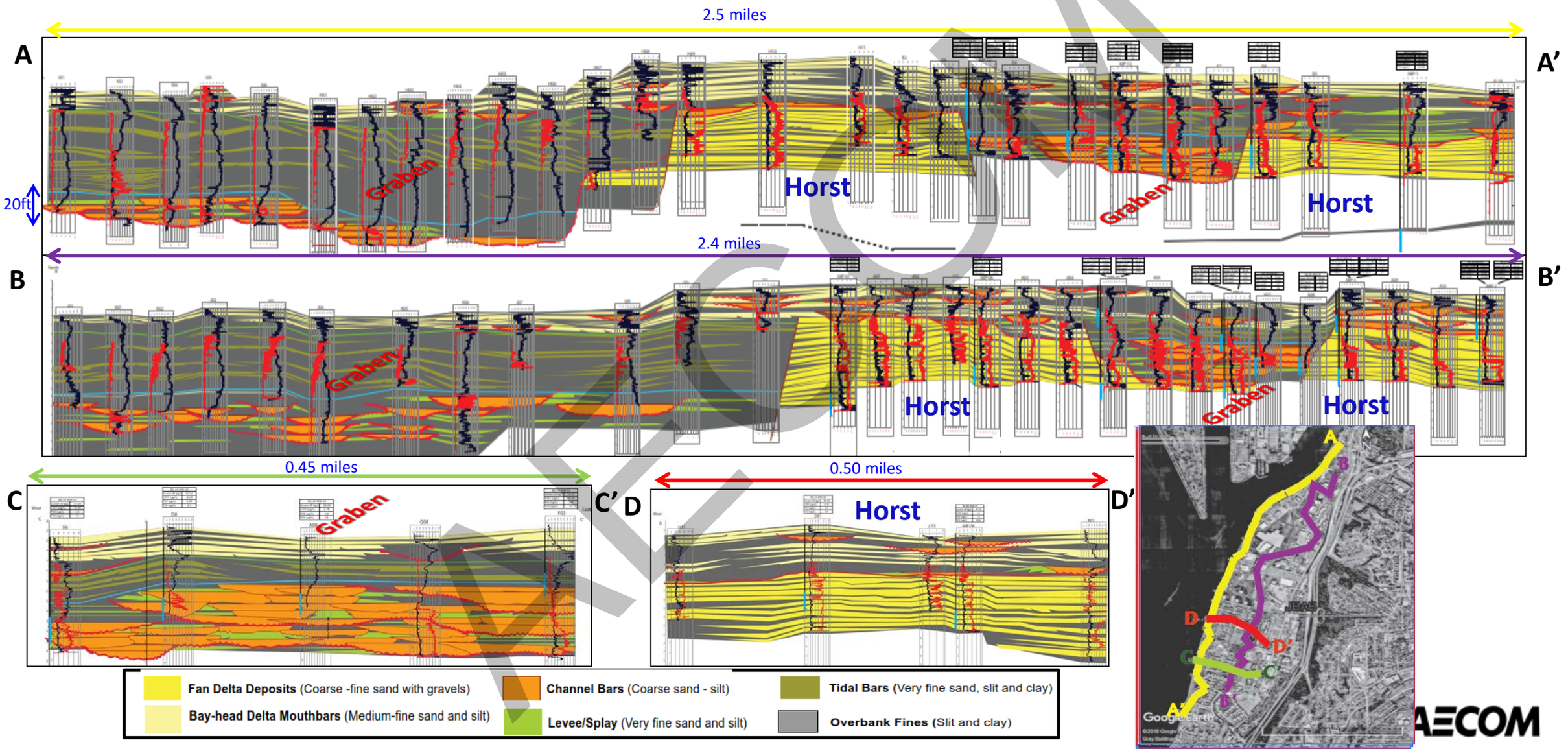
Stratigraphic Cross-sections at the Site



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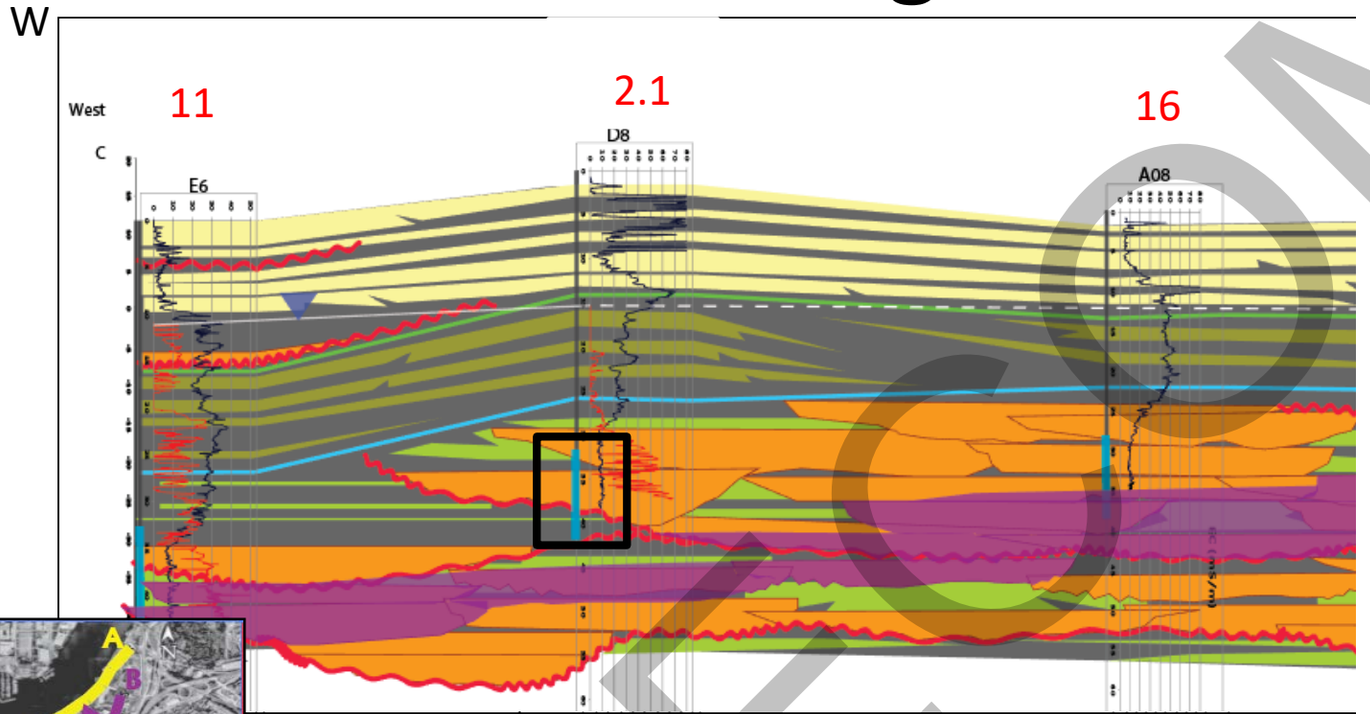
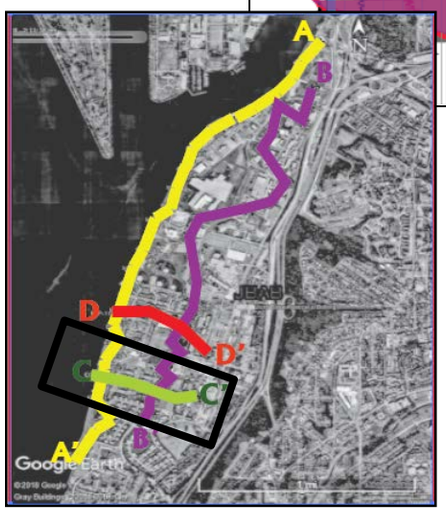
Evaluating Well Screens



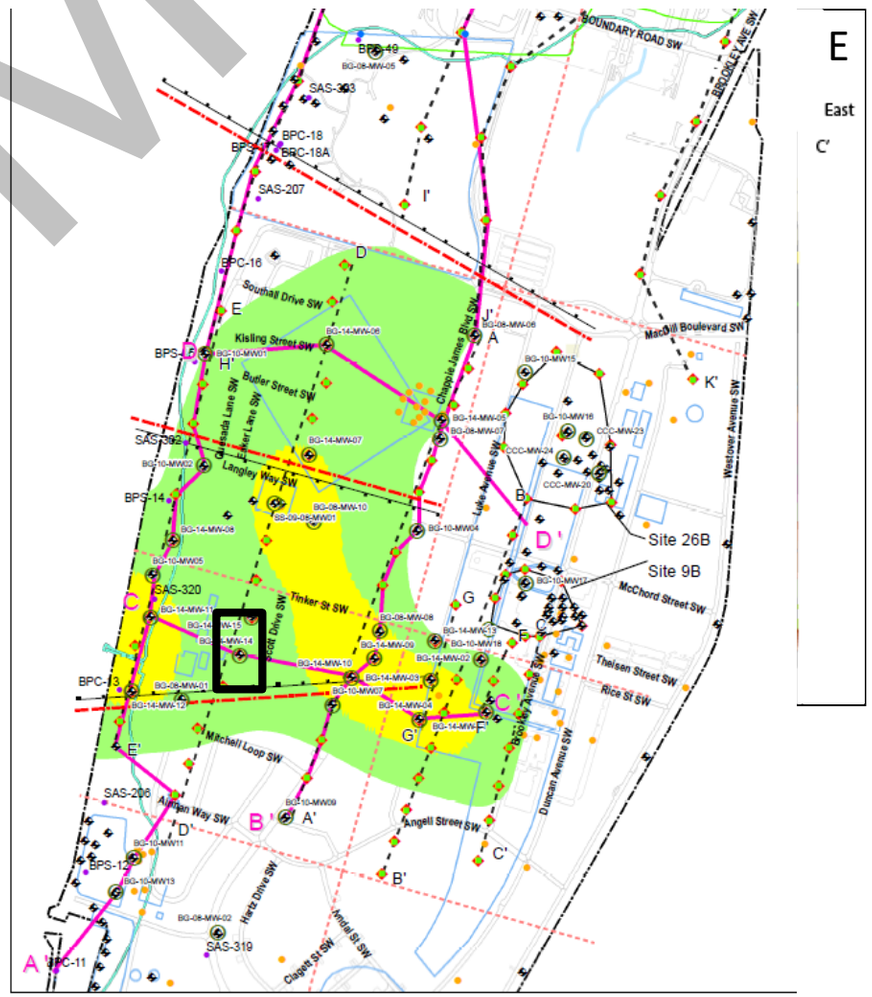


Fan Delta Deposits (Coarse -fine sand with gravels)

Channel Bars (Coarse sand

Bay-head Delta Mouthbars (Medium-fine sand and silt)

Levee/Splay (Very fine sand



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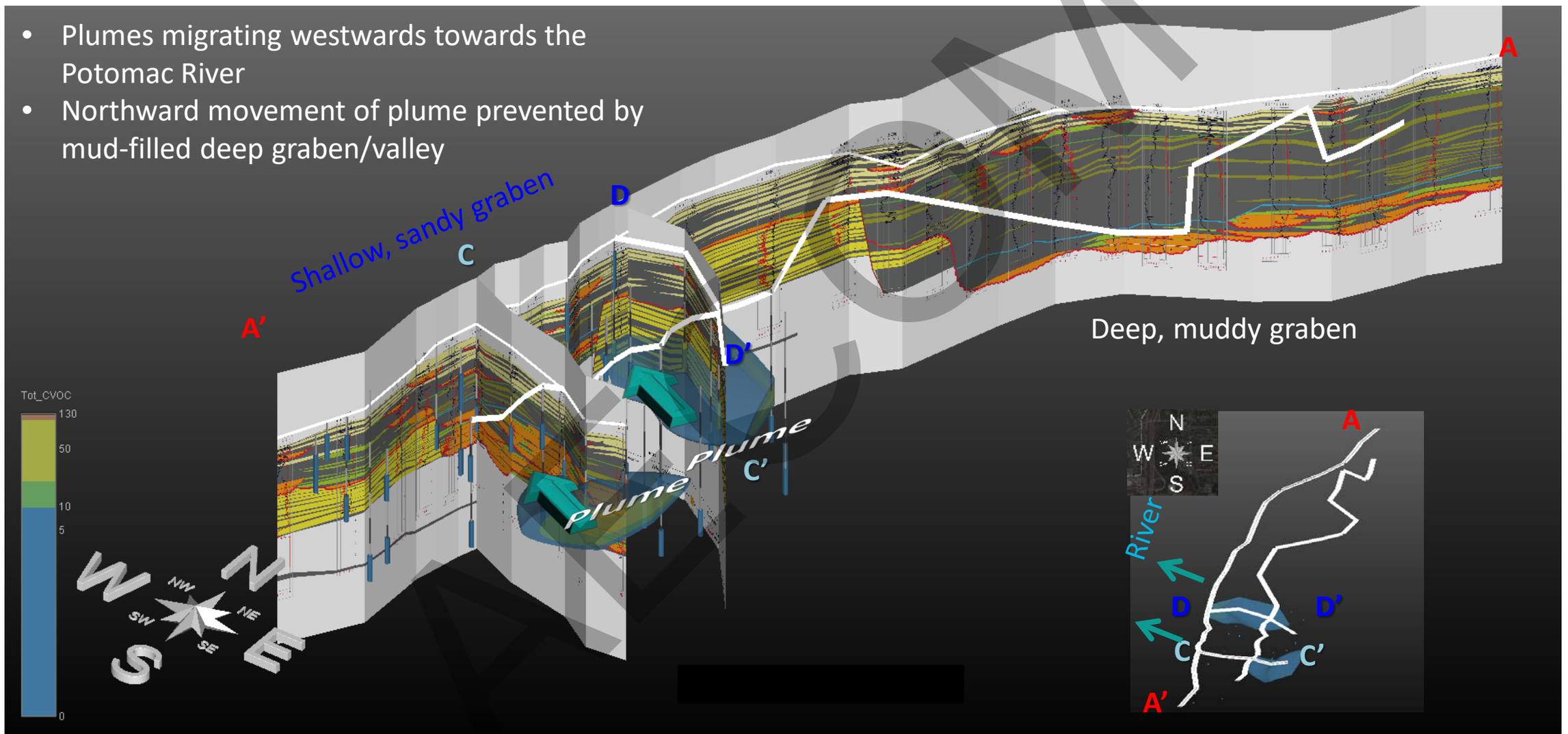
Updated EVS Model – With Stratigraphy

E3_1440_#124_Sadeque_Video.wmv

Stratigraphic Control on Plume Migration

- Plumes migrating westwards towards the Potomac River
- Northward movement of plume prevented by mud-filled deep graben/valley



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CSMs are living, breathing things - Update them regularly

- Improve 3D visualization/HRSC Integration
- Reduce costs by optimizing the next phase of investigative activities
- Refine Mass Flux Estimates
- Re-evaluate the existing well network
- Build Stakeholder trust
- Creating a management tool for future releases/emerging contaminants

Major Takeaways

- Understanding the subsurface geology is crucial for developing more effective remedial strategies!
- Beware the pitfalls of Lithostratigraphy!
- Sequence Stratigraphy is a model-based predictive tool for mapping the true heterogeneity of aquifer rocks
  - This is essential to understanding and predicting the flow path of plume migration
- Sequence stratigraphy incorporates knowledge of depositional environments and facies to map the subsurface
  - Interplay of Accommodation vs. Sediment Supply
- Sequence Stratigraphy takes years of experience to master…
  - Facies analysis is an important building block of sequence stratigraphy
  - Sequence Stratigraphy is not equal to facies analysis!
- Good data collection = good results!
  - Continuous geophysical logs (Gamma, resistivity, SP, etc.)
  - CPT/HPT logs
  - Detailed boring logs that utilize the Wentworth classification scheme!

"We already have a CSM, we already know what the subsurface looks like"

Time for a paradigm shift!