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Groundwater Issue

Best Practices for Environmental Site Management:
A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models

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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 the Office of Land and Emergency Management's (OLEM) 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 on the application of the geologic principles of sequence stratigraphy and facies models (see "Definitions" text box, page 2) to the characterization of stratigraphic heterogeneity at hazardous waste sites.

Application of the principles and methods presented in this issue paper will improve Conceptual Site Models (CSM) and provide a basis for understanding stratigraphic flux and associated contaminant transport. This is fundamental to designing monitoring programs as well as selecting and implementing remedies at contaminated groundwater sites. EPA recommends re-evaluating the CSM while completing the site characterization and whenever new data are collected. Updating the CSM can be a critical component of a 5 year review or a remedy optimization effort.

DEFINITIONS

Sequence Stratigraphy: The study of sedimentary deposits in the context of their depositional environments and changes in relative sea-level, sediment supply, and available sediment storage areas.

Facies Model: Conceptual construct describing the processes acting in a particular depositional environment to transport, deposit, and preserve sediment, usually presented as a three-dimensional block diagram illustrating the organization of sedimentary bodies in the stratigraphic record.

These methods are applicable to sites underlain by clastic sedimentary aquifers (*e.g.,* intermixed gravels/sands/silts/clays). The scientific principles and methods presented in this document bring clarity to the challenges posed by lithologic heterogeneity thereby facilitating successful site management strategies. Lithologic heterogeneities can be characterized by the use of high resolution site characterization (HRSC) techniques (http://www.cluin.org/characterization/technologies/hrsc/). The application of sequence stratigraphy can be applied to new site investigations as well as existing site data to update the Conceptual Site Model (CSM). These methods allow the practitioner to place environmental subsurface data in a geologic and hydrogeologic context, and predict the geology where subsurface data are absent.

Application of Environmental Sequence Stratigraphy and facies models benefit groundwater remediation projects by improving the ability to:

1. Interpret lateral continuity between borehole data and correlate site data in three dimensions;
2. Identify groundwater flow paths and preferential contaminant migration pathways;
3. Map and predict contaminant mass transport (high permeability) and matrix diffusion-related storage (low permeability) zones;
4. Identify data gaps and assess the need and cost benefit of high resolution site characterization;
5. Determine appropriate locations and screen intervals for monitoring and remediation wells, and;
6. Improve efficiency of remediating and monitoring of contaminated groundwater.

The first two sections (I and II) present the technical basis of Environmental Sequence Stratigraphy. Section III presents a three phase process for practical application of Environmental Sequence Stratigraphy, ending with stratigraphic “rules of thumb” developed through experience in a wide variety of environments of deposition from outcrop and subsurface data sets worldwide. Appendix A presents six case studies of various applications of Environmental Sequence Stratigraphy and Appendix B is a glossary of terms used in the document.

I. INTRODUCTION – The Problem of Aquifer Heterogeneity

Permeability heterogeneity is inherent in the subsurface and interacts with regional groundwater gradient to control groundwater flow and contaminant transport. In clastic sedimentary aquifer systems (*i.e.,* gravel, sand, silt, and clay deposits), this permeability heterogeneity is primarily due to lithologic and grain-size heterogeneity in three dimensions, termed "stratigraphic heterogeneity", with post-depositional changes (bioturbation, compaction, cementation, alteration, etc.) as contributing factors. Stratigraphic heterogeneity is imparted by the physical processes acting to transport, deposit, and bury sediments and is present at all scales from pore (microscale) through regional (macroscale) (Figure 1).

While the impacts of stratigraphic heterogeneity on groundwater flow and contaminant transport have long been recognized (*e.g.,* Koltermann and Gorelick, 1996; Puls and Barcelona, 1996; EPA, 2004, Weissman, et al., 1999), the treatment of aquifers as isotropic and homogeneous porous media remains commonplace in groundwater remedy design and implementation. At many legacy sites, pump and treat remedies were applied, which served to recover contaminant mass and provided a degree of hydraulic containment of same. However, stratigraphic heterogeneity and associated issues including matrix diffusion, (*e.g.,* Sale and Newell, 2011) make groundwater site cleanups particularly challenging. For sites where sedimentary aquifers are impacted, detailed understanding of stratigraphic heterogeneity at all scales is required to inform future site management decisions.

As with the groundwater remediation industry, problems related to subsurface fluid flow arising from stratigraphic heterogeneity have long challenged the petroleum industry, impacting exploration success and field production. Tools such as sequence stratigraphy and facies models were developed to address these problems and to make predictions in between individual wells regarding reservoir continuity and heterogeneity. This paper provides instruction on application of these tools to contaminated aquifers. The concepts presented herein are equally applicable to the unsaturated zone, including prediction of contaminant and vapor migration pathways.

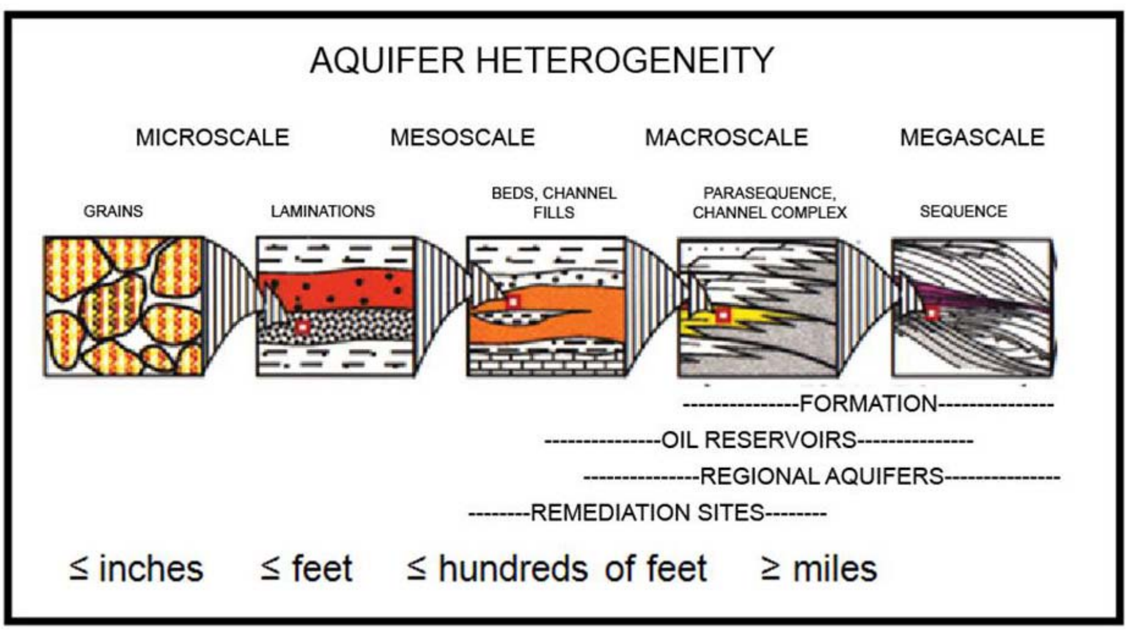


Figure 1. Scales of stratigraphic heterogeneity in clastic aquifers. Facies models and sequence stratigraphy are applicable across all scales. (Modified from Krause et al., 1987). AAPG©1987 Reprinted by AAPG whose permission is required for further use.

Impact of Stratigraphic Heterogeneity on Groundwater Flow and Remediation

As emphasized in this paper, groundwater flow directions can vary greatly from regional groundwater gradient due to anisotropy resulting from lithologic heterogeneity. In many cases, sand and clay elements are not deposited as a "layer cake" with one unit stacked upon the other, but rather deposited in a "shingled" or "laterally offset" fashion. This common phenomenon spans a wide range of depositional environments (see Table 1), and imparts a first-order control on groundwater flow (see Figure 2).

Regardless of their geographic location, sites with similar depositional environments also share characteristic distribution of lithologic units. Coarse-grained (sand-rich) lithologic units (*e.g.,* point bar deposits, channel fills, alluvial fans) typically define the primary groundwater flow pathways, and are referred to herein as permeable "hydrostratigraphic units" ("HSUs"). Because HSUs behave as the subsurface "plumbing", one goal of site characterization is HSU identification and mapping. Once HSUs are defined, well screen positions (in X, Y, and Z coordinates) can be related specifically to them. This approach provides a superior tool for contaminated site management and remediation compared to contouring groundwater elevations and contaminant plumes in aquifer zonations based primarily on depth. Commonly, aquifer zonations used in groundwater remediation project areas are found to be poor predictors of subsurface architecture and contaminant fate and transport.

Sequence Stratigraphy and Environmental Sequence Stratigraphy

The science of sequence stratigraphy was initially developed based on basin-scale reflection seismic studies, and identification of termination of seismic reflectors on continental margins as related to global sea level changes for petroleum exploration purposes (*e.g.,* Mitchum et al., 1977). However, during the decades since this seminal work the concepts have been applied at increasingly finer scales on well logs and cores, outcrops, petroleum reservoirs, and aquifers (Van Wagoner et al., 1990). Sequence stratigraphy and facies models are applied as a best practice in the petroleum industry for delineating reservoir geometry and continuity. These methods are equally applicable to groundwater systems and related groundwater contaminated sites.

The deposition of sediment in a particular location is controlled not only by the depositional processes operating, but also by the interplay of multiple factors. These factors include sea-level change (magnitude and rate), amount of sediment being delivered, climate, and tectonic history of an area (*e.g.,* Miall, 2000). As these factors change with time, depositional environments shift laterally or may change altogether. During a *transgression*, for instance, as sea-level rises, the shoreline moves landward, placing marine deposits atop terrestrial deposits. Conversely, during a *regression*, the shoreline moves seaward, often leading to erosion of sediments. The science of sequence stratigraphy is concerned with how the factors above interrelate, their impact on processes which operate to transport, deposit, and preserve sediments, and the organization of the resultant deposits (*e.g.,* Posamentier and Allen, 1999). For more information regarding the interaction of these factors, and the impact on sedimentary geometry, the reader is referred to the Society of Sedimentary Geology (SEPM) website: http://www.sepmstrata.org/page.aspx?pageid=1

"Environmental Sequence Stratigraphy", or "ESS" as used herein, refers to the application of both the concepts of sequence stratigraphy and facies models (discussed below) to the types of datasets collected for environmental groundwater investigations, which are typically at the outcrop scale (tens to hundreds of feet vertically, hundreds to thousands of feet laterally). In order to develop this environmental application of sequence stratigraphy, some liberty was taken in generalizing the science of sequence stratigraphy so that it may be of use to practitioners with varying levels of expertise in the field. Although the application to the environmental industry is not focused on changing sea level as it is in the petroleum industry, it does satisfy a key aspect of the sequence stratigraphic approach which is to encourage the integration of data sets and research methods, and it focuses on changes in depositional trends and their correlation across the study area.

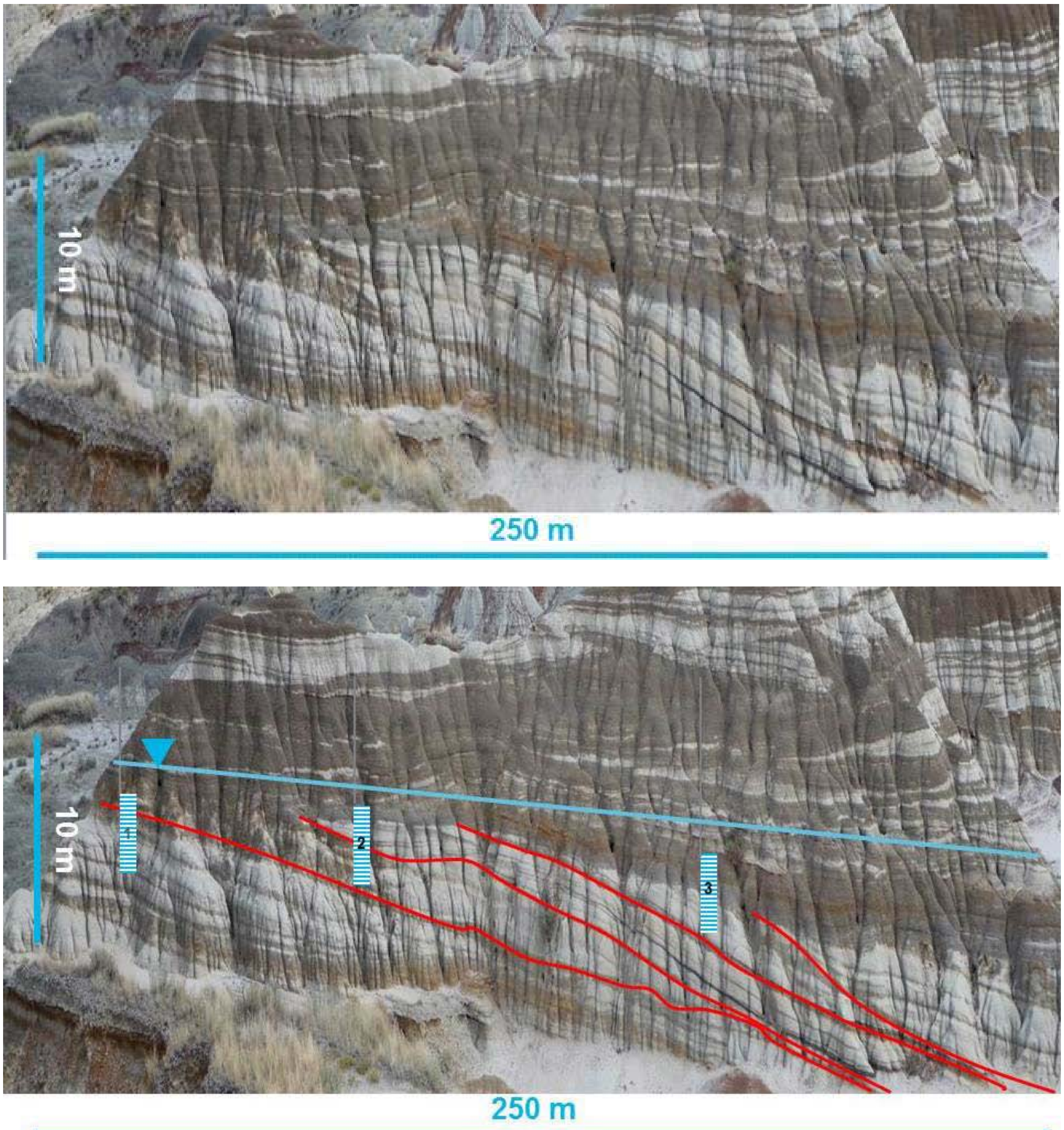


Figure 2. Unannotated (top) and annotated (bottom) photograph illustrating stratigraphic heterogeneity in outcropping strata. In this meandering river deposit, laterally offset-stacked, or "shingled" sand units (point bar deposits, light colored) are separated by clay units (dark colored) (Upper Cretaceous, Alberta, Canada). Bottom photo highlights clay beds dipping from upper left to bottom right (red lines). Blue rectangles indicate hypothetical well screens in the "first encountered saturated sand" (commonly referred to as the "A sand" during groundwater remediation investigations). Though screened at a similar depth, and in a similar sandy lithology, the wells are screened in distinctly different hydrostratigraphic units separated by the laterally continuous, dipping clay beds. Thus, they are not in hydraulic communication and contaminant concentration data from any one well is only representative of the hydrostratigraphic unit in which it is screened. Hydraulic conductivity into and out of the photograph plane (and in the direction of dip) may be orders of magnitude higher than that from left-hand side to right-hand side. Also of note is that "high resolution" subsurface data logs for these three locations would look identical, and, without knowledge of the depositional environment and stratigraphy, the lateral shingling would not be identified. Facies models predict such heterogeneity and hydrostratigraphic unit delineation in a meandering fluvial setting. (Photo courtesy S. Hubbard, University of Calgary, personal communication [2/3/2015])

ESS analyses have been applied to groundwater remediation and water resource studies since the 1990s (Ehman and Cramer, 1996; Ehman and Cramer, 1997), and the importance of advanced stratigraphic methods for understanding aquifer heterogeneity has been emphasized by numerous authors (*e.g.,* Koltermann and Gorelick, 1996; Weissmann and Fogg, 1999; Biteman, et al., 2004; Ponti, et al., 2007; Payne, et. al., 2008; Scharling, P. B., et. al., 2009).

Most groundwater basins have had regional scale stratigraphic analysis undertaken which can greatly benefit site characterization if carefully integrated into remediation studies (*e.g.,* USGS Water Supply Papers at https://pubs.er.usgs.gov/browse/usgs-publications/WSP). However, the number of studies which have applied these concepts to data from remediation sites is very limited (*e.g.,* Ehman and Cramer, 1996).

Examples of Benefits of Applying ESS

The following are some examples where applying ESS methodology to existing data sets on sites with heterogeneous aquifers have provided significant benefits to groundwater remediation projects (see Appendix A).

- In fluvial channel and point bar deposits in the Santa Clara Valley (Silicon Valley), fining-upward sequences bounded by paleosol units were correlated and mapped using existing boring log data. Detailed examination of well screen intervals and integration with facies maps allowed separation of distinct hydrostratigraphic units with different three-dimensional arrangements. Contaminant fingerprinting validated that coarse-grained units represent hydrostratigraphic units (contaminant pathways). This mapping allowed the responsiblie party at this multiparty site the ability to separate onsite vs offsite-derived contamination, providing a basis for modification of cleanup metrics and re-negotiation of proportional liability. (Case Study #1)
- In a glacial outwash fluvial channel system, a keen understanding of the glacial sub-environment and associated stratigraphic "rules of thumb" for correlation results in a significantly different stratigraphic framework to understand and manage dense non-aqueous phase liquid (DNAPL) occurrence. (Case Study #2)
- In an aquifer composed of glacial deposits, a site-specific depositional model identified contaminant migration pathways from a DNAPL release that was not apparent using groundwater contour maps and isoconcentration maps. This provided the blueprint for optimized site characterization, groundwater monitoring, and remediation design. (Case Study #3)
- In an aquifer composed of desert alluvial fan deposits, ESS defined dipping thin, continuous, clay layers that compartmentalized the aquifer into several hydrostratigraphic units. This was critical for targeting and monitoring the injections for the in-situ bioremediation program. (Case Study #4)
- In a perchlorate-impacted aquifer composed of alluvial (river) deposits, ESS defined channel-controlled preferential pathways prior to the pilot test of a pump-and-treat / plume containment system resulting in a system re-design and over 75% reduction in projected groundwater extraction and treatment volume. (Case Study #5)
- In a chlorinated volatile organic compound (CVOC)-impacted aquifer composed of incised valley fill deposits, ESS identified channel-controlled preferential migration pathways that are perpendicular to the regional groundwater gradient, which helped to understand the performance of the remediation injection and extraction programs. (Case Study #6)

II. Depositional Environments and Facies Models

The geographic areas where sediments accumulate over geologic time spans are referred to as “depositional environments” (Figure 3).

In each depositional environment, characteristic processes operate to erode, transport, distribute, and deposit sediment. Due to these processes, each depositional environment leaves characteristic building blocks of sediment in the geologic record. These building blocks are commonly referred to as “architectural elements”, and have characteristic vertical grain size profiles, dimensions, lithology, and facies associations (see Table 1). These architectural elements fit together in three dimensions to form the “stratigraphic architecture” of a sedimentary unit.

Observations of sedimentary deposits in modern environments, outcropping systems, and subsurface systems have been distilled over decades of research, and conceptualizations of how these processes interact and the three dimensional organization of architectural elements they produce exist for virtually all depositional environments. These conceptual models are referred to as “depositional models” or “facies models” (See Figure 4).

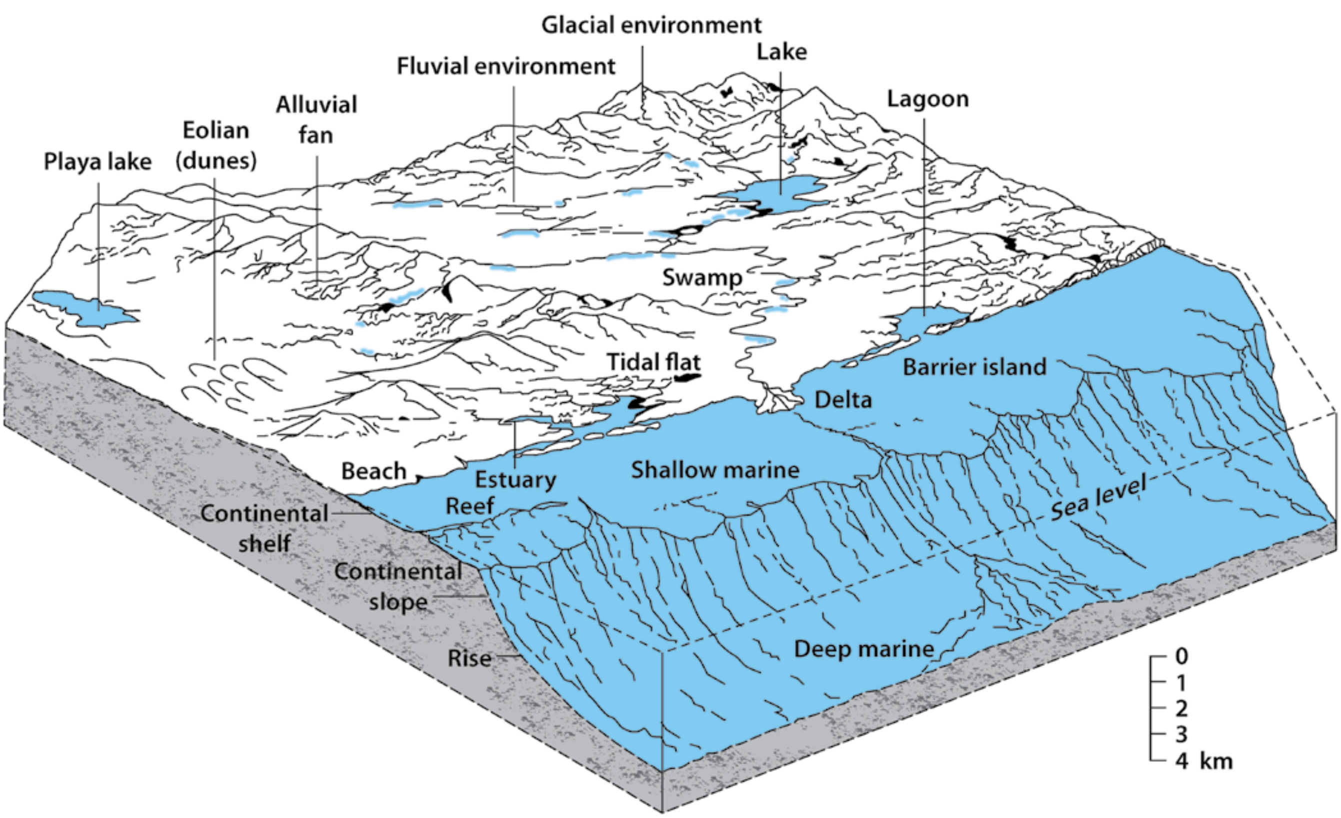


Figure 3. Block Diagram illustrating typical sedimentary depositional environments (from Jones, 2001).

Table 1. Table showing vertical grain size profiles typical of a variety of depositional environments, major aquifer and aquitard elements and their common dimensions, impact on CSMs, and implications for required data resolution for characterization of groundwater remediation sites.

Depositional environment and typical grain size profile	Major aquifer elements and their common dimensions	Major aquitard elements and their common dimensions	Impact on CSM	Data resolution needs
Alluvial Fan  coarsening-upward	Proximal fan channels, mid-fan sheet sands, distal fringe sands X: 10^2 m – 10^4 m Y: 10^1 m – 10^3 m Z: 10^{-1} m – 10's m	Playa lake deposits or paleosol formations commonly vertically separate fans. Debris-flow deposits also commonly clay-rich. X: 10^2 m – 10^3 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10's m	Laterally extensive paleosol or playa lake deposits may be thin (10's of cm to meters), but can vertically compartmentalize aquifers. Such thin aquitards may not be recognized by non-continuous sampling methods due to their thin nature. Fans have a primary stratigraphic dip basinward at 1-6 degrees, and are laterally offset stacked ("shingled"). Fans are constructed primarily by channels encased in sheet-flood deposits. Channels are radial from a point source and represent permeable pathways. Channel density decreasing down-fan.	High in vertical sense, need for lateral resolution decreases down-fan where channels are less predominant.
Meandering Fluvial  fining-upward	Channel axial fill, point bar, crevasse splays X: 1 m – 10's m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Floodplain deposits, levee deposits, clay drapes on lateral accretion surfaces, plugs filling abandoned channels. X: 10^2 m – 10^3 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10's m	Channel and point-bar deposits are encased in fine-grained floodplain deposits and represent the groundwater flow pathways. Traditional potentiometric surface maps are poor predictors of specific groundwater flow paths and contaminant migration pathways. Coarse-grained "lags" at the bases of channels and point bars represent high-permeability pathways. Lateral accretion drapes can form "shingled" aquifer units. Clay plugs filling abandoned channels ("oxbow lakes") common and provide barriers to groundwater flow and contaminant fate and transport.	High both laterally and vertically
Braided Fluvial  blocky	Channel axial fill, bar complex X: 1 m – 10^1 m Y: 10^1 m – 10^2 m Z: 10^{-1} m – 10^1 m	Floodplain deposits, silt and clay plugs filling abandoned channels. X: 10^2 m – 10^3 m Y: $10^{'s}$ m – 10^2 m Z: 10^{-1} m – 1's m	Low-sinuosity high-permeability streaks encased within an overall permeable matrix may dominate groundwater flow and contaminant migration. Laterally discontinuous silt and clay units may be significant at the plume scale, and are more continuous in the down-channel direction compared to the cross-channel direction.	High both laterally and vertically, greater lateral resolution required perpendicular to depositional axis (i.e., cross-channel transects) versus parallel to depositional axis (down-channel)
Marine or Lacustrine  symmetrical or bow	Offshore bar, shelf, transgressive sand X: 10^1 m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Fair-weather fine-grained draping shales X: 10^1 m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Gradational base and top related to shifting sea-level or environment. High degree of lateral continuity. Interbedded storm deposits (coarser grained) with fair-weather deposits (finer-grained) lead to high degree of vertical heterogeneity and "layer cake" stratigraphy.	Low in lateral sense, high in vertical
Near-shore, Deltaic  coarsening-upward	Shoreface (beach), distributary channels in upper part, prodelta in lower part X: 10^1 m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Marine flooding shales capping sequences, interdistributary fluvial overbank in upper parts X: 10^1 m – 10^2 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Laterally extensive, sand-rich near-shore units in upper parts of sequences and delta-plain channels. High degree of interbedding of coarse and fine-grained units in lower parts. Silt and clay flooding shales capping sequences dip basinward, may lead to erroneous correlations at distances of hundreds of meters to kilometers.	Low in lateral sense, high in vertical. Higher resolution required in upper parts of sequences due to the presence of distributary channels.

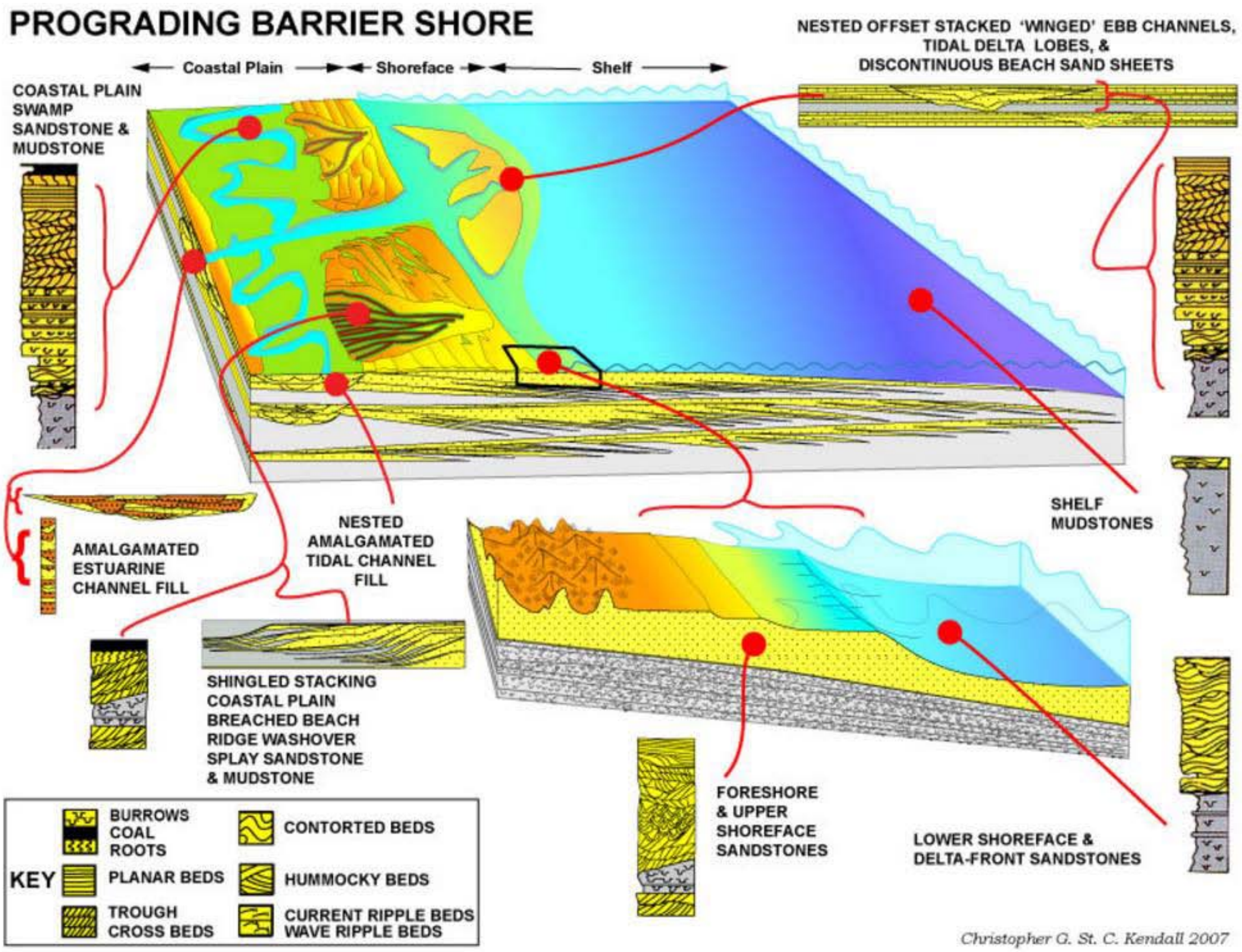


Figure 4. Three dimensional facies model of a prograding barrier shoreline developed through integration of observations of modern barrier island systems, outcropping ancient systems, and subsurface datasets worldwide. "Prograding" refers to the shoreline system migrating seaward, due to an abundance of sediment being supplied, falling sea level, or both (the converse is referred to as "retrograding"). Note the "sheets" of the barrier island beaches, the "lobes" of the ebb tidal deltas, the "stacked and amalgamated channel fill" and " shingling" of the washover splay sandstones. Each sub-environment has corresponding vertical grain size trends. Scale has been intentionally omitted, as a variety of scales exist for each sub environment. This depositional model applies to many remediation sites located in coastal areas of the Atlantic and Gulf Coasts of the United States as well as coastal regions worldwide. From http://www.sepmstrata.org/CMS_Files/553_lecture1_introduction.ppt
Used under Creative Commons fair use policy with thanks to Dr. Christopher G. St. C. Kendall.

In the prograding barrier island facies model example, a variety of sub-environments are present and produce architectural elements (*e.g.,* ebb tidal delta lobes), which also have characteristic vertical grain size trends. Thus, with the knowledge that a site lies within a prograding barrier island depositional environment, vertical grain size profiles can be used to predict lateral relations away from the known data points, and the facies model serves as a guide to interpreting depositional elements and correlating site data in three dimensions.

Facies models for fluvial systems

Extensive areas of the United States located in river valleys and on alluvial plains are underlain by aquifers that were deposited in channelized (fluvial) depositional environments. As such, a brief overview of fluvial classification and facies models is presented herein. The reader is referred to the extensive literature (*e.g.,* Walker and James, 1992; Miall, 2000) for detailed information. While a continuum between styles exists, fluvial systems can be broadly subdivided into braided, meandering, and, less commonly, anastomosing (Figure 5).

Sinuous, meandering-type rivers are common in the Eastern United States due to the abundance of clay and sand-sized material in the river system, relatively low topographic gradient, perennial river discharge, and abundant vegetation. Meandering river processes result in deposition of "point bars", which are laterally accreted sand units deposited on the inner bend of channels as the outer bend of the channel (cutbank) erodes the older deposits and the channel axis migrates towards the outer bend of the meander (Figures 5 and 6). While the vertical grain size trend of a meandering fluvial deposit is the "classic" fining-upward point bar sequence, additional architectural elements are present with characteristic grain size trends and architecture (Figure 6).

Another common element of meandering fluvial systems is the "clay plug" which is deposited in abandoned meanders, or oxbow lakes (*e.g.,* Walker and James, 1992).

In contrast to the Eastern United States, arid regions such as much of the Western United States are often near mountainous areas, and their rivers have abundant coarse sediment supply, ephemeral flashy runoff, and less vegetation on riverbanks. This leads to riverbank instability and rapid shifting of the active channel, and streams tend to take on braided-type morphology (Figure 5).

Glacial geology and related depositional systems

Because sequence stratigraphy seeks to identify genetically related packages of sediment, reflective of a depositional event or series of depositional events, its concepts are applicable universally. While a sequence-based approach has not been applied widely to glacial sediments to date, it is applicable. Glacial advance and/or retreat is distinctly recognizable in the stratigraphic record in the Midwest USA via predictable successions of facies, many consisting of the depositional systems detailed in this document. For example, successions of subaqueous fans and lacustrine sediments grading upward in to subaerial fan deltas and outwash, basal-till and ice contact deposits provide a clear record of glacial advance that is recognizable in both lithologic and geophysical logs. Case Study 3 provides a remediation-scale example of how lithologic data was used to recognize and reconstruct distinct facies in a glacial setting.

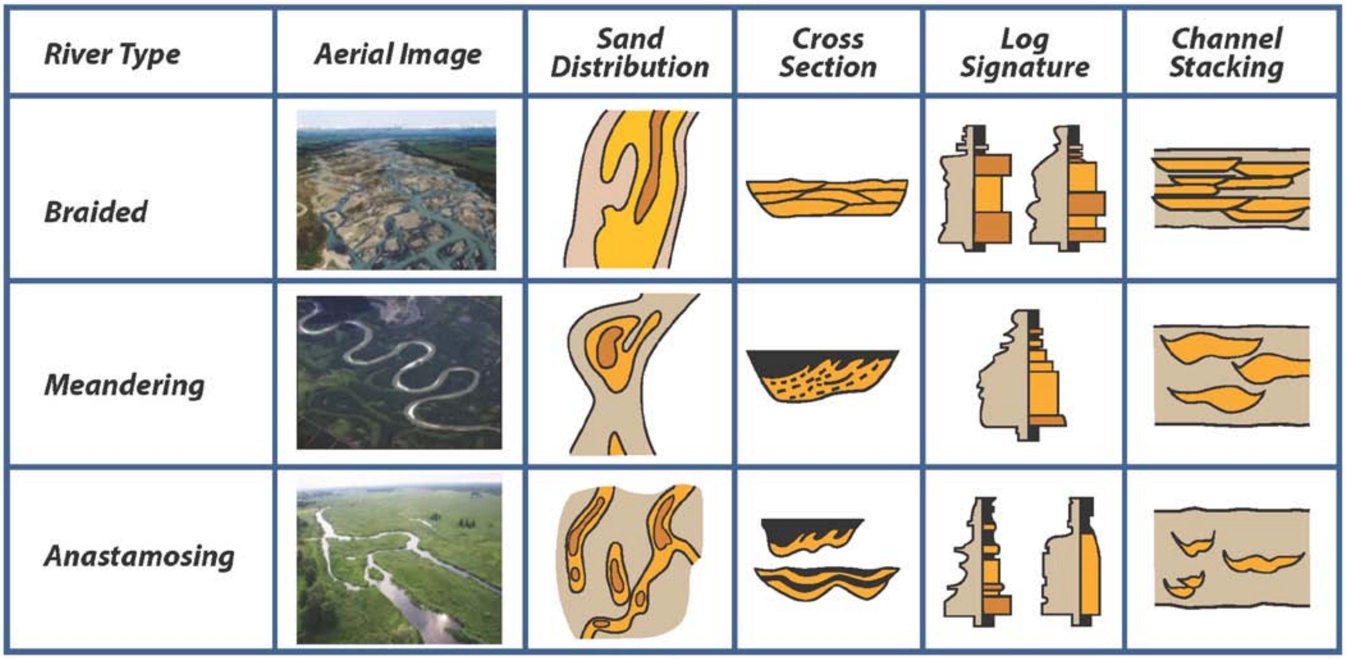


Figure 5. General classification of fluvial systems and their deposits (modified from http://www.beg.utexas.edu/agi/mod03/graphics/9180.gif). Courtesy of the Bureau of Economic Geology, University of Texas at Austin).

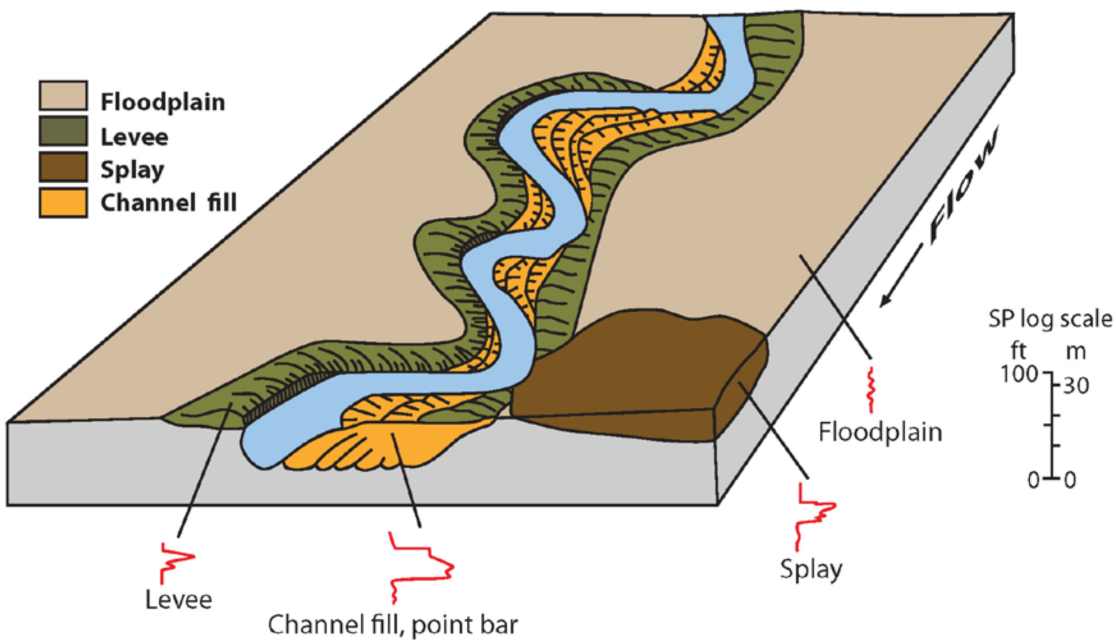


Figure 6. Meandering fluvial sub-environments. Within a meandering fluvial environment, many sub-environments are present and can be differentiated on the basis of geophysical log signatures that represent vertical grain size patterns associated with the sub-environments (log plots showing increasing grain size to the right). Deposits of different sub-environments have characteristic dimensions, orientations, and impact on groundwater flow. Figure courtesy of Bureau of Economic Geology, University of Texas at Austin (http://www.beg.utexas.edu/agi/mod08/m08-step2-02.htm).

III. Application of Environmental Sequence Stratigraphy

ESS methodology begins with an understanding of the depositional environment and the use of existing lithology data to elucidate vertical grain size patterns. Work products include geologic cross sections and facies maps that form a basis for integration and interrogation of groundwater chemistry and hydrogeology data.

The application of ESS to contaminated groundwater sites can be broadly subdivided into three general phases.

> **Phase 1:** Synthesize the geologic and depositional setting based on regional geologic work, and identify facies models which are applicable to the site.
>
> **Phase 2:** Review the existing CSM and site lithology data in light of Phase 1 findings and format existing lithology data to highlight vertical grain-size patterns (sequences) as a basis for correlations honoring stratigraphic "rules of thumb" (presented later in this paper).
>
> **Phase 3:** Construct a hydrostratigraphic CSM consisting of maps and cross sections that depict the HSUs present as a basis to integrate and interrogate hydrogeology (*e.g.,* water levels, pump test, slug test) and chemistry data (*e.g.,* constituents, concentrations).

Subdividing an "ESS Methodology" into three phases outlined above may facilitate implementation, but it is an integrated, iterative process and is meant to be revised when additional data are collected.

Phase 1: Synthesize the geologic and depositional setting based on regional geologic work

Phase 1 analysis is focused on developing a thorough understanding of the depositional environments present, identifying applicable facies models against which the HSU framework can be evaluated, and developing a conceptualization of the series of erosional and depositional events which formed the aquifer. While a short description of geologic setting is commonly included in historic site characterization documents, this material typically relies on previous work, seldom incorporates a discussion of depositional environments, and typically does not incorporate facies models into correlation strategy or a discussion of permeability heterogeneity. Often overlooked are local and regional geologic mapping and studies that may be directly applicable to remediation sites.

In tectonically active areas or older sedimentary deposits, review of geologic maps and identification of structural dip (tilting by tectonic forces such as near faults) is especially important. As most natural sedimentary deposits are highly vertically anisotropic (*i.e.,* Kh>>Kv), structural dip will impose a strong lateral anisotropy in the subsurface and impact fluid flow accordingly.

Geomorphology of Modern Landforms as Predictors of HSUs

Geomorphic features at or near the project site provide insight into aquifer heterogeneity and site hydrostratigraphy. Consult Google Earth, current and historic aerial photographs, and topographic maps and identify surface features (*e.g.,* scroll bars in meandering river systems) that indicate depositional trends and HSU orientations (Figure 7).

Satellite imagery and geologic maps are extremely valuable for interpretation of subsurface conditions in coastal depositional environments (Figure 8).

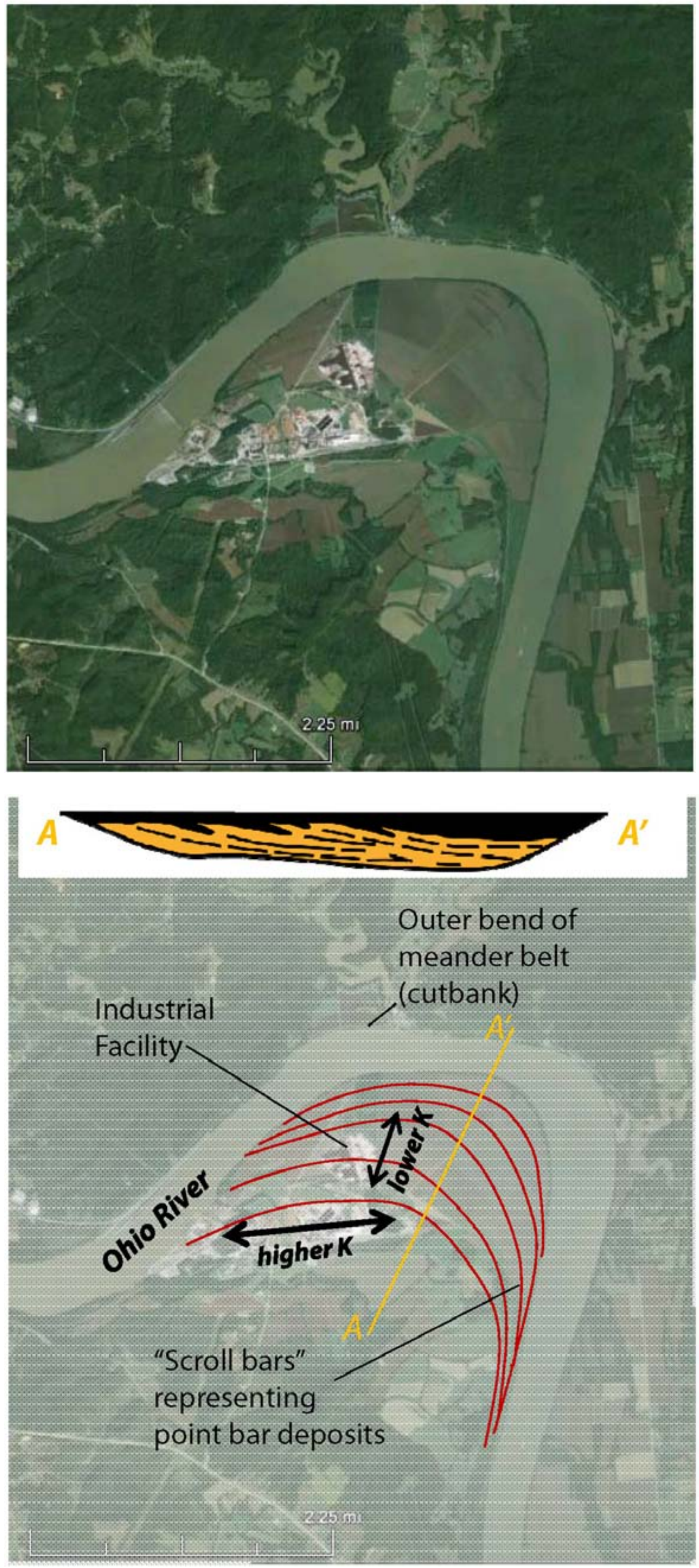
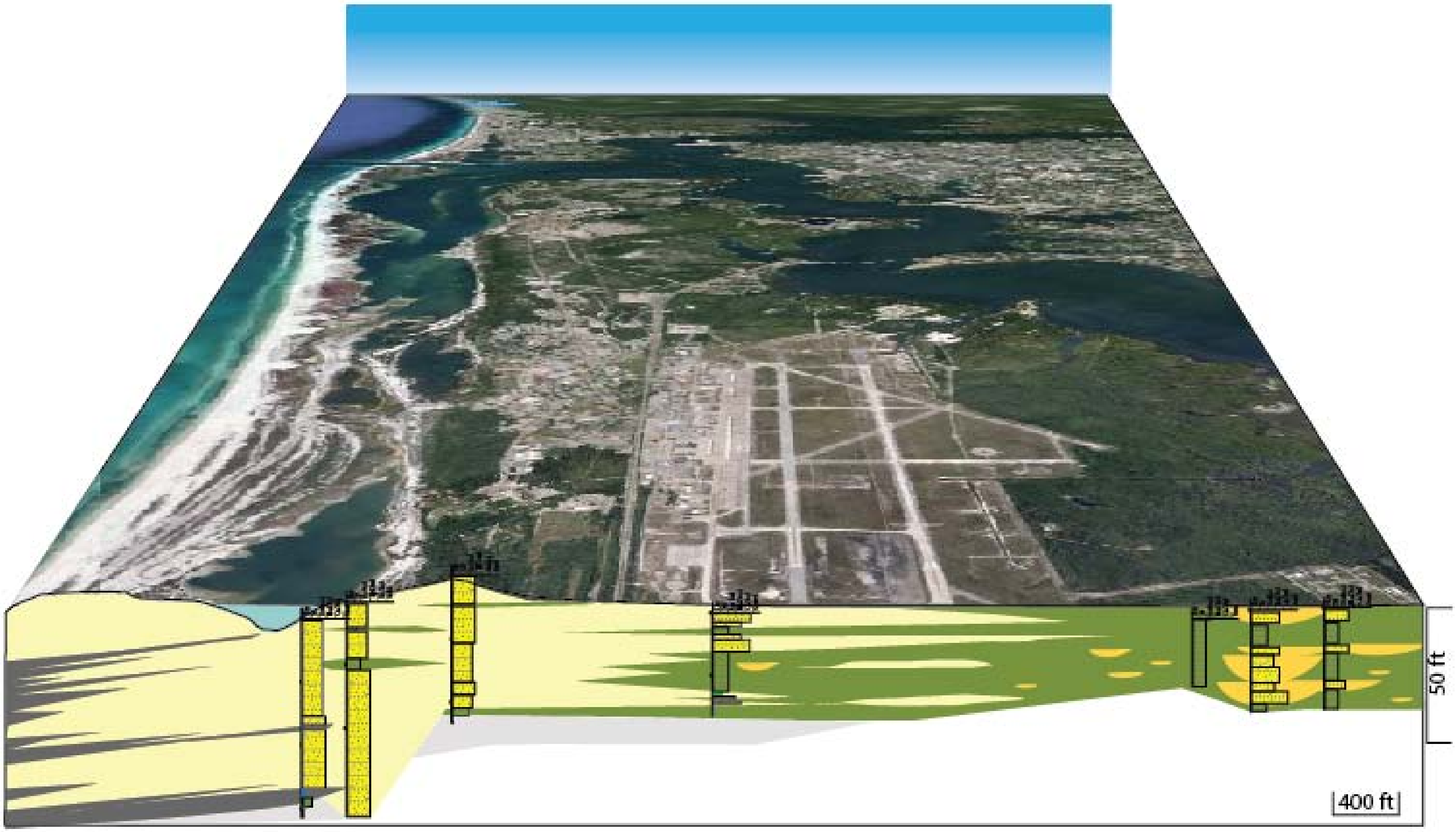


Figure 7. Satellite image of an industrial facility in the Ohio River Valley constructed on point bar deposits. Depositional grain is visible (meander loop migration to north) and suggests subsurface anisotropy with relatively lower permeability across point-bar deposits.



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

Figure 8. Block diagram showing subsurface nature of a Department of Defense facility in the Gulf Coast as predicted from boring logs and surface geomorphology. Satellite imagery shows an active barrier island system (far left) and a relict barrier island system separated by a lagoon. The relict barrier island system passes landward into a mid- and back-barrier island system, respectively. Facies models for barrier island systems predict high continuity of washover fan and tidal deltas in the mid-barrier environment, and discontinuous tidal channel fill units in the back barrier environments.
(Yellow = beach/eolian sands; Gold = tidal sand channel fills and point bars; Black = clay; Green = silt/clay deposits).

Impact of Sea-Level Change in Quaternary Systems (2.5 million years ago to present)

In coastal regions, fluctuations in sea-level resulting from Quaternary glacial and interglacial cycles resulted in a series of erosional and depositional events, and caused depositional environments to shift landward and seaward with rising and falling sea levels, respectively. During glacial periods, seawater was sequestered in continental ice sheets. As a result, sea-level was lowered by as much as 400 feet, exposing the modern continental shelves to erosion. During these times, river systems entering the ocean carved erosional valleys known as "incised valleys," which are prevalent in coastal regions worldwide. During deglaciation, these valleys were filled with fluvial deposits or flooded by rising sea level.

Interplay of marine incursions with sediment delivery via rivers produced characteristic incised valley-fill sequences which have been extensively studied and documented in coastal areas of the East and Gulf Coasts of the United States (*e.g.,* Anderson et al., 2004), and worldwide (*e.g.,* Posamentier and Allen, 1999). Many remediation sites are located within areas where these studies have been undertaken. In such settings, the known Quaternary sequence stratigraphic architecture controls permeability architecture, and integrating site stratigraphy with this information is critical to subsurface interpretation.

Leveraging Nearby Off-Site Data to Augment Site Data

In areas with a high density of remediation sites within the same geologic setting, data from nearby sites can augment site data. For instance, a nearby site may have data of different types or resolution that provide insights into vertical sequences, channel dimensions and orientations, the nature of stratigraphic contacts, and hydrogeologic parameters directly applicable to the site in question. Regional data are in most cases publicly available through state and/or local regulatory agencies, and represent additional site characterization data available to project teams at minimal cost.

As stated, Phase 1 analysis focuses on identifying existing resources to develop a deeper understanding of the depositional environments present, and identifying applicable facies models against which the HSU framework can be evaluated. At the conclusion of Phase 1, project teams will document key findings and working hypotheses. These can include but are not limited to the following:

- sources of geologic information;
- interpretation of depositional environments;
- preliminary selection of analogs and facies models;
- expected dimensions and types of heterogeneities observed (*e.g.,* channel occurrence and scale); and
- data resolution required to evaluate heterogeneities observed and predicted from facies models.

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Phase 2: Formatting lithologic data and identifying grain size trends

Phase 2 is focused on formatting existing lithologic datasets to accurately represent data density, vertical resolution, and vertical and lateral grain size trends. The following briefly summarizes typical subsurface lithology data types at groundwater remediation sites and recommends a method of formatting and displaying vertical grain size patterns to maximize the value of these existing data for stratigraphic interpretation. While, in general, coarser-grained units are expected to have higher permeability, other characteristics, such as sorting, can have a significant influence on the permeability. Where differences in sorting are noted in boring logs and can be shown to be consistent among various site datasets (*e.g.,* SP vs SW), then a higher permeability is expected in the well sorted (poorly graded) deposits. Such patterns may be equally important as grain size differences and should be considered.

Existing Lithology Data

Borehole logs typically capture lithologic descriptions in terms of color and grain size and, in the environmental industry, are typically classified according to the Unified Soil Classification System (USCS). The USCS was developed for engineering or geotechnical purposes with little emphasis on identifying geologic features indicative of depositional processes or environments. While we advocate a “facies-based” approach for describing strata instead of USCS classification (see "Facies-based" Description of Sedimentary Deposits, herein), a wealth of information beyond the USCS classification is often present in legacy boring log data, which can be extracted to reveal trends in grain sizes and used to make stratigraphic interpretations (see Graphic Grain Size Logs section below). The detail of the borehole log descriptions may vary widely depending on drilling and sampling methods and the experience and biases of the geologist logging the borehole. Logging biases as well as data quality are variable among different generations of boring log descriptions. Descriptions may be from continuously cored boreholes (*e.g.,* direct-push sampling, hollow stem auger, mud rotary, air rotary, or sonic drilling methods), or from depth-discrete samples (*e.g.,* 18-inch samples collected at 5-foot intervals using a hollow-stem auger drill rig). In some cases drill cuttings logs from air or mud rotary drilled boreholes are available. The quality of the lithologic description is dependent on these factors and needs to be considered when evaluating existing lithology data. Formatting legacy lithologic datasets in a way that emphasizes relative vertical grain size trends as described herein serves to normalize seemingly inconsistent lithologic datasets.

Cone penetrometer testing (CPT) logs may be available and provide continuous tip resistance, sleeve friction, and pore pressure data that serve as a proxy of formation grain size and relative permeability. The CPT typically has a maximum depth of penetration of approximately 100 feet. It is best practice to collect at least one continuous core next to a CPT boring to calibrate the CPT response to the lithology. While CPT is historically widely used for lithologic data collection, a wide variety of other direct-push characterization tools are currently in use (ITRC, 2015), and may provide valuable information depending on the specific site characteristics.

Downhole geophysical logs provide a continuous representation of formation properties (see Figure A24). As with the CPT logs, it is a best practice to calibrate the geophysical log response with continuously cored lithology description. Electrical conductivity logs from MIP or other direct push characterization programs provide lithologic information as well. Such continuous resolution provided by geophysical logs provides data on degree of interbedding and grain size patterns.

Lithologic Data Formatting to Identify Grain-Size Trends: Graphic Grain-Size Logs

Borehole log data are commonly represented on cross sections of remediation sites as vertical “strip logs” with USCS classification indicated. However, to maximize the value of existing lithology data for stratigraphic interpretation, borehole log data can be formatted as graphic grain-size logs to emphasize vertical grain size patterns. Graphic grain-size logs are constructed by plotting the maximum grain size described in the boring log (Figure 9a). The coarser grained sands and gravels plot away from the axis while the silts and clays plot closer to the axis, with the goal being to create a vertical grain size profile. As maximum grain size provides an estimate of the energy level (*e.g.,* current velocity) in the depositional system, this provides a superior indicator of depositional environments. This representation of the lithology data offers the following advantages vs. USCS strip logs (refer to Figure 9a).

- Grain size details are identified that are otherwise masked by the USCS classification, such as the shallow unit at 0 to 20 ft that is described as silty sand (SM) is composed of fine to medium-grained silty sand, whereas the SM unit at 30 ft is composed of fine to coarse-grained silty sand with gravel.
- The sample density (*i.e.,* vertical resolution of data) is represented, showing that samples are collected every 5 ft, and not continuously.
- The vertical grain size pattern clearly shows two fining upward sequences representative of separate channel complexes. These sequences are not apparent within the USCS strip log.

When evaluated on the ESS cross section (Figure 9c), the two channel-fill cycles correlate with surrounding logs and help to define sand/gravel-filled channels. These channels provide preferential contaminant transport zones within this transect, and represent a starting point for channel mapping. Using USCS-based cross sections, no such patterns are apparent, and these channel features had not been previously identified at the site. Case Study #1 is another good example of the value that graphic grain-size logs can extract from existing borehole logs.

As is the case with graphic grain-size logs, CPT and geophysical log data are posted as curves on cross sections to represent vertical grain size and guide correlations.

At the conclusion of Phase 2, project teams will have:

- identified lithologic datasets and reviewed them for quality, drilling methods, data resolution, and consistency;
- created a sufficient number of graphic grain-size logs to identify grain size trends

and have developed ideas regarding

- depositional environments (see Table 1, and Appendix A for multiple case studies)
- degrees and orientations of heterogeneity
- their potential to impact groundwater flow and contaminant migration.

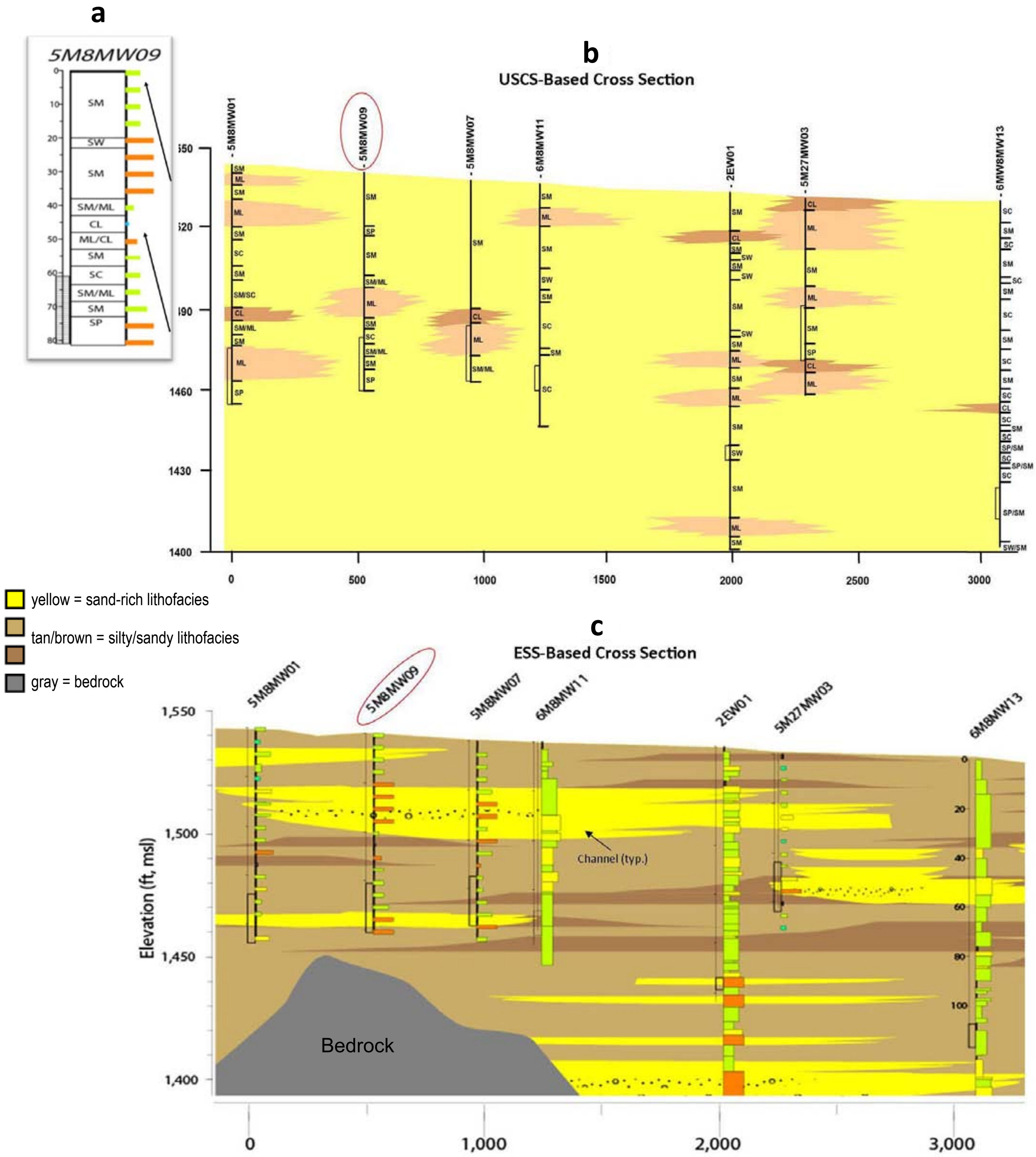

Figure 9. Graphic Grain-Size Logs Used to Define Channel Occurrences. a) A graphic grain-size log prepared from boring log data to emphasize vertical grain size trends. Two fining-upward sequences representing channel-fill cycles are visible in this log, which are not visible in traditional USCS "strip logs". Two channel-fill cycles are correlated on the lower ESS cross section (c) to define channel occurrence. Note that these channel features are not apparent on the USCS-based cross section (b) and would not be identified by kriging algorithms.

Phase 3: Identify and map HSUs

With a detailed understanding of site lithology data and grain size trends in vertical boreholes obtained during Phase 2, Phase 3 is the data integration and interpretation step aimed at identification of depositional elements which may comprise HSUs. Candidate HSUs can be tested and validated by integrating hydrogeology data and groundwater chemistry data. This is accomplished by creating a series of cross sections, identifying candidate HSUs and their bounding surfaces, attempting to map said units in three dimensions, and examining water levels and analytical results in the context of the working interpretation. This is an iterative process, arriving at a best fit between all data.

Cross sections in traditional CSMs are typically oriented parallel and perpendicular to general groundwater gradient and through contaminant source areas. However, cross sections oriented parallel and perpendicular to depositional trends as identified in Phase 1 are also valuable with respect to contaminant fate and transport. For example, in a braided stream environment, cross sections should be oriented parallel and perpendicular to channel orientations. As cross sections are constructed and candidate HSUs are identified, additional cross sections and maps may be required to validate the interpretation. Maps required may include facies maps showing lateral changes within HSUs, isopach (equal thickness) maps, clay or paleosol continuity maps, or other maps depending on local conditions. Integration of other available data (*e.g,*, hydrogeology and groundwater chemistry data) in the context of the depositional environment provides the multiple lines of evidence for a geologically defensible HSU interpretation.

Interpretation Methodology and Stratigraphic "Rules of Thumb"

While there is no substitute for experience in application of facies models and sequence stratigraphy for accurate stratigraphic interpretation, the following generalized "rules of thumb" are presented to assist practitioners in the groundwater remediation community to improve subsurface correlations and prediction.

1. Identify a suite of applicable facies models for a particular site and use them as a guide in correlation of sand units. Interpret depositional elements (*e.g.,* channel axis, margin, and overbank) as potential HSUs and define the criteria used to classify elements. Develop hypotheses regarding site specific conditions and how they might cause the site stratigraphy to vary from the facies models identified.

2. Vertical patterns in grain size (*i.e.,* sequences) are indicative of the relative energy level present in the depositional environment and hence are better indications of correlative units than tops or bases of sand units.

3. Aquifers are usually correlated in a "top down", lithostratigraphic fashion; however, sediments were originally laid down from the bottom up or in laterally-offset fashion (Appendix A, desert alluvial fans Case Study #4, Figure A22), and are often eroded by younger units. Thus a conceptual model of how sedimentation and erosional events occurred is necessary for accurate stratigraphic correlation.

4. Correlate clay units first. In "channelized" fluvial (riverine) settings, channel bases are often erosive and irregular in elevation, whereas floodplain clays and paleosols capping channel sequences tend to be more horizontal (see Appendix A, glaciofluvial Case Study #2). However, in some cases, clay-filled channels may be encountered as a result of channel abandonment and passive filling by fine-grained materials. This is especially prevalent in meandering stream deposits.

5. Paleosols commonly form within floodplain deposits, and form superior correlation markers to bases or tops of individual channel sands, and are likely to be continuous over large areas. Paleosols may be identified in borings logs by mention of soil nodules such as caliche or siderite, relative hardness as identified by blow count or changes in drilling conditions, or zones of high tip resistance in CPT logs.

6. For channel deposits, identify channel bases that are generally erosive and irregular in topography, and contain the coarsest grain-size fraction present in the overall system, representing potential high-permeability zones which may move a large proportion of the groundwater and contaminant mass through a very small percentage of the overall cross-sectional area. Bases of channel complexes are more likely to be hydraulically connected than the upper portion of individual channel deposits.

7. Channel systems that are characterized by a relatively high clay content overall (*e.g.,* meandering river systems) are likely to be more compartmentalized than sand-rich (*e.g.,* braided) systems, and correlations of channel packages may, therefore, have greater uncertainty. Clay-filled abandoned channels, or "plugs", resulting from cutoff meanders are common in meandering systems. These arcuate features can serve as barriers to groundwater flow and can dramatically affect hydraulic gradients.

8. The degree of lithologic heterogeneity (interbedding) observed in a vertical log is generally a good first-pass indicator of lateral heterogeneity. However, thin clay beds present in an otherwise sand-rich aquifer system may be laterally continuous for long distances (hundreds to thousands of feet or more) and may form effective barriers to groundwater flow. At sites where data have been collected at 5' intervals by split spoon or other methods, these clay units may not be represented in many borings. The potential for thin, laterally continuous clays to be present is high in marginal marine, playa lake, fluvial overbank, and glacio-lacustrine depositional environments (see Appendix A, desert alluvial fan Case Study #4).

9. In coastal areas, during the relative highstands of sea level, the incised valleys of the Gulf coast and Atlantic coast of the United States became inundated with marine waters. This caused depositional environments to shift inland and resulted in deposition of laterally continuous marine clay deposits referred to as maximum flooding surfaces. There are industrial facilities that are located in incised valleys of the Gulf and Atlantic coast areas (see Appendix A, incised-valley fill Case Study #6). These maximum flooding surfaces can be identified by high gamma-ray counts and relatively pure clays and have high potential to compartmentalize aquifers in incised valleys.

10. Clay units correlated in a way which shows "mounding" or positive topography are suspect unless tectonic deformation has impacted the site (Appendix A, glaciofluvial deposits Case Study #2), or deep burial and extensive compaction of the sedimentary sequence has occurred, which can lead to "compaction folds" resulting from clays being more prone to compaction than sands. This is uncommon within the upper several hundred feet from the surface.

11. Vertical stacking of facies or "pillars" (see Figure 10) is a common mistake in groundwater CSMs and results from variability in boring log data quality or logging bias (*e.g.,* one geologist may log a facies as an SM, and another may log the same facies as SP). Some interpreters may take this information literally without considering the potential for logging bias and hence may place a facies change between every well, resulting in a "pillar" style interpretation of facies. Such an interpretation is non-geologic, and is of limited value in understanding subsurface conditions or planning remediation.

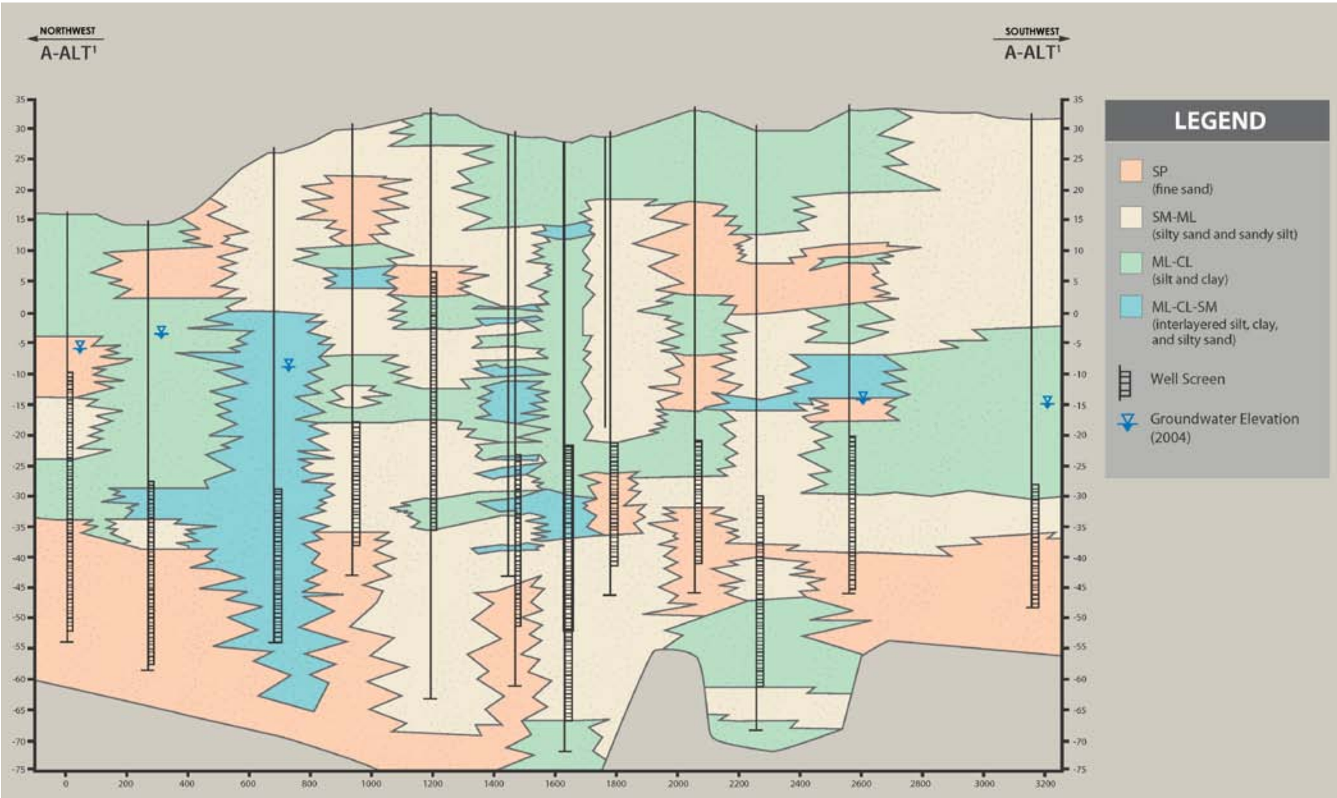

Figure 10. Cross section showing a common mistake in correlating subsurface data. Interpreted vertical facies patterns ("pillars") corresponding to individual borehole locations with interfingering facies changes laterally. This cross section reflects biases in USCS classification between different geologists or vintages of data collection, is not geologically defensible, and is of extremely limited utility in understanding subsurface conditions.

As stated, defining the HSU includes integrating hydrogeology and chemistry data, which provide further evidence for hydraulic continuity. This iterative process further interrogates and refines the CSM with multiple lines of evidence. The HSU interpretation is revised and refined as additional site data are collected and updated as necessary to be consistent with all available data.

At the conclusion of Phase 3, the project team will have:

- an improved understanding of vertical and lateral trends in grain sizes, and a clear understanding of existing lithologic data types and resolution;
- a network of correlated cross sections which tie together in three dimensions, consistent with the facies models applicable to the site;
  (Correlations generated by kriging or other computer programs are to be used with caution as they do not abide by the "rules of thumb" presented herein [see Case Study #4].)
- identified and mapped candidate HSUs as a basis for integrating hydrogeology and chemistry data to validate their impact on groundwater flow and contaminant fate and transport.

CONCLUSIONS

The uncertainty with respect to fluid flow controlled by geology is the primary risk to the success of groundwater cleanup programs. Fluids in both the vadose and saturated zone flow along preferential pathways controlled by the stratigraphy. This is important because it often results in contaminant transport directions that diverge significantly from groundwater gradients inferred from groundwater elevation data. This fact presents challenges for characterization, monitoring, and remediation of contaminants in the subsurface, as evidenced by challenges historically encountered for groundwater remediation projects.

The conceptual tools of sequence stratigraphy and facies models developed in the petroleum industry represent a step-change in our ability to manage subsurface heterogeneity, and are directly applicable to groundwater remediation projects. These tools are founded on an understanding that each depositional environment has characteristic processes which act to transport, deposit, and preserve sediment, and therefore leave characteristic vertical and lateral grain size trends in the sedimentary record. Thus, aquifers that were laid down in the same depositional environments, regardless of their geographic location, share a host of characteristics impacting fluid flow. Therefore, an appreciation of depositional environments corresponding to a particular aquifer allows for a great number of predictions to be made regarding heterogeneities and acts as a guide to subsurface data correlation.

This paper provides suggested data presentation methods for identifying grain-size trends in existing data, generalized stratigraphic methods and rules of thumb for correlation of subsurface logs, and a three-phase approach to applying "Environmental Sequence Stratigraphy". Practical guidance presented herein will help move projects away from a homogeneous and isotropic subsurface CSM to a more geologically defensible CSM which takes advantage of facies models and sequence stratigraphy to identify contaminant pathways. Case studies presented in Appendix A highlight benefits of using facies models to guide well log correlations, and the benefits of stratigraphic correlations to CSMs for groundwater remediation, resulting in robust CSMs that guide groundwater remediation project success.

“Facies-based” Description of Sedimentary Deposits

Strategically located continuously cored boreholes provide a direct observation of the geology that can be used to calibrate proxy representations of lithology (*e.g.,* direct-push HRSC tools, geophysical tools). Another advantage of strategically located continuous core is it can be sampled and analyzed to determine relative concentrations of contaminants in coarse- and fine-grained strata to evaluate the potential for fine-grained strata to act as long-term sources of contamination to groundwater (*i.e.,* matrix diffusion [Sale and Newell, 2011]), and better evaluate mass flux across transects. The Unified Soil Classification System (USCS) has traditionally been used to describe sedimentary deposits of contaminated sites. The USCS was developed for geotechnical investigation and is focused on the engineering properties of the deposits and is of limited use for identifying depositional processes or environments recorded in the strata. A “facies-based” description of strata is focused on depositional characteristics and provides a better way to interpret depositional processes and environments.

- When drilling, care should be exercised to recover a continuous, intact core. While drilling methods commonly used in environmental investigations may disturb the materials, scraping the surface with a knife and/or or spraying the coating away with a spray type water bottle often allows for a clearer view of sedimentologic features such as laminations, cross-bedding, degree of interbedding and bed thickness, etc. If rotosonic methods are required, work closely with the driller to minimize liquefaction and destruction of sedimentologic features.
- A “facies-based description” of core materials includes information that can be used to determine depositional processes. If possible, slice the core in two down the vertical axis to expose a planar surface to examine features. If the core is to be used for analytical sampling as well, care should be taken to sample appropriate intervals prior to complete core splitting or to slice the core across the barrel width using a core guillotine-type device to avoid transposing contaminants vertically with the motion of a knife up or down the core barrel.
- While a USCS-based description of subsurface core materials might be “SM, very dark gray (5Y 3/1), 70% fine sand, 30% silt, loose, dry”, a facies-based description of the same interval might be “fine-grained, current ripple-laminated sand with interbedded silty sand”.
- Additional description would include bed thickness, ripple morphology, bounding surfaces or erosional surfaces present, root casts or other biogenic structures, soil formation features, etc. The reader is referred to sedimentology and stratigraphy texts for additional information (*e.g.,* Walker and James, 1992; Miall, 2000).

Facies-based descriptions provide identification of the depositional features which can be used to interpret depositional environments. The reader is referred to stratigraphy and sedimentology textbooks for information on mechanics of sediment transport and deposition and resultant sedimentary structures as well as paleoenvironmental interpretation.

Limitations of Kriging and Overreliance on Visualization Tools

Three-dimensional computer-generated graphical displays of subsurface data are an important data visualization and interrogation tool, but should not be mistaken for a conceptual site model. High resolution lithologic data are valuable for site characterization, but it is recommended that they be interpreted in the context of the depositional environments. Often, such data are acquired and used to generate 3D computer models which are thought to represent a highly quantitative CSM. However, these models rely on kriging, which provides an oversimplified and/or unrealistic view of the subsurface geologic architecture. This can be especially problematic in geologic settings characterized by a primary depositional dip and/or laterally continuous thin clay beds. The alluvial fan Case Study #4 Figure A23 shows an example of this in alluvial fan environments with thin draping clays where a kriged model does not correlate thin clay beds. This can be misleading when in fact the system is highly compartmentalized and the compartments are oriented systematically and predictably when a facies model is considered. Modeling approaches and geologic analysis are merging in academia and the petroleum industry, but not so in the environmental industry. Current research in computer modeling of aquifers (Michael and Gorelick, 2010), and oil reservoirs (*e.g.,* Pyrcz, and Deutsch, 2014) has focused on generating models which use “training images” (Mariethoz and Caers, 2014) or geologic “rules” to produce more geologically realistic simulations and improve predictions over traditional kriging-based models. The takeaway here is to ensure that geologic cross sections are constructed by geologists, not computer software.

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APPENDIX A

Case Studies

Case Study 1: Fluvial Channel Deposits, Silicon Valley, California

Introduction to the Site

This case study documents a site representative of many contaminated groundwater sites in the Santa Clara Valley, or “Silicon Valley” of northern California (Figure A1). Historic contaminant releases related to semiconductor and other electronics manufacturing resulted in extensive groundwater contamination (primarily VOCs) in the basin. The groundwater table in the basin is relatively shallow (approximately 10’ below ground surface [bgs]), contaminant concentrations in groundwater may be high, and the highly urbanized area is characterized by dense commercial and residential construction. Thus, vapor intrusion poses risks to human health.

The heterogeneous aquifers in the Silicon Valley are composed of high-permeability sand and gravel channel-fill deposits encased in low permeability clay and silt floodplain deposits and/or paleosol horizons. The sand channels result in complex groundwater flow and contaminant migration pathways that are not reliably discerned with groundwater gradient maps. This results in challenges in contaminant plume characterization (particularly with comingling plumes), design of groundwater monitoring wells, and remedy design, performance, and monitoring.

At this site, despite considerable source remediation work over the past decades, increasing contaminant concentrations were observed in monitoring wells considered “down-gradient” of the source area, and a CERCLA five-year review recommended additional source remediation. Using the ESS approach, two channel deposits underlying the site were mapped, one of which could be traced back to the on-site source area, and another which was oriented oblique to the presumed groundwater gradient and represents a contaminant pathway from off-site sources. Analysis of contaminant constituents associated with these two pathways revealed differing “chemical fingerprints” and indicate that these channel deposits are in fact separate and distinct hydrostratigraphic units (HSUs). These findings enabled the responsible party to differentiate which monitoring wells were representative of on-site-related contamination, and those impacted by off-site sources. The multiple lines of evidence provided by hydrostratigraphic mapping and groundwater chemistry fingerprints indicate off-site contaminant contributions to onsite wells.

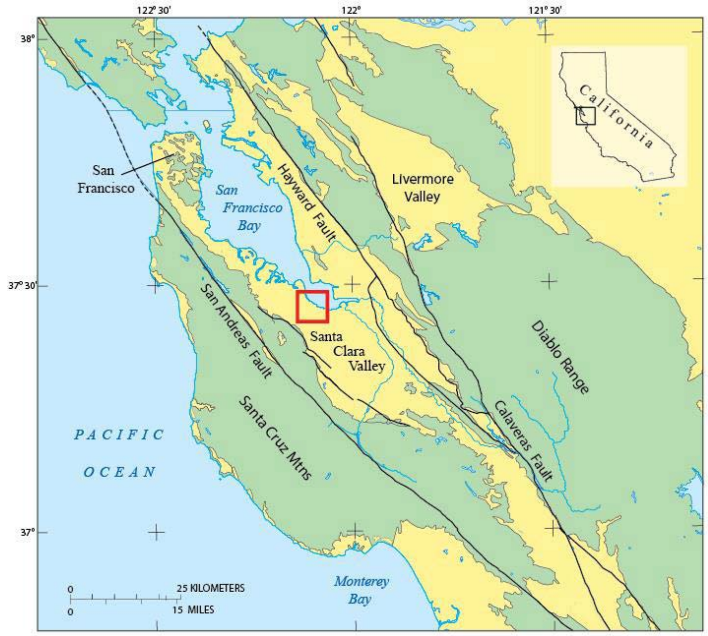

Figure A1. Map showing location of the Santa Clara Valley in the southern San Francisco Bay region, California. Alluvial lowlands (yellow) are distinguished from bedrock uplands (green). Principal faults are shown in black. Red box indicates general location of case study site. (Modified from Wentworth et al., 2014)

This case study demonstrates that:

- *Channel deposits control groundwater flow and contaminant transport and represent distinct HSUs*
- *Mapping of such HSUs is feasible with existing boring log data*
- *In settings such as the Santa Clara Valley where groundwater flow is highly channelized, a hydrostratigraphic mapping approach is superior to a depth-based aquifer zonation approach for characterization, monitoring, and remediation*
- *Anomalies in isoconcentration maps such as “bullseyes” of high concentration result from well screens which penetrate multiple HSUs which are transporting waters with different contaminant concentrations*

Depositional Setting and Fluvial Channel Facies Models

The Quaternary alluvial stratigraphic section which comprises the impacted aquifers in the Silicon Valley was deposited in channel and floodplain environments by mildly sinuous (anastomosing or meandering-type) streams draining the Santa Cruz Mountains and flowing into San Francisco Bay (Figure A1). As these channels migrated across the landscape, sand and gravel were deposited in channel axes and possibly as point bars. During flooding events, silts and clays were deposited outside the channels in the floodplain, and rivers periodically abandoned their previous courses and formed new channels. Figure A2 presents the various depositional components resulting from an anastomosing river.

The resultant sedimentary deposit is characterized by highly permeable sand and gravel channel deposits encased in relatively low-permeability silt and clay floodplain deposits. Groundwater flow and contaminant transport occurs primarily within the permeable channel deposits, and the variable orientation of channels deflects contaminant migration directions from the regional groundwater gradients. This can cause plumes to appear to spread laterally, and assume complex plan-view morphologies (*i.e.,* Figure A3). Due to this channelized groundwater flow and large number of source areas in proximity to one another, many plumes have become commingled, creating challenges for plume management in the Silicon Valley.

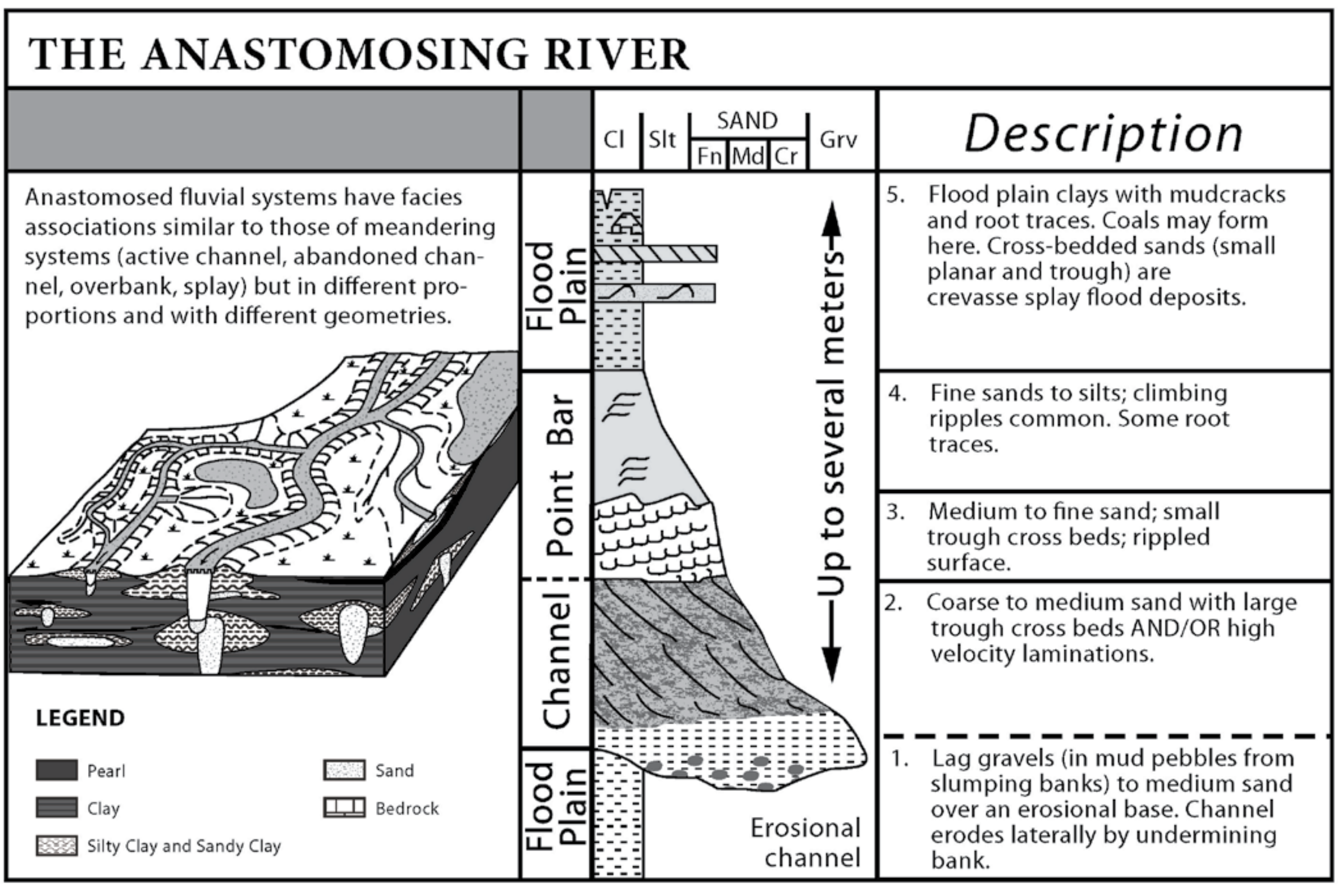

Figure A2. Depositional components of anastomosing river depositional environment including fining upward vertical grain size pattern, representative of channel fill deposits.

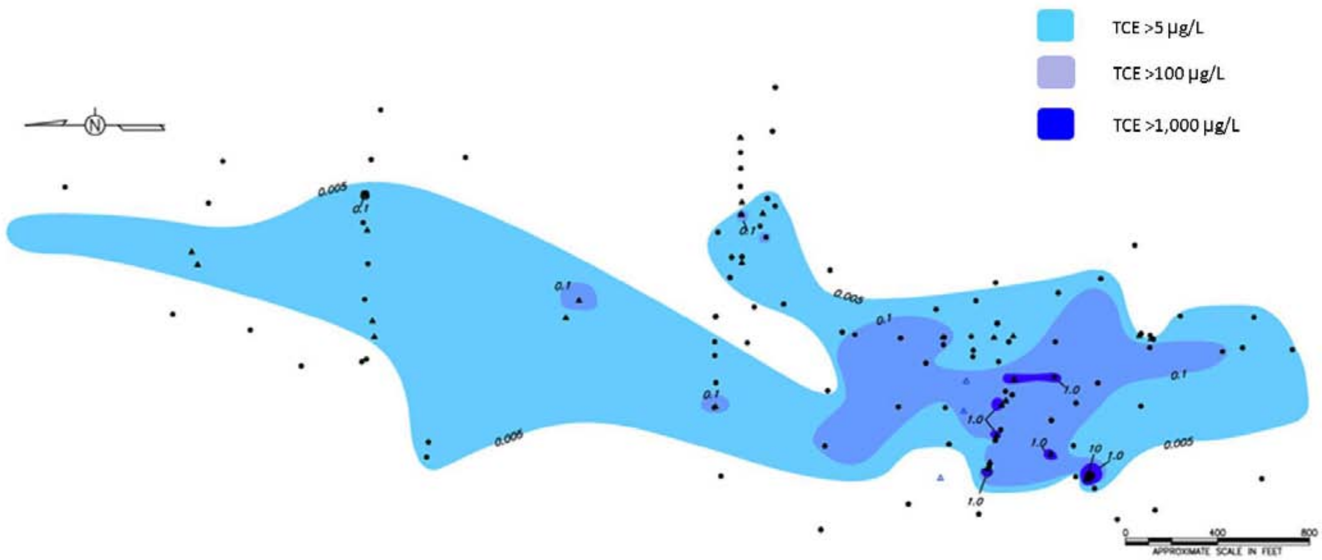

Figure A3. TCE isoconcentration map of the Silicon Valley B1 aquifer zone groundwater plume discussed in this case study ("the plume"). Note 1) irregular plume morphology resulting from channelized groundwater flow pathways and groundwater extraction, and 2) "bulls eyes" of isolated wells showing high concentration resulting from well screens penetrating multiple channel deposits containing groundwater with relatively higher contaminant concentrations.

Review and Format Existing Subsurface Data and Apply Stratigraphic "Rules of Thumb"

The database for this project consisted of boring logs (from direct push, hollow-stem auger, and mud-rotary drilling methods), well construction data, and chemical analyses from groundwater samples. As described in Section III, Phase 2 herein, graphic grain size logs were constructed to highlight vertical grain size patterns captured in the boring logs. As shown in Figure A4, fining-upward channel fill sands encased in floodplain silts/clays are apparent which allows for mapping of individual channel deposits.

In order to address increasing contaminant concentrations in areas downgradient of the onsite source area, cross section A-A' (location shown on Figure A5 and cross-section shown on Figure A6) was prepared using data-formatting methods described in Section III, Phase 2 herein.

The following rules of thumb were applied to correlate the grain size patterns between boring logs, as depicted in Figure A6.

- Channel deposits tend to have erosive bases and relatively flat tops, and clays make superior correlation markers (paleosol horizons)
- Gravels define channel bases and grain size fines upward
- Channel margins are sharp and erosive, and result in strong segregation of channel-fill sands and gravels from floodplain clays

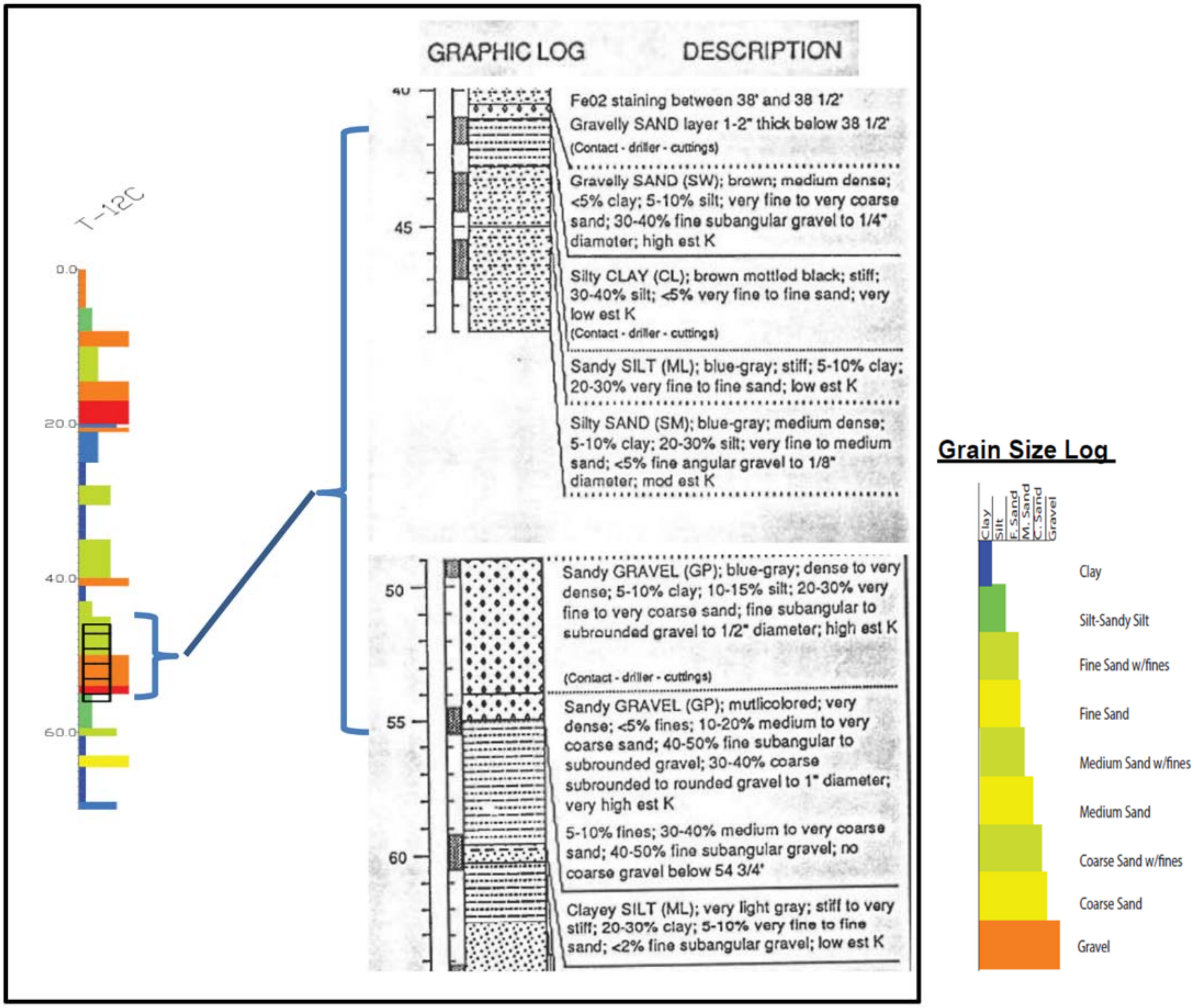

Figure A4. Data formatting for stratigraphic analysis. Portion of a boring log from the site illustrating a clear fining-upward sequence from 55' to 41' bgs representing a channel-fill and abandonment deposit (see Figure A2). Basal gravel lag and overlying fining-upward sequence occurs at 41' below ground surface (bgs). Lithologic contacts were identified on the basis of sampling, cutting returns and drilling behavior. Graphic grain size log (at left) shows this fining-upward sequence within a well screen interval.

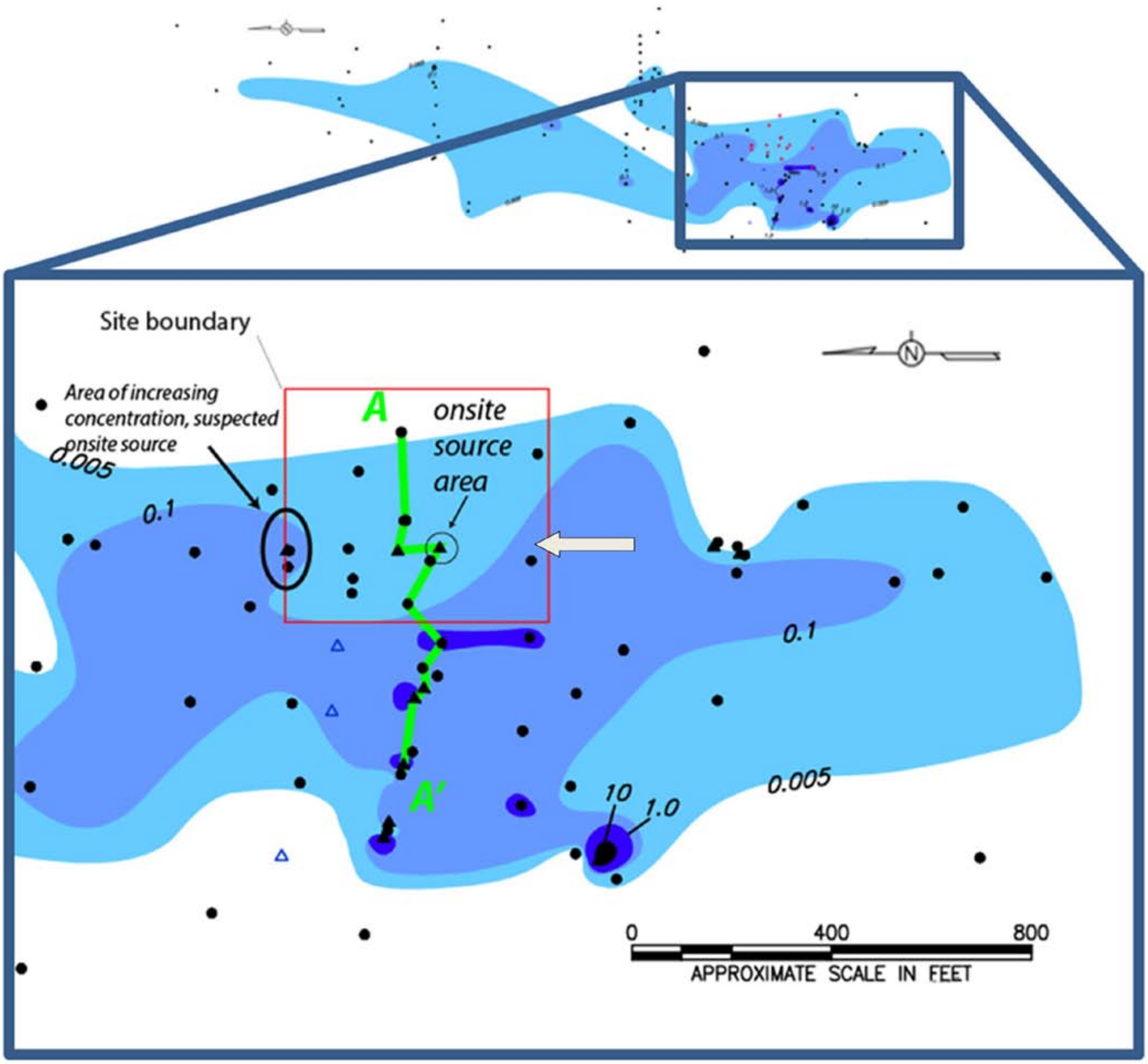

Figure A5. Map showing a portion of the B1 aquifer zone TCE plume, onsite source area, area of increasing contaminant concentrations, site property boundary, direction of presumed groundwater flow based on the groundwater gradient inferred from groundwater elevation data (white arrow), and location of cross section A-A'.

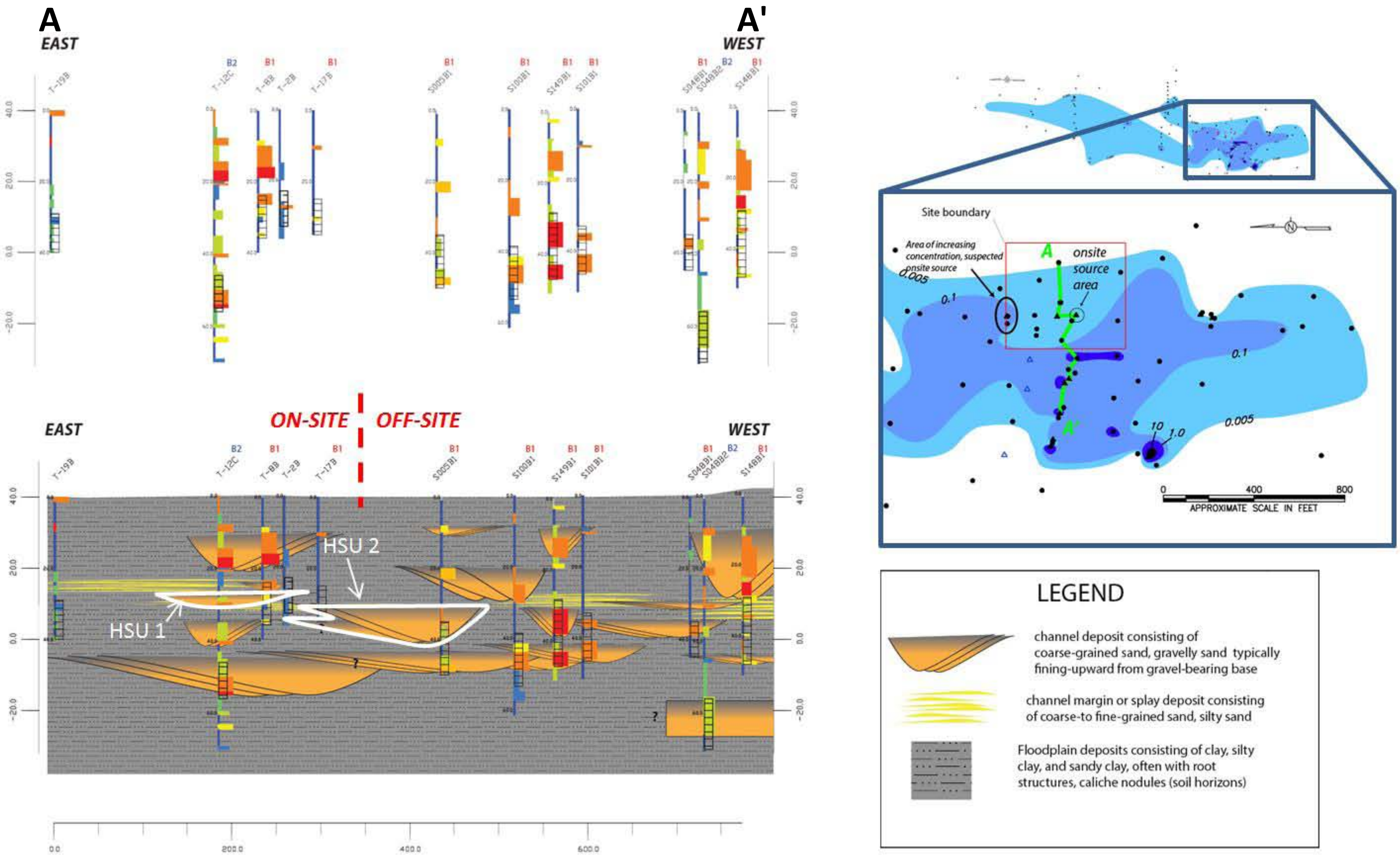

Figure A6. Uninterpreted (top), and interpreted (bottom) cross section A – A' from study area. General groundwater gradient is to the north (out of the plane of the cross section towards the viewer, and towards the left on the map view). "B1" or "B2" at the top of the boring indicates aquifer zone designation corresponding to the screened interval of each well. Note that several "B1" wells are screened across multiple channel deposits (*e.g.*, S005B1, S149B1, S101B1), and that, while T-12C is designated a "B2" well, it is in fact screened in the same channel unit as "B1" designated wells S005B1, S101B1, and S101B1. See Figure A4 for legend for graphic grain size logs created from boring logs. Channel dimensions interpreted based on detailed mapping at the site and closely-spaced high-resolution datasets at other nearby sites in the same stratigraphic interval.

Inspection of cross section A-A' (Figure A6) reveals that onsite groundwater monitoring wells designated as B1 aquifer zone wells (T-8B, T-2B, T-17B) are screened in a shallower, isolated channel complex (indicated as HSU-1) relative to the offsite wells S005B1, S100B1, S149B1, S101B1, and S048B1. Onsite well T12C, which is designated as a B2 aquifer zone monitoring well, is screened within the same HSU as offsite wells designated as B1 monitoring wells. This highlights the confusion related to depth-based water-bearing zones for plume mapping in channelized depositional environments and the difficulty in interpreting plume maps which combine multiple HSUs. Offsite well S005B1 is screened across two distinct channel deposits, and TCE concentrations are significantly higher in this well, suggesting that groundwater in the shallower channel indicated as "HSU-2" contains a relatively high concentration of contaminants.

Extensive on-site contaminant source removal coupled with in-situ bioremediation resulted in significant decrease in VOC concentrations in groundwater near the source area. Vinyl chloride (VC) was generated as a daughter product. However, monitoring well T-9B at the downgradient extent of the property showed increasing VOC concentrations, up to 390 µg/L, an order of magnitude higher than other on-site wells. High TCE and *cis*-1,2 DCE concentrations are observed in well S005-B1 compared to adjacent wells suggesting that the upper channel across which the well is screened represents a contaminant pathway. Thus, a detailed ESS analysis was undertaken to map HSU-1 and HSU-2 and evaluate lithologic pathways from T-9B area to the south (Figure A7).

As mentioned, on-site monitoring wells typically contain VC, occurring as a daughter product of TCE. Freon-113 is associated with the off-site source and was not used in on-site operations. Thus, VC is unique to the on-site source and Freon-113 is unique to the off-site source. After completing the ESS assessment, groundwater contaminant chemistry data (trichloroethene [TCE], tetrachloroethene [PCE], *cis*-1,2-dichloroethene [cDCE], vinyl chloride [VC], and Freon 113 [freon]) were interrogated with respect to the updated stratigraphic framework (*i.e.,* HSUs) to provide an independent line of evidence for off-site related contamination (Figure A8).

Cross section B-B' (Figure A8) is oriented such that it includes on-site wells along the path of HSU 1, and then traverses to the south west to include the high-concentration, deep HSU-2 channel in T-5B. Note that the wells screened only across HSU 1 (T-10B, T-8B, and T-2B) contain groundwater with TCE, *cis*-1,2 DCE, and VC, and lack Freon-113. The well that is screened only across HSU 2 (T-5B) contains groundwater with Freon-113, and lacks VC. Well T-9B is screened across both HSU 1 and HSU 2 and thus contains mixed groundwater with both indicator parameters (VC and Freon-113).

A similar trend is observed in cross section C-C', which illustrates the continuity of the HSU 2 channel sands, which is corroborated by the chemistry fingerprint. The wells that are screened solely in HSU 2 lack the on-site source indicator VC and contain Freon-113 (T-4B has historically contained Freon-113, but not during the 1-5 year average timeframe used to create fingerprint graphs). Well T-9B is screened in both HSU 1 and HSU 2 and contains groundwater that is a mixture of HSU 1 and HSU 2, containing all four analytes.

The chemistry fingerprint data provide an independent line of evidence, and corroborate the geologic interpretation that channel HSU 1 is a contaminant pathway representative of the on-site contaminant source and channel HSU 2 is a contaminant pathway representative of the off-site contaminant source.

This case study exemplifies why defining the details of the subsurface geology is critical for distinguishing hydrostratigraphic pathways, particularly when there are multiple source areas for commingled contaminant plumes. As shown in Figure A9, the original CSM inferred contaminant migration pathway based on the groundwater gradient interpreted from groundwater elevation data, which assumes that the subsurface conditions are homogeneous. However, as presented here, the underlying geology is heterogeneous due to the channelized depositional environment. The updated ESS-based CSM defines HSUs that are the primary control of contaminant migration, as corroborated by multiple lines of evidence (Figure A10). This realistic CSM provides a basis for improved management of this complex, commingled plume.

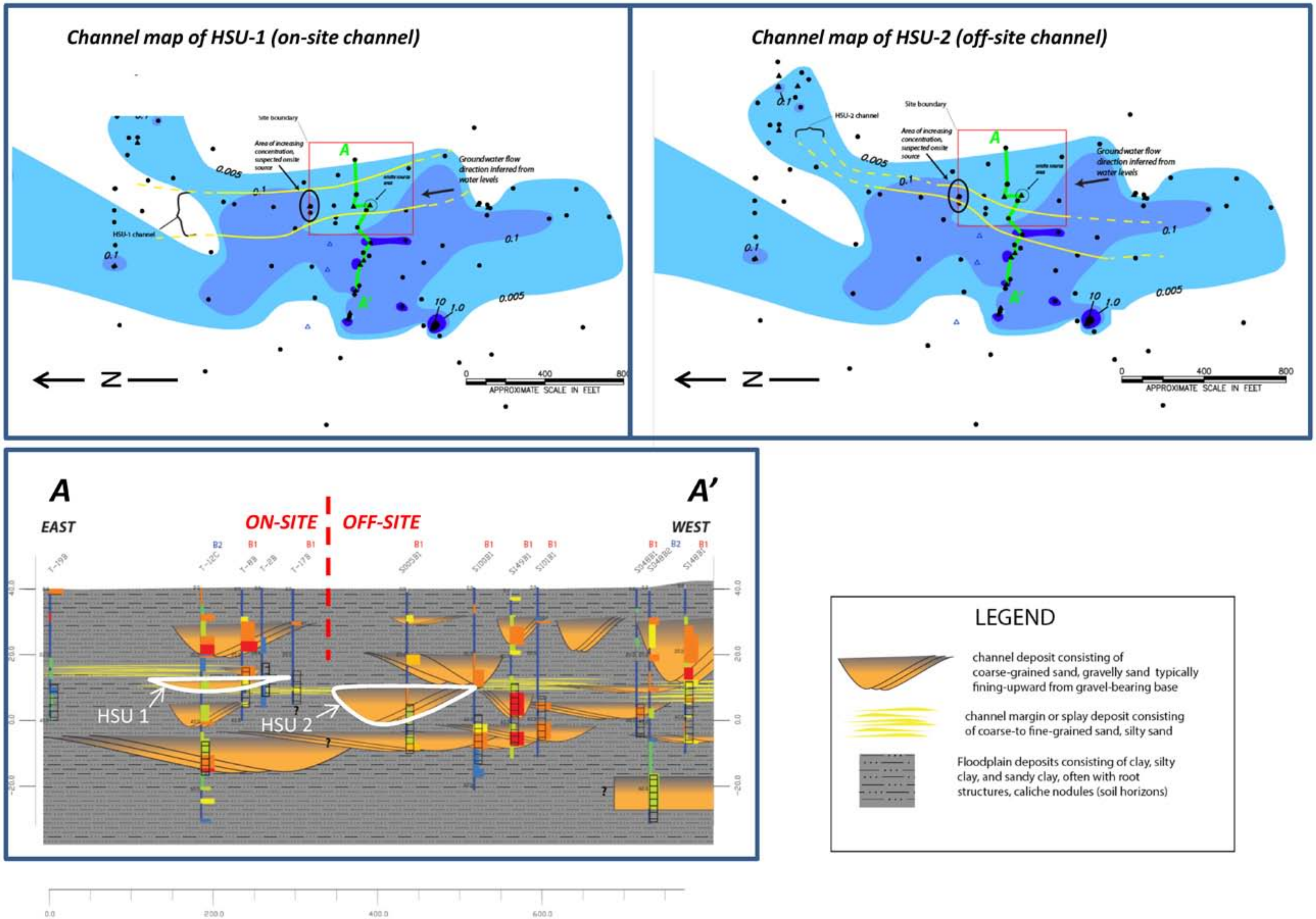

Figure A7. Detailed mapping of HSUs. Maps of HSU 1 and HSU 2 channel axis facies (sand- and gravel-bearing, indicated by yellow outlines), and cross section A-A' (lower figure). The deeper channel HSU-2 provides a direct lithologic connection and hence potential contaminant pathway from off-site sources to well T-9B. Note that the channel widths and morphology depicted on the cross sections are constrained by three dimensional facies mapping of the channel complexes and floodplain deposits.

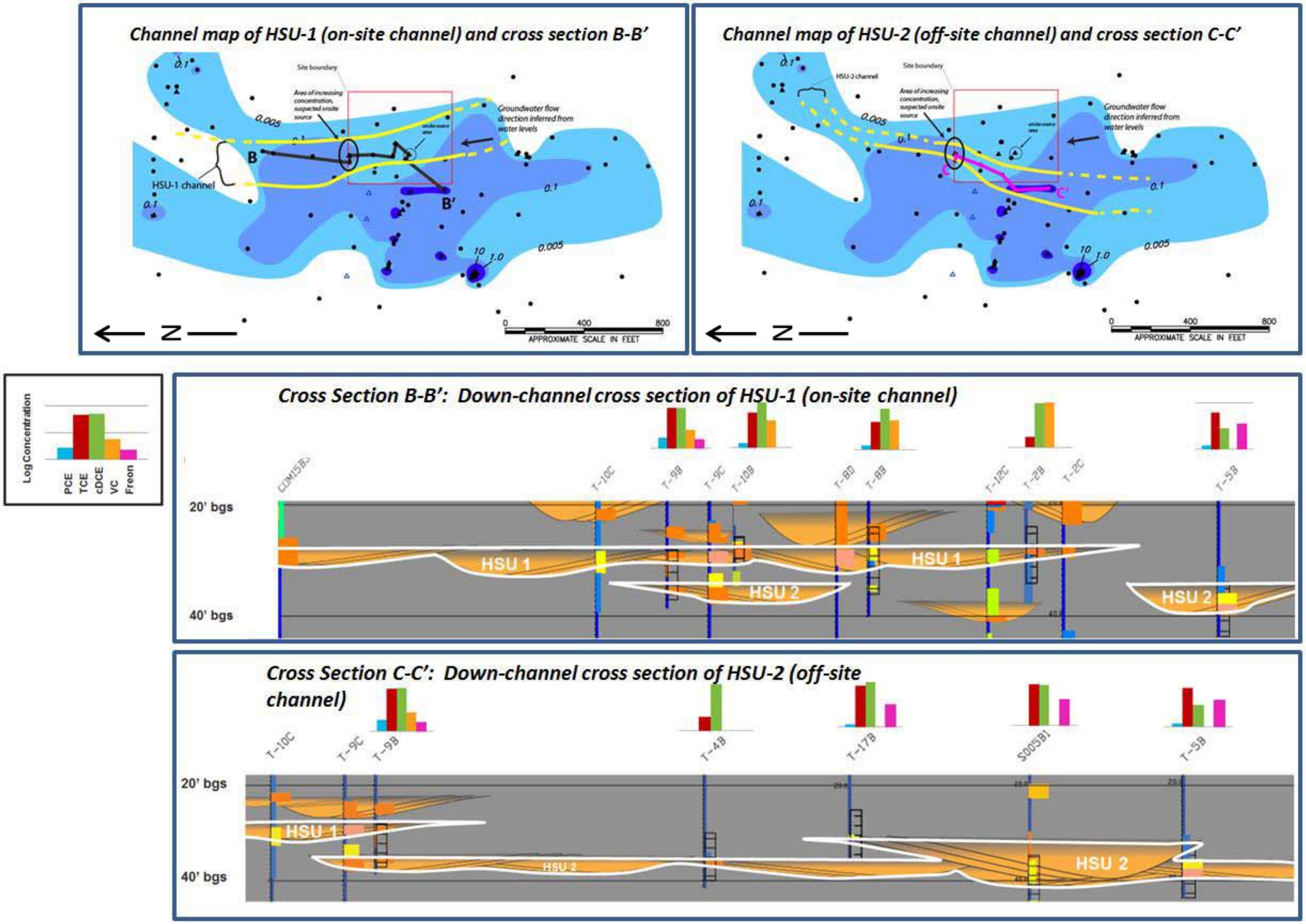

Figure A8. Contaminant fingerprinting. Cross sections B-B' and C-C' oriented down the axes of channel HSU-1 and HSU-2 with contaminant fingerprint charts corresponding to groundwater samples. Fingerprint charts post the log of the concentration of the different indicator contaminants, and as such are useful for discerning the constituents. Fingerprint charts represent an average value of concentrations over the last five years.

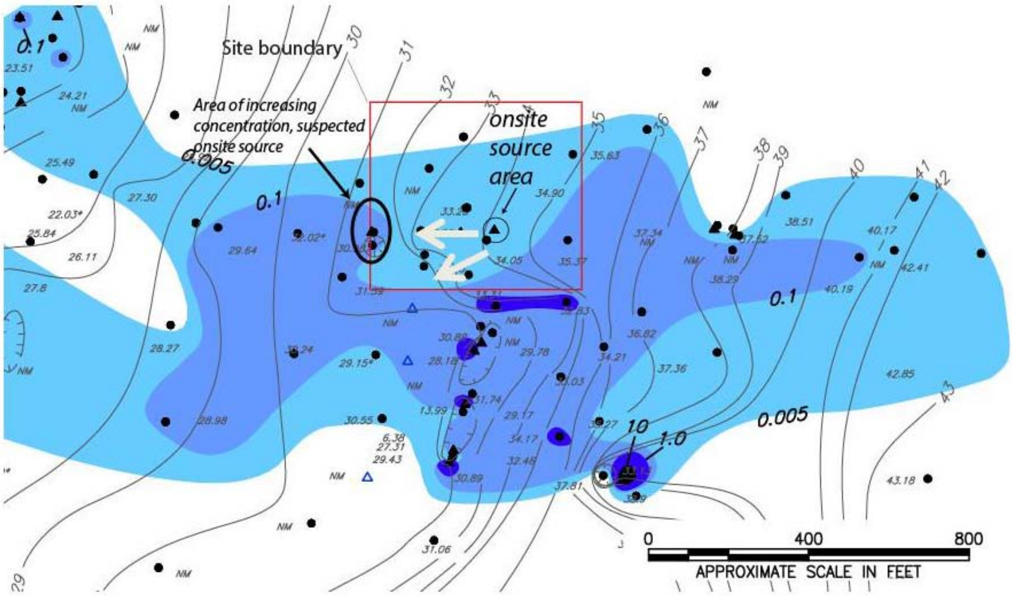

Figure A9. Original CSM based on simplifying assumption of homogeneous aquifer conditions. This interpretation of contaminant migration is based on the groundwater gradient (groundwater elevation contours) and does not focus on the geology and depositional environment. White arrows show interpreted groundwater flow directions and contaminant transport directions from the on-site source to the down-gradient impacts at the property boundary. Based on this assumption, additional source area remediation had been proposed.

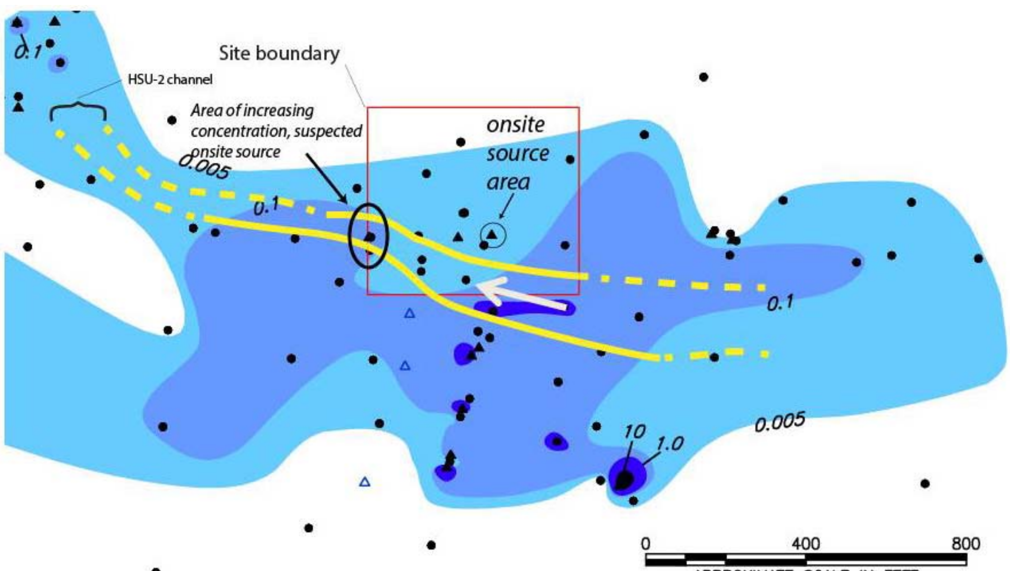

Figure A10. ESS-based CSM focused on underlying geology to define HSUs. The HSU-2 channel (bounded by yellow lines) controls the contaminant migration pathway (white arrow) showing that, unlike Figure A9, an off-site source is contributing to the impact occurring at the property boundary. At this complex site, groundwater flow is strongly influenced by lithology, and contaminant transport directions deviate significantly from those predicted from the potentiometric surface maps.

REFERENCES

Wentworth, C.M., Jachens, R.C., Williams, R.A., Tinsley, J.C., and Hanson, R.T., 2015, Physical subdivision and description of the water-bearing sediments of the Santa Clara Valley, California: U.S. Geological Survey Scientific Investigations Report 2015–5017, 73 p., 2 plates, http://dx.doi.org/10.3133/sir20155017.

Case Study 2: Glacial Outwash Channel Systems, Northeast US; DNAPL Source for VOC Groundwater Impact

Introduction to the Site

Case Study 2 relates to a former manufacturing site impacted by dense non-aqueous phase liquid (DNAPL) and related VOC impacts to groundwater. This example shows that an understanding of the depositional environment and associated stratigraphic "rules of thumb" for correlation results in a significantly different CSM for groundwater management.

During relative lowstands of sea level in the Quaternary, large erosional valleys known as "incised valleys" were formed in coastal regions due to erosion by fluvial (river) systems issuing from glaciers. In northern parts of the USA, many of these river valleys were filled by glacial outwash fluvial systems prior to flooding during sea level rise (*e.g.,* Chesapeake, Delaware, and Hudson River Valleys). This case study documents glacio-fluvial outwash channels and emphasizes a stratigraphic "rule of thumb" that clay units tend to be flat and make better correlation markers than sand channels, which tend to have erosive, irregular bases. The conceptual site model at this site consisted of a three-aquifer system separated by two aquitard units (Figure A11). Note the convex-up morphology of the lower clay aquitard (a.k.a . "mounded clay").

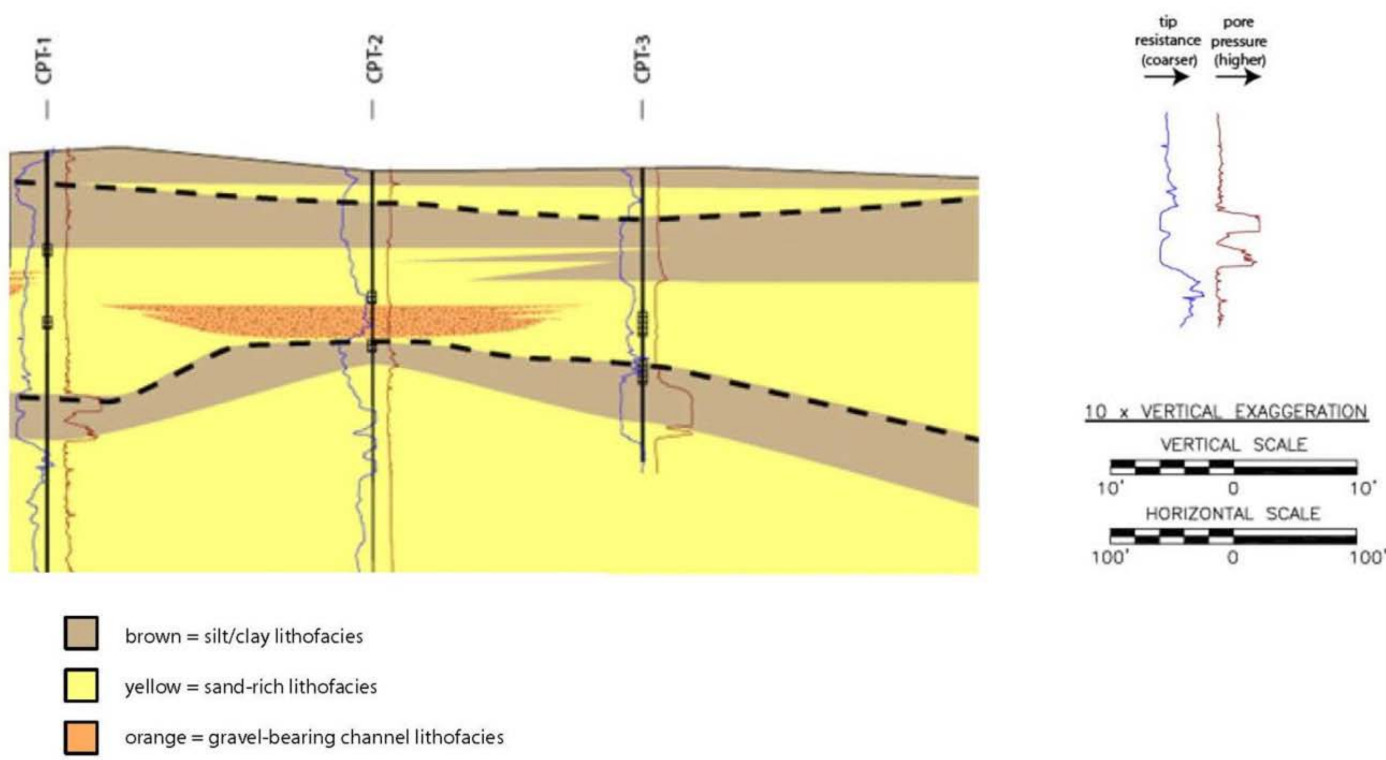

Figure A11. Existing CSM depicting three aquifer units (yellow) with gravel-bearing channel zone (orange) separated by aquitard units (brown). Lower aquitard unit shows convex-up morphology ("mounded").

Research and experience in subsurface and outcropping channel deposits indicate that channel bases, due to the erosive nature of energetic river systems, tend to be irregular, and that floodplain units (silts and clays) tend to be horizontal in nature (Figure A12).

Figure A13 shows an alternative interpretation of the site data based on stratigraphic "rules of thumb" and supported by the details of the CPT data collected.

The fundamental difference in interpretation of the continuity of the aquitard unit between the previous CSM and the ESS CSM has important implications for risk of contaminant migration from source to potential receptors. This highlights the importance of objectively evaluating lithologic data according to established stratigraphic concepts and facies models, and is a caution against artificially forcing subsurface data into a previously-established hydrogeologic framework.

Figure A12. Photograph of outcropping fluvial channel (unannotated above, annotated below) showing light-colored sand channel fill encased in floodplain deposits (dark colors). Note erosion at base of channel (blue arrows indicate truncated beds). The top of the channel-fill is completely flat (although it appears slightly rounded due to perspective of the photograph (looking upward at outcrop)). Erosive base and flat top is a common relationship in fluvial depositional environments and calls into question the interpretation in Figure A11.

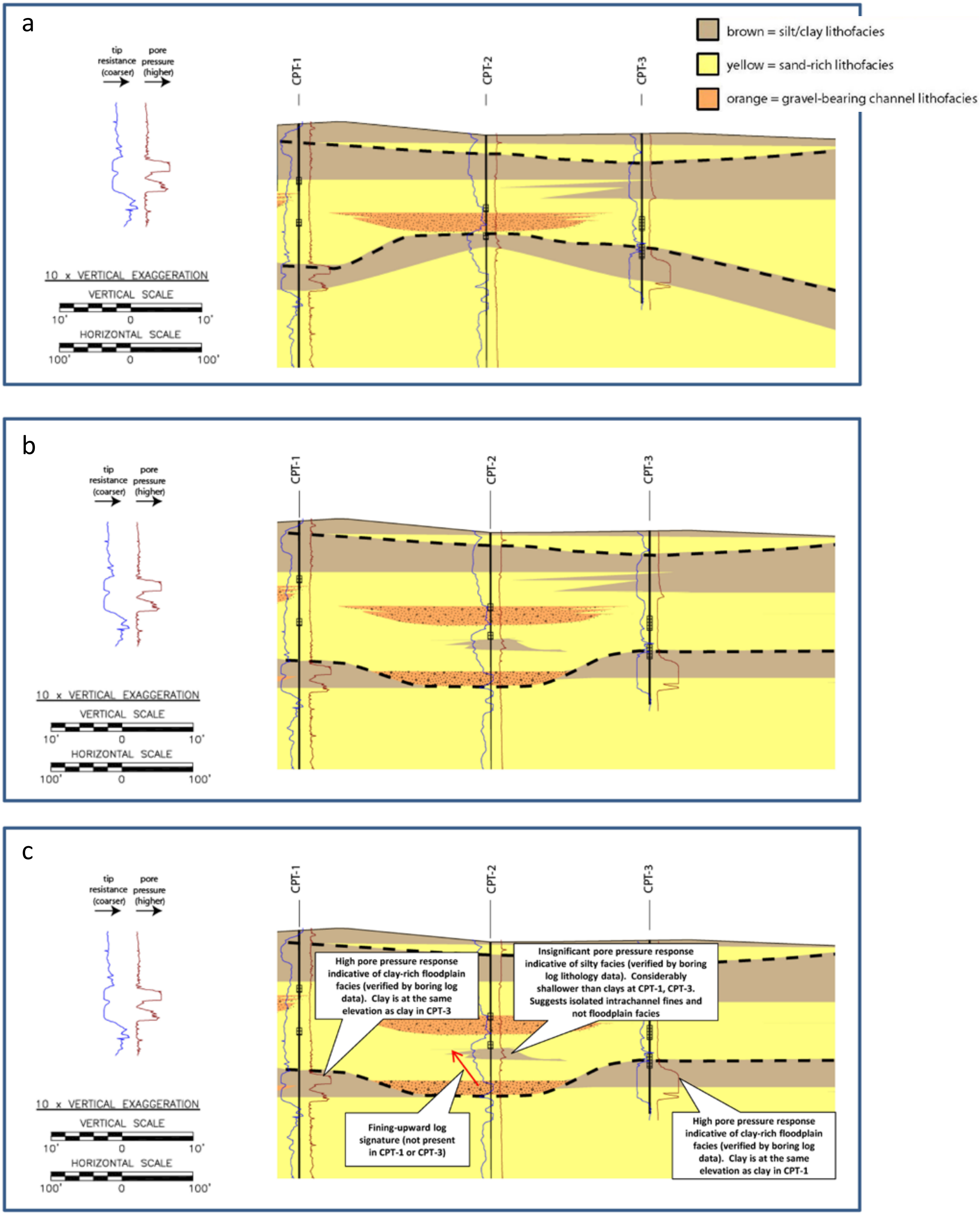

Figure A13. a) The original CSM. (b,c) ESS CSM stratigraphic interpretation of CPT data showing a channel deposit which has breached the principal aquitard unit through erosion. This interpretation is supported by the fining-upward nature of the channel deposit in CPT-2, the low pore pressure response of CPT-2 relative to CPT-1 and CPT-3, the similarity in elevation of the floodplain facies in CPT-1 and CPT-3, and the anomalous elevation of the silt unit in CPT-2.

Case Study 3: Glacial Terrain, Till, and Lacustrine Deposits, Upper Midwest US; LNAPL and Dissolved Phase Impact at a Manufacturing Facility

Introduction to the Site

Case Study 3 relates to a former manufacturing site underlain by glacial deposits. Groundwater is impacted by light non-aqueous phase liquid (LNAPL) and related dissolved-phase constituents. This case study illustrates the importance of understanding the geologic evolution pertinent to a site and the value added from a review of publicly available geologic resources. With a geologic context established for the site, the vertical grain-size trends observed in boring logs were used to create interpretations of the subsurface which explain observed phenomena and provide a basis for successful site management.

An ESS review of lithologic borings from a network of 30 monitoring wells was conducted in order to address an anomalous divergent groundwater flow pattern moving away from the site. Migration of LNAPL and dissolved contaminants moving with groundwater away from the facility was of primary concern. This site is located on the north shore of Lake Ontario (Figure A14) and the original CSM predicted groundwater flow to follow a pathway southward toward the lake. Kriging the hydraulic head data resulted in a divergent pattern (Figure A15) that could not be explained with the existing CSM.

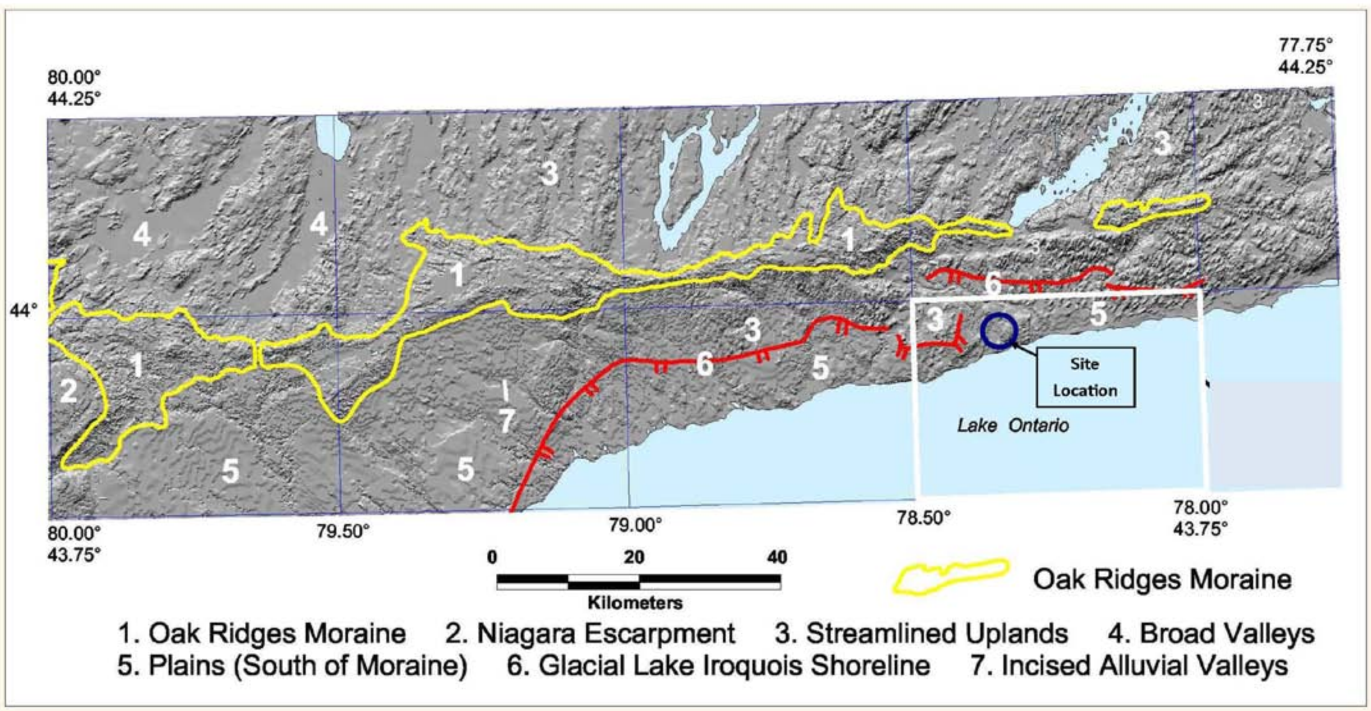

Figure A14. General site location (blue circle) and some pertinent geological features including the shoreline deposits of Glacial Lake Iroquois (red) and the plains (5) and streamlined uplands (3) known to include drumlin landforms (Brennand, T.A., 1997: Surficial Geology of the Port Hope Area, NTS 30M/16, southern Ontario; Geological Survey of Canada, Open File 3298, Scale 1:50,000).

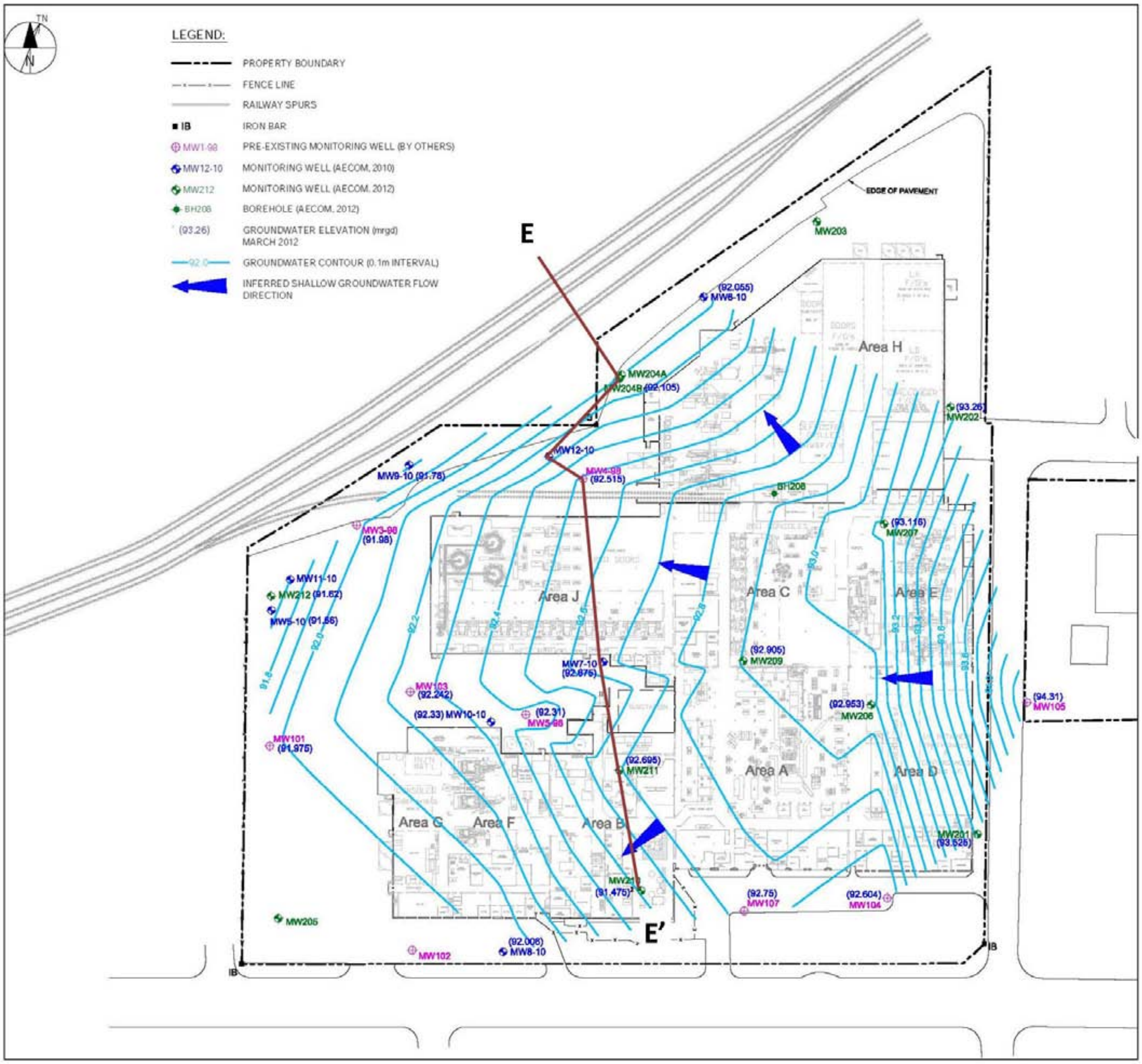

Figure A15. Divergent groundwater flow pattern observed at site based on computer contouring (kriging) of hydraulic head data.

Buried/"Drowned" Drumlin Model

Inspection of Canadian geological survey maps (Brennand, 1997) showed that the site was located within the southernmost portion of a drumlin field composed of the Bowmanville Till. In this area, drumlins (mounded and lensoidal landforms created during glacial retreat) are surrounded by the fine-grained deposits of glacial lake Iroquois, a proglacial precursor to modern day Lake Ontario.

The retreat of continental glaciers shaped tills and left behind drumlin forms (Figure A16). These forms persisted as islands of sand, gravel, and clay as glacial meltwater filled the basin surrounding them. High sediment loads of fine material shed from the glacier and entrained in the melt water were deposited regionally around the drumlins as layered, and relatively flat lying silts and clays. Because they were exposed to natural weathering and covered with little to no vegetation in the immediate aftermath of deglaciation, the drumlins would shed sediments from their crests into the surrounding lake water as small alluvial fans. Coarsening upward fans would interfinger with lake derived clays around the drumlins (Figure A17).

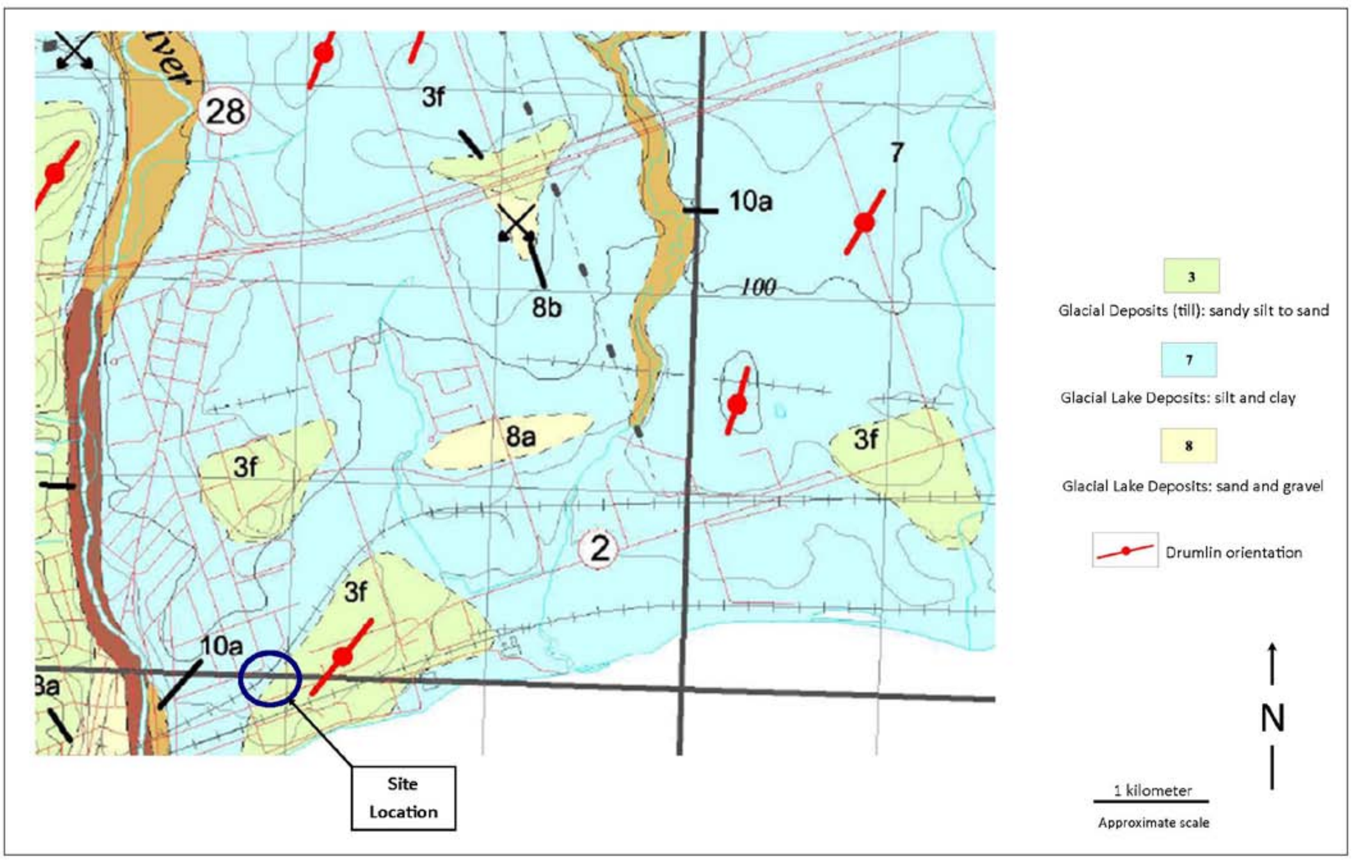

Figure A16. An excerpt from local surficial geology map (Brennand, 1997) showing the site is located on the crest and western side of a drumlin (green area with axis of orientation shown in red) which is surrounded by fine (silts and clays) lake deposits.

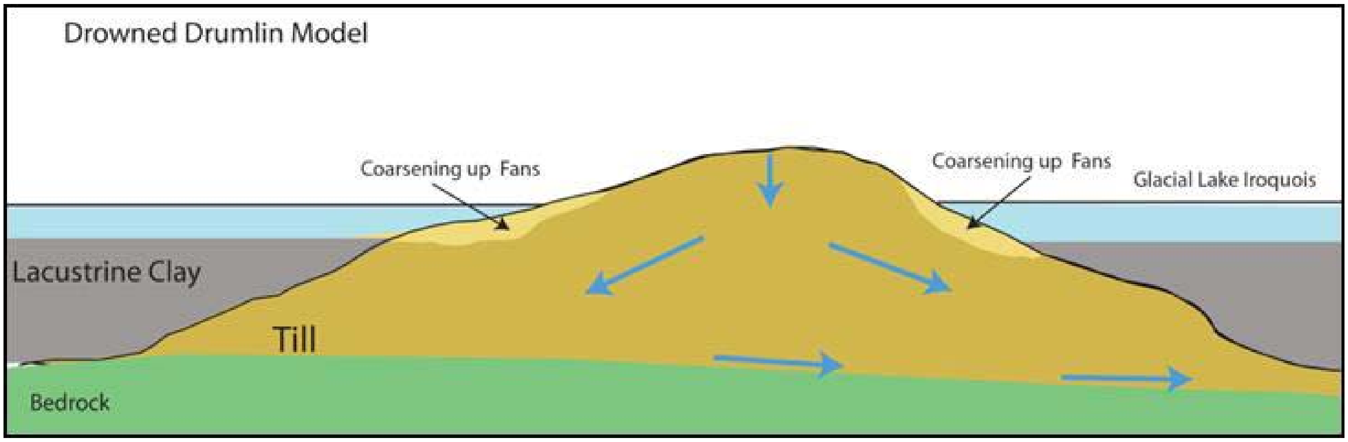

Figure A17. Conceptual summary cross section – Drowned Drumlin Model. Blue arrows are interpreted groundwater flow.

Graphic grain size logs from the site exhibit a lithologic pattern that was consistent with the interpreted geological scenario (Figure A18). Borings closer to the mapped drumlin crest are composed almost entirely of unstratified sandy and clayey sands and gravels typical of the Bowmanville Till. Borings located on the margin of the drumlin show a thick basal package of laminated silts and clays, consistent with sediments deposited in the low energy lake environment. Coarsening upward sequences of sediments occur atop, and in some cases interfingered with the fine grained lake sediments. These were interpreted as fans of material shed from the drumlin crests as they sat exposed as islands surrounded by the glacial meltwater of Lake Iroquois.

While site topography is generally flat, the site's location on the crest of the drumlin, coupled with fans of coarse materials extending radially off the drumlin margins, produces the radial groundwater flow as groundwater percolated down and away from the drumlin crest (Figure A17).

This improved site understanding using existing data to develop a CSM based on glacial depositional model explained the groundwater flow and potential contaminant migration pathways, saving the project additional investigation costs. It also provides a blueprint for optimized site characterization, groundwater monitoring, and remediation design.

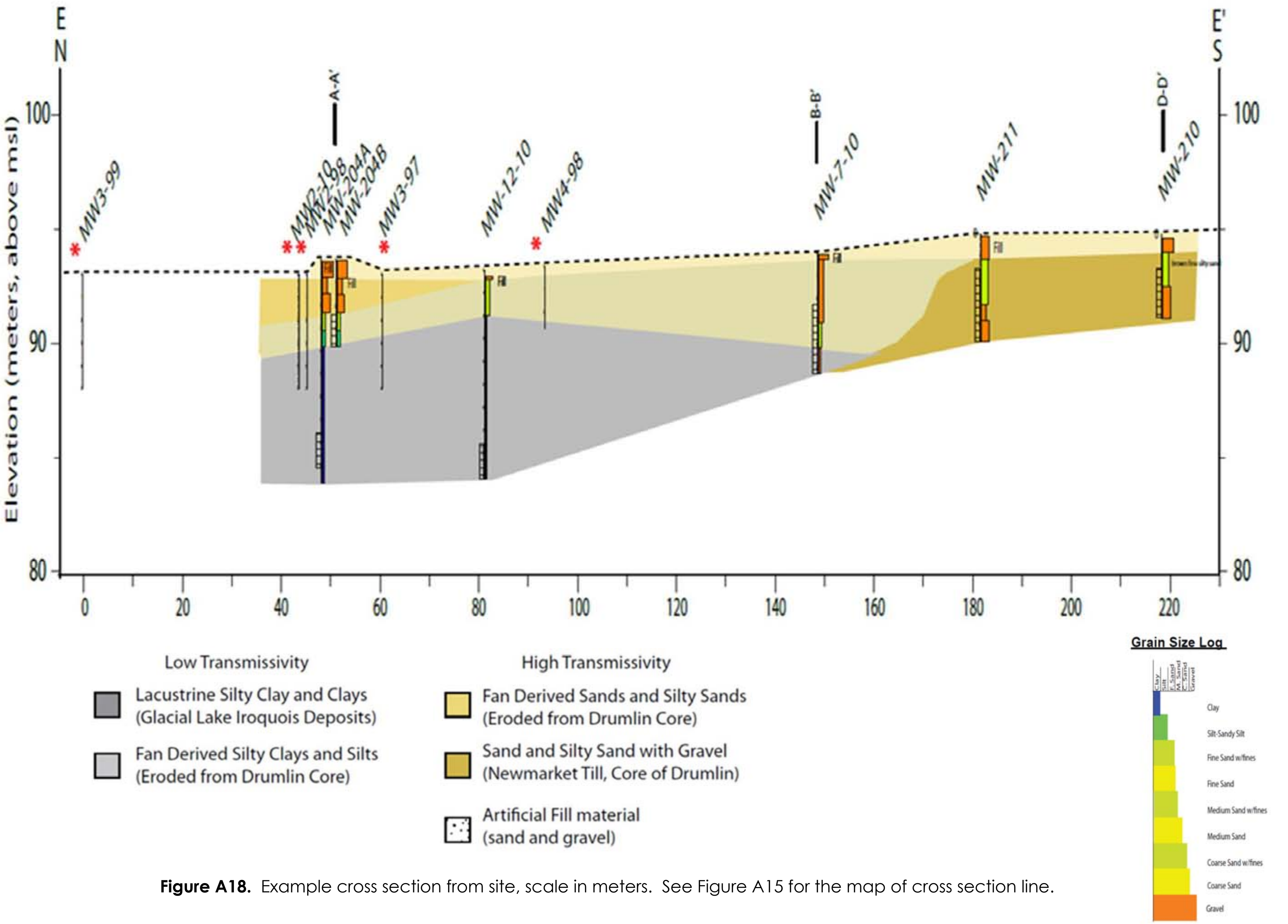

Figure A18. Example cross section from site, scale in meters. See Figure A15 for the map of cross section line.

Case Study 4: Desert Alluvial Fan Environments, Western US; Hexavalent Chromium Impacts to Groundwater at an Industrial Facility

Introduction to the Site

Groundwater underlying this site was impacted by VOCs and hexavalent chromium. High-resolution lithology data were collected using CPT to identify sand zones to design injection and monitoring wells. The CPT data were correlated using a computer kriging software. This case study exemplifies the limitations of kriging correlations, even with high-resolution data, and the value of facies models to guide correlations. The impacts of stratigraphic dip and thin clays bounding individual fan units were not recognized, and this limited remedy effectiveness and led to byproduct generation, necessitating installation of additional remediation systems.

Alluvial Fan Facies Models

Alluvial fans form where coarse-grained material issues from mountain fronts onto basin floors. At this change from higher to lower gradient, streamflow becomes less energetic and coarser material is deposited in the upper (proximal) fan environment where current velocity is high. Finer-grained material is transported to the lower (distal) fan where current velocity is low. The fan surface is concave-up, with a relatively steeper gradient at the head and a flatter gradient at the distal end (Figure A19).

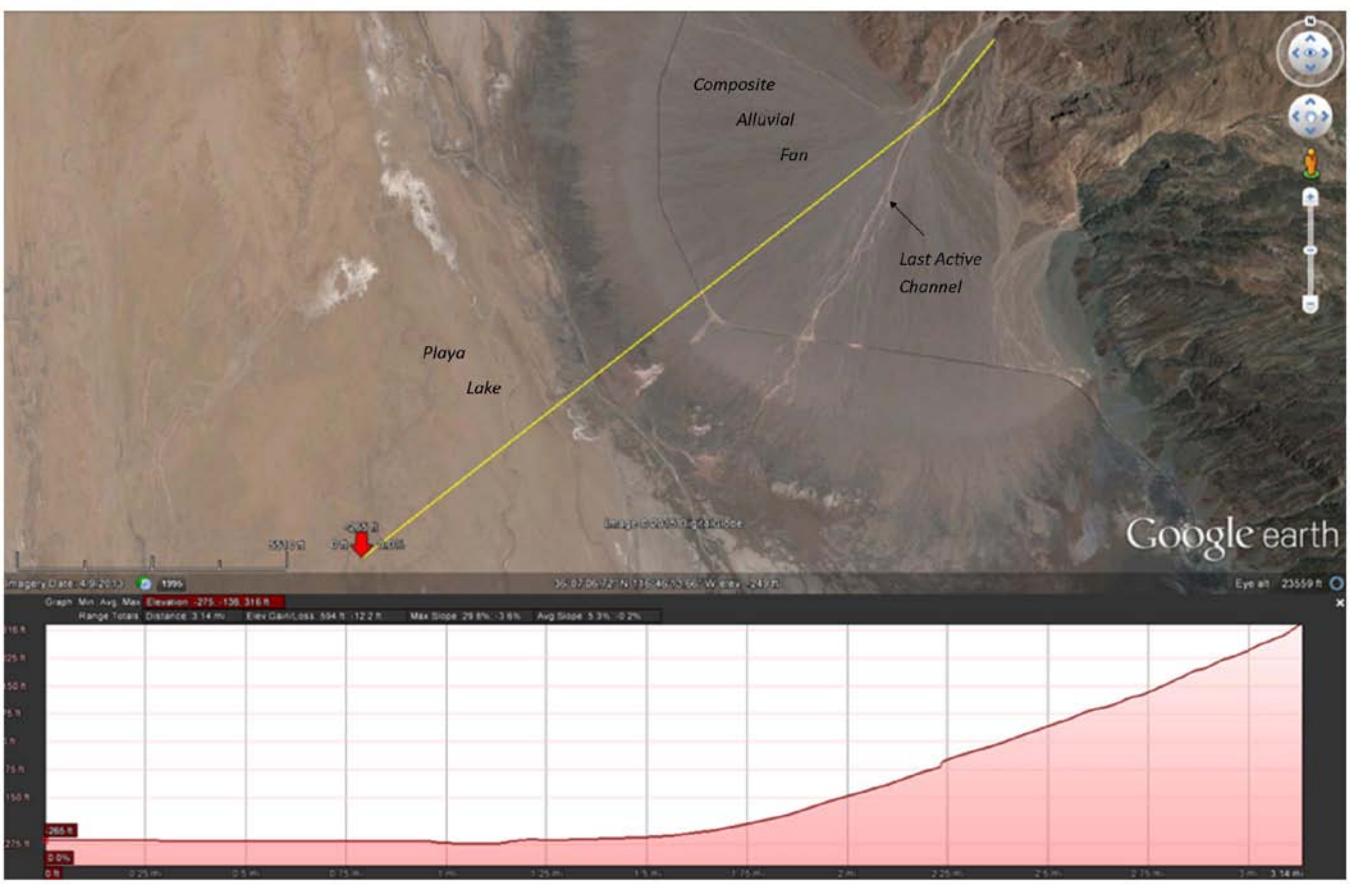

Figure A19. Google Earth view of a large alluvial fan in Death Valley, CA with topographic profile shown below.

With time, fans "prograde" (*i.e.,* advance) out onto the basin floor, placing coarse proximal-fan deposits atop fine distal-fan deposits, producing coarsening-upward profiles. This occurs in a punctuated, stepwise fashion resulting in smaller multiple-stacked coarsening-upward sequences separated by playa lake or soil formation (paleosol) horizons. Multiple smaller fans are stacked to form the larger fan and the overall progradational pattern (Figure A20).

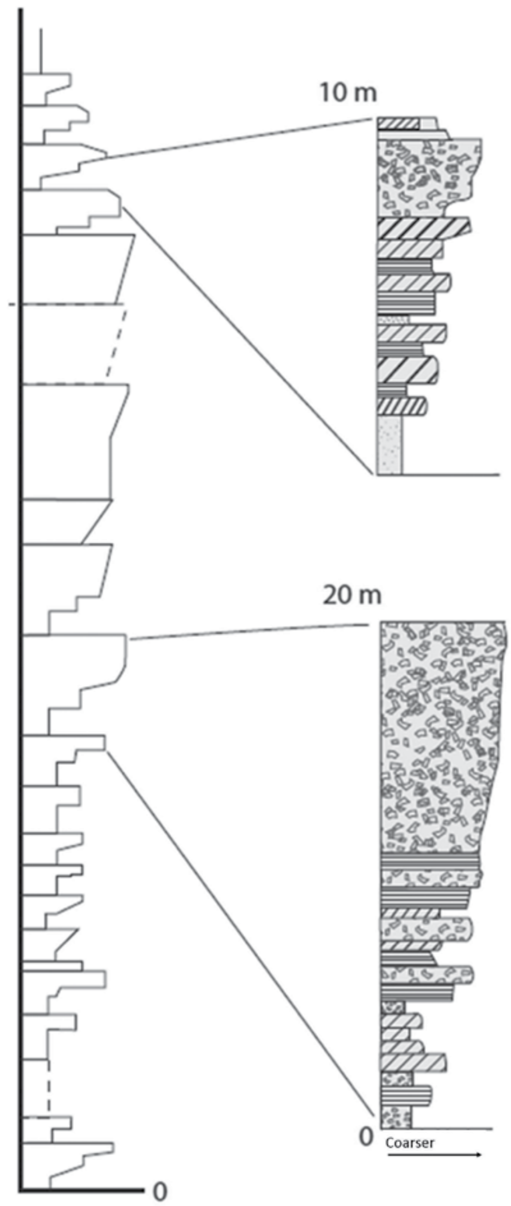

Figure A20. Vertical profile through cyclic alluvial fan deposits, showing the characteristic coarsening-upward profiles of individual packages which stack to form the overall alluvial fan. (Redrawn from Steel and Gloppen, 1980)

Due to arid climate, active tectonics resulting in topographic relief, and associated coarse-grained sediment supply, alluvial fans are common in the desert southwest of the USA. At a site in the US desert southwest, CPT data were collected for the purposes of identifying sand-rich zones for well screen placement (Figure A21).

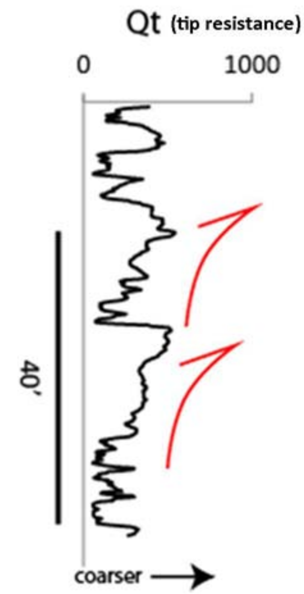

Figure A21. Cone penetrometer testing data show two stacked coarsening-upward sequences (red arrows) separated by thin clay units.

Multiple, stacked coarsening-upward profiles are seen within the saturated interval reflecting buried alluvial fans. The fans are laterally offset-stacked or "shingled", dipping and stepping basinward, and are bounded by basinward-thickening clay deposits representing paleosols or playa lake deposits which are laterally continuous for hundreds of feet to miles (Figure A22).

Clay units which separate individual fans, while relatively thin, form effective barriers to groundwater flow and reduce the hydraulic connectivity within the system as seen in contaminant concentrations in wells where a single fan is screened (*e.g.,* HSU-B, Figure A22). Thus, the fans represent HSUs. Most wells at this site are screened across multiple fans, and thus the water quality variation among individual fans is unknown. Wells screened across multiple fans may provide pathways for cross-contamination. Some fans (*i.e.,* HSU-B) are not in communication with source areas and were not impacted with hexavalent chromium. When reducing reagent was injected (targeting hexavalent chromium) into unimpacted zones, naturally occurring manganese byproduct was released into solution.

It is illustrative to compare the stratigraphic cross section to a cross section generated by a computer model utilizing kriging of the same CPT data (Figure A23). On the computer-generated cross section, the thin clays do not appear to correlate due to the primary stratigraphic dip of these units. The kriged section gives an appearance of "randomness" of facies distribution and compartmentalization is not indicated. The compartmentalization and offset-stacked shingling (stratigraphic dip) of alluvial fan deposits was not recognized at this site prior to in-situ remediation implementation, leading to compromised remedy efficiency and by-product generation. This case study highlights the risks posed by reliance on kriging data for remedy planning without a facies model to guide correlation.

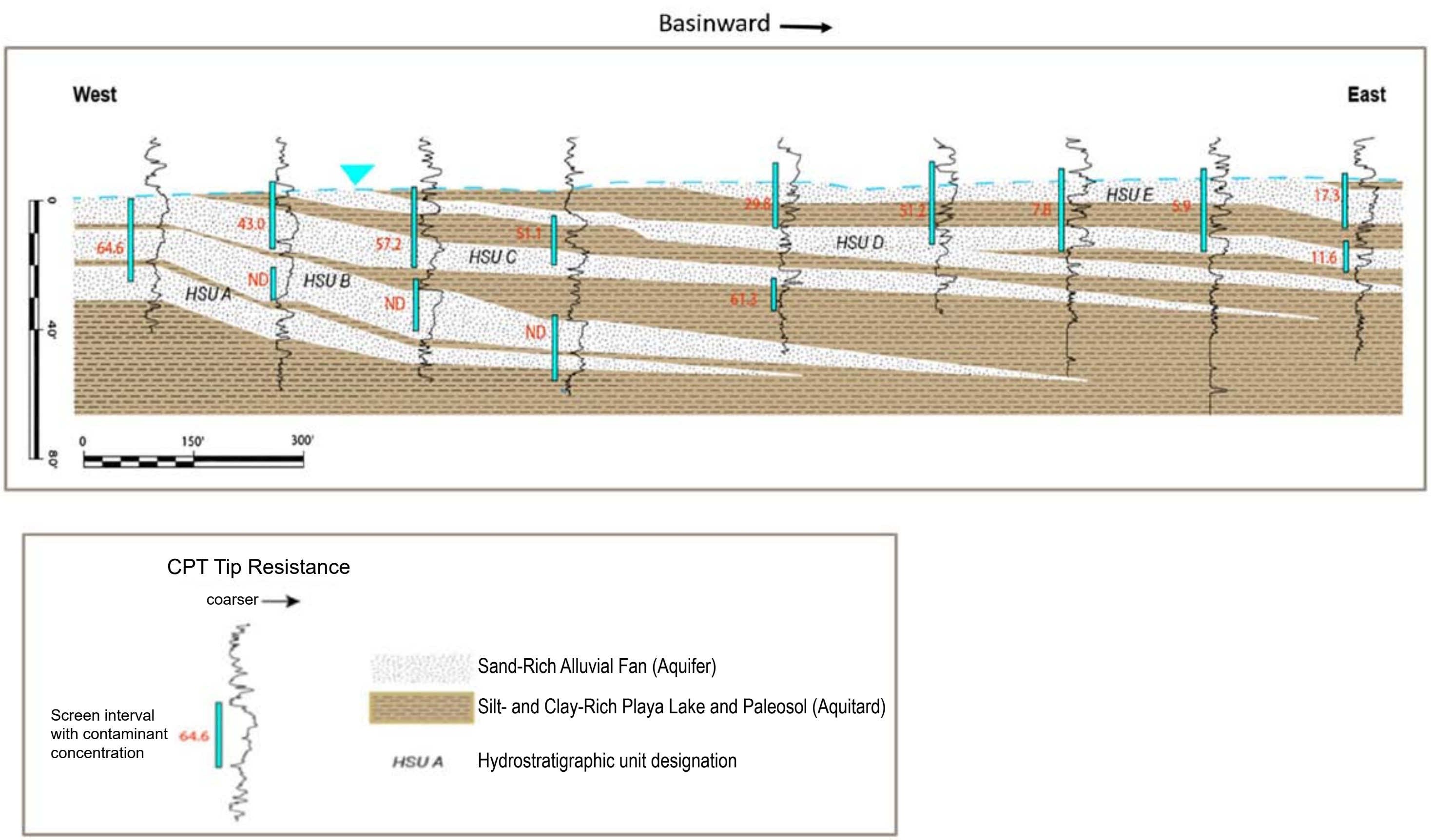

Figure A22. Stratigraphic cross section with CPT logs showing shingled, dipping alluvial fan deposits in the saturated zone.

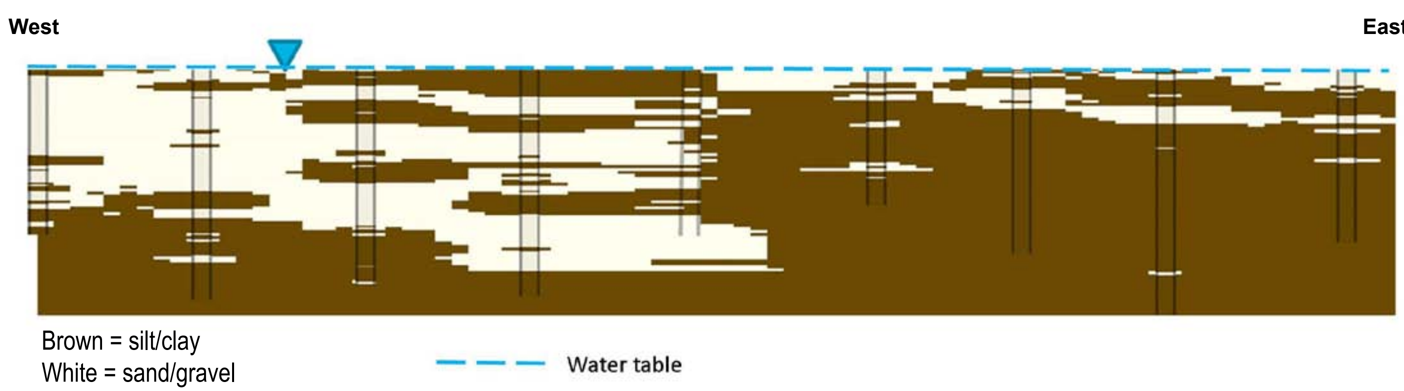

Figure A23. Kriging of CPT data presented in Figure A22 produces a cross section that miscorrelates thin clay beds, giving an appearance of randomness in lithology and stratigraphic architecture.

Case Study 5: Fluvial Channel and Overbank Deposits, Southern California; Updated CSM for Perchlorate Plume Containment Remedy

Introduction to the Site

The site is a 1,000 acre former explosives manufacturing property underlain by a heterogeneous fluvial aquifer impacted by VOCs and perchlorate. The original CSM was the basis for the groundwater containment system approved by the regulatory agencies as the means to protect further impact to nearby groundwater production wells. However, as part of the pilot study for the containment system, it was determined that the existing CSM oversimplified the hydrostratigraphy underlying the site, bringing to question the efficacy of the proposed containment system design. Using existing data, the CSM was revised by applying ESS methodology.

A sequence stratigraphic review of a 1,000 acre site in southern California was undertaken prior to implementation of a pilot containment remedy for groundwater. The hydrostratigraphy underlying the site consist of approximately 500 feet thick series of highly interbedded sands and clays corresponding to Plio-Pleistocene fluvial channel and overbank deposits (Figure A24).

This study highlights the potential for relatively thin floodplain clay units to significantly reduce the hydraulic connectivity within aquifers.

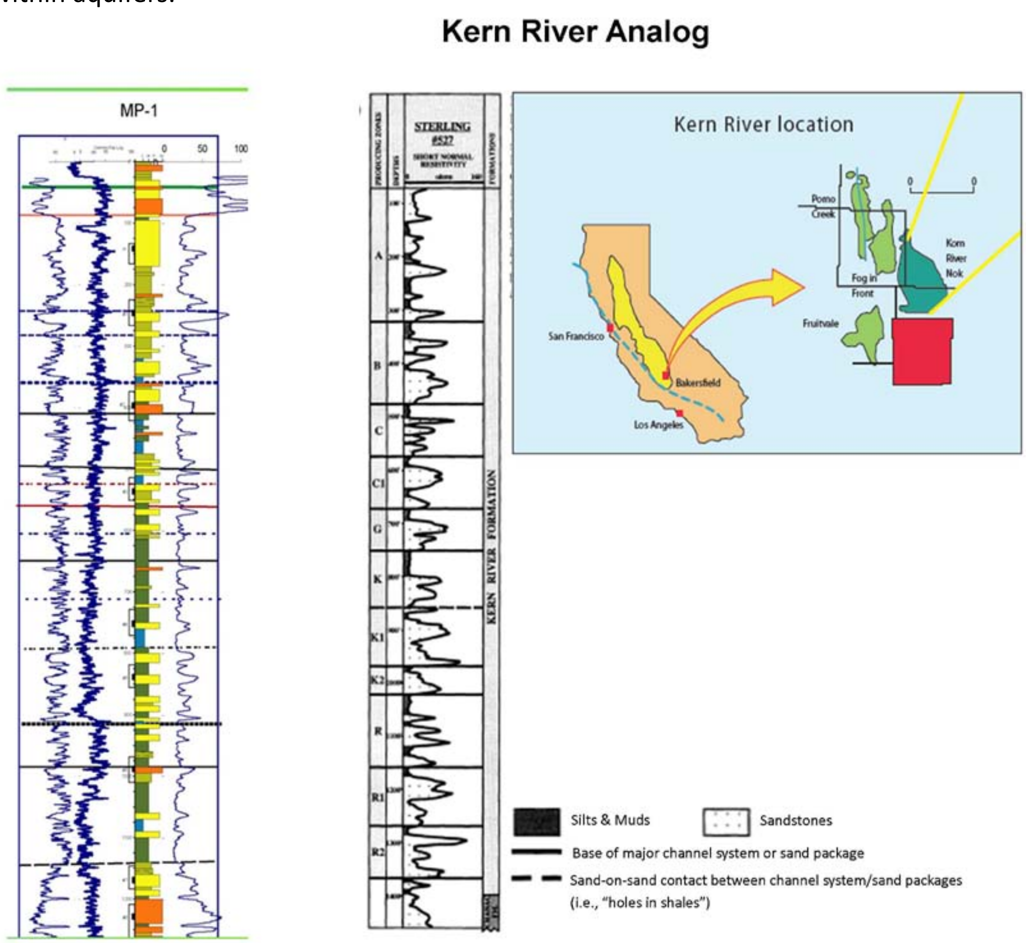

Figure A24. LEFT - Geophysical log suite calibrated to lithologic log showing highly interbedded nature of fluvial channel and overbank deposits. RIGHT – Kern River analog, studies of nearby oil fields in the same depositional setting show high continuity of higher-frequency floodplain facies. (from Knauer, et. al., 2003)

The original conceptual site model consisted of a layer-cake system of five hydrostratigraphic units (Figure A25). The selected and regulatory-approved containment remedy called for extraction from 125' well screens (Figure A25, red box).

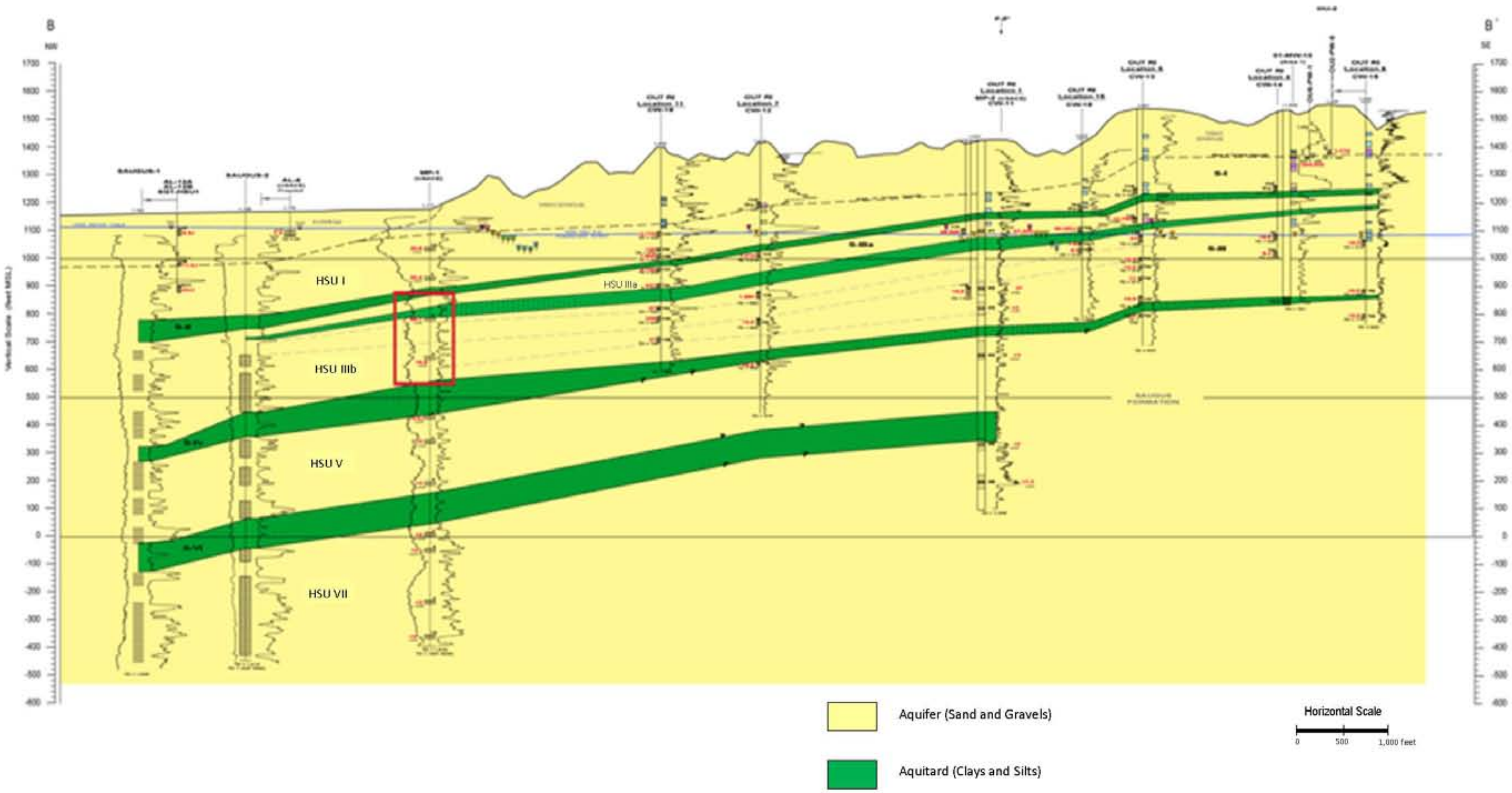

Figure A25. Original CSM depicting five hydrostratigraphic units (HSU I, HSU IIIa, HSU IIIb, HSU V, HSU VII) and extraction well screened interval (red box).

Fluvial facies models, and local knowledge from nearby Kern River oil field in the equivalent stratigraphic interval suggested high continuity of thin floodplain facies (possibly climate-driven) silt/clay units, and a stratigraphic analysis was performed to refine the conceptual site model. Well logs were correlated on the basis of vertical trends, and structural dip removed (*e.g.,* the sections were datumed on a major site-wide floodplain clay so fluvial architecture could be interpreted) (Figure A26).

This analysis was carried out on a series of 12 intersecting cross sections, and all units were loop-tied to create a high-resolution three dimensional definition of aquifer architecture.

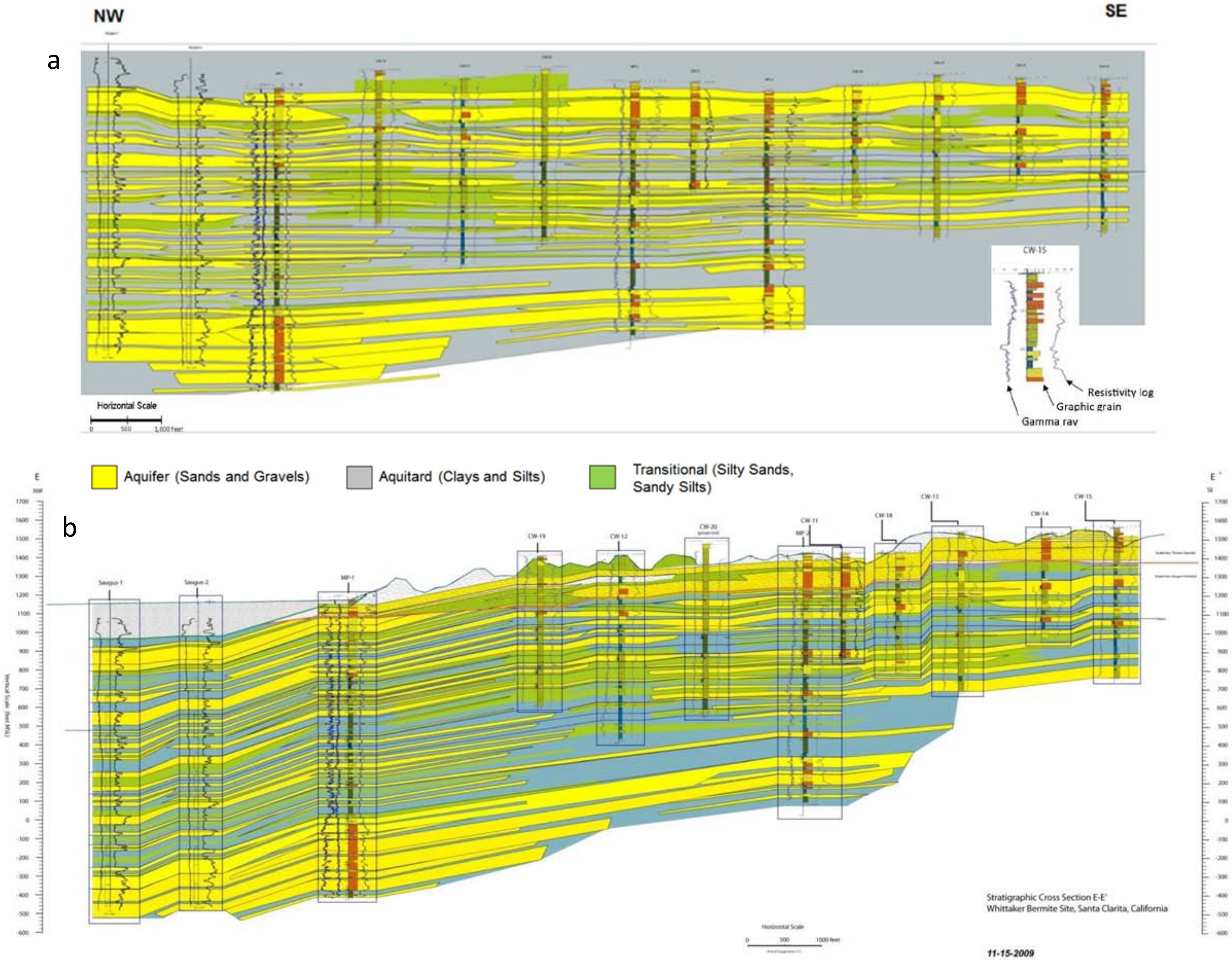

Figure A26. a) Stratigraphic section where a key floodplain clay is used as a datum to correlate the lithology of fluvial facies architecture based on stratigraphic rules for channel evolution. b) The same stratigraphic cross section datumed on mean sea level elevation showing the structural dip.

Targeted aquifer testing and a high-resolution groundwater sampling field program was implemented to validate clay aquitard correlations and further refine the CSM and determine the extraction well design (Figure A27).

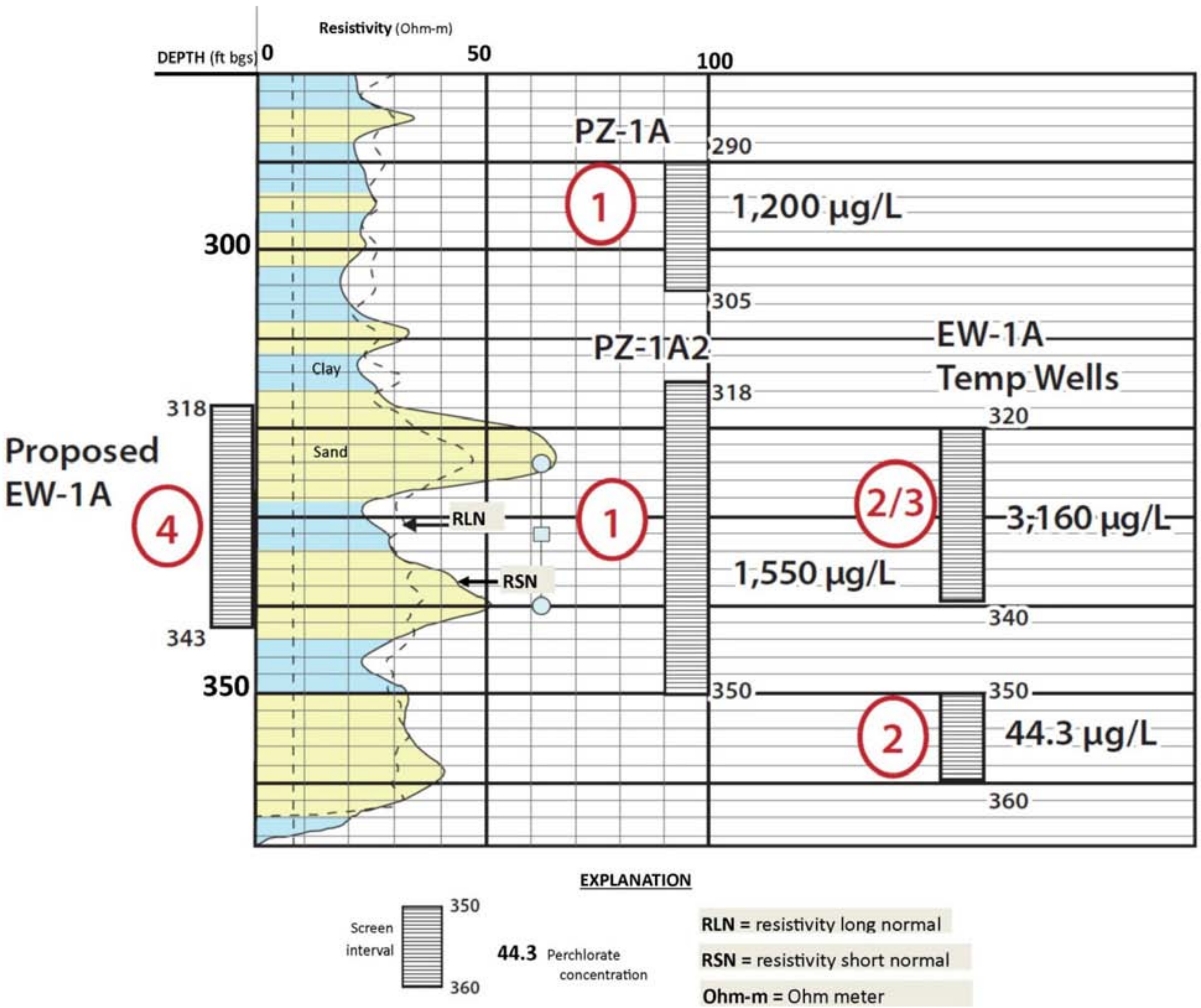

Figure A27. Extraction Well Design – Strategic and Systematic. Based on the ESS CSM, HSU designations of specific well screen intervals were evaluated based on strategic, sequential aquifer tests and groundwater chemistry data to validate the stratigraphic framework and optimize the groundwater extraction well design. Screens **1** are initial pilot hole/piezometers for lithology and monitoring. Screen **2** represents temporary wells to collect depth-discrete groundwater chemistry. Screen **3** represents monitoring wells, and screen **4** is the final extraction well interval.

As shown in Figure A28, the estimated extraction volume and cost for plume containment based on the original containment design was significantly higher than the more optimized design based on the ESS-based stratigraphic framework. It showed that a single channel sequence approximately 35' was impacted, not the entire 125' interval.

This is an example of how a relatively small upfront investment in expertise to reinterpret data from a stratigraphic perspective pays big dividends in project lifecycle cost savings and risk reduction.

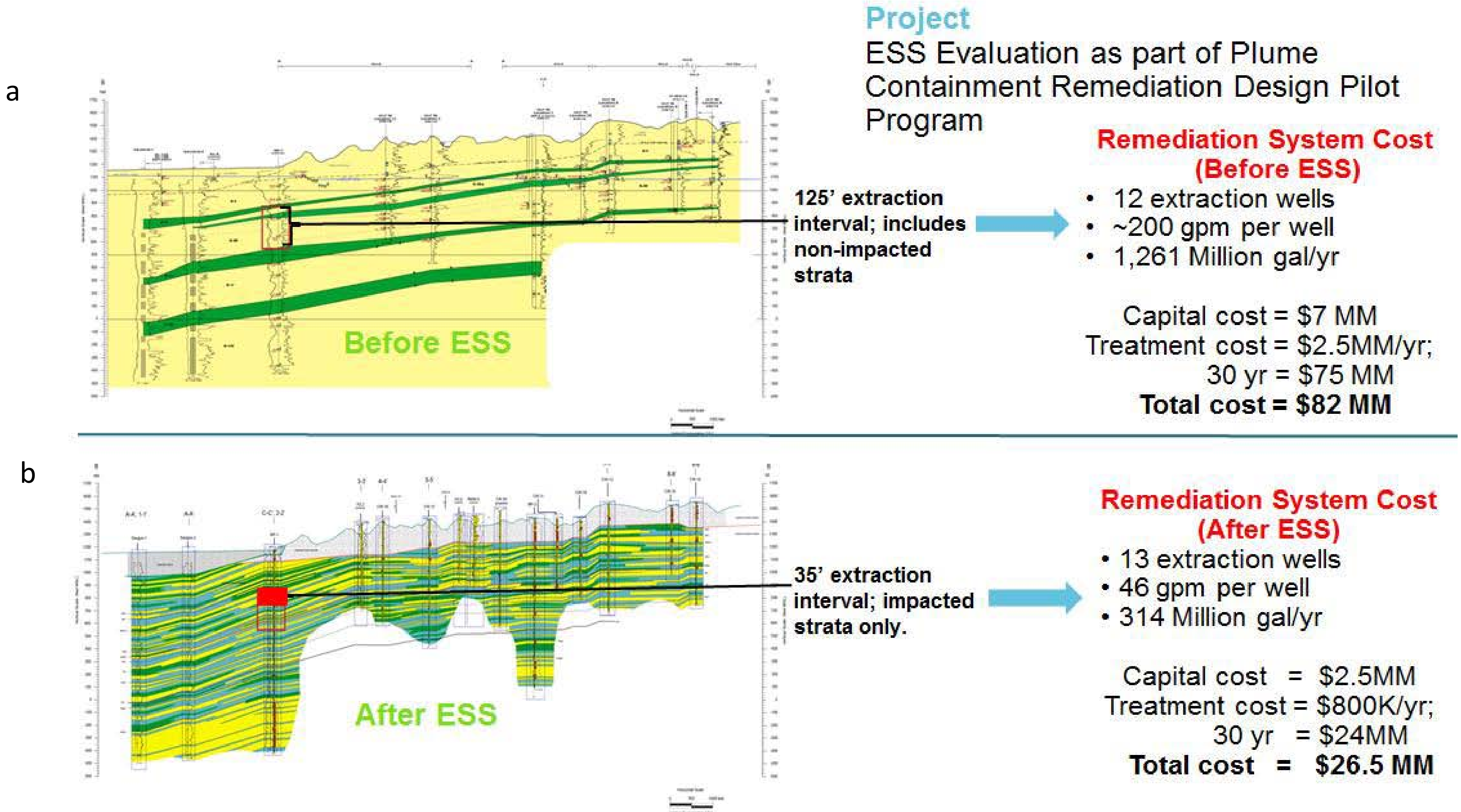

Figure A28. Comparison of Site CSM used for pilot containment design (a) with refined CSM based on high-resolution sequence stratigraphic interpretation (b) and projected water treatment and cost savings estimates.

Case Study 6: Incised Valley Fills, Gulf Coast Region, US; Optimize VOC Plume Containment and In-situ Remediation

Introduction to the Site

This case study documents a former manufacturing site where groundwater was impacted by VOCs and mercury. Due to the complexity of the subsurface, multiple approaches to groundwater remediation were employed including pump and treat, and in-situ bioremediation. The subsurface was defined by cross sections using lithostratigraphic correlation of USCS strip logs and gamma ray geophysical logs. Groundwater and contaminant migration was estimated based on groundwater gradient maps, assuming homogeneous/isotropic conditions.

Because of the limited success of the remedies that were employed, the CSM was revisited by applying the ESS approach to the existing subsurface data to define the groundwater and contaminant preferential pathways. The following exemplifies the value of understanding the sequence stratigraphy (sea-level changes and impact on environment of deposition) and applying ESS concepts to improve groundwater cleanup.

In the area of the project site, sea level fell by as much as 400' relative to present sea level during Quaternary glacial periods. This led to exposure of the continental shelf, downcutting of rivers by erosion, and formation of "incised valleys" in coastal areas including the US Gulf Coast (Figure A29). The site lies within the well-studied Mobile Bay incised valley.

The different environments of deposition which occupied the valleys, and the manner in which they evolved and changed as sea-level rose are well documented for Mobile Bay, as well as other incised valleys of the Gulf and East Coasts of the USA, as well as many other areas worldwide. However, this information was not considered during initial site investigation or remediation.

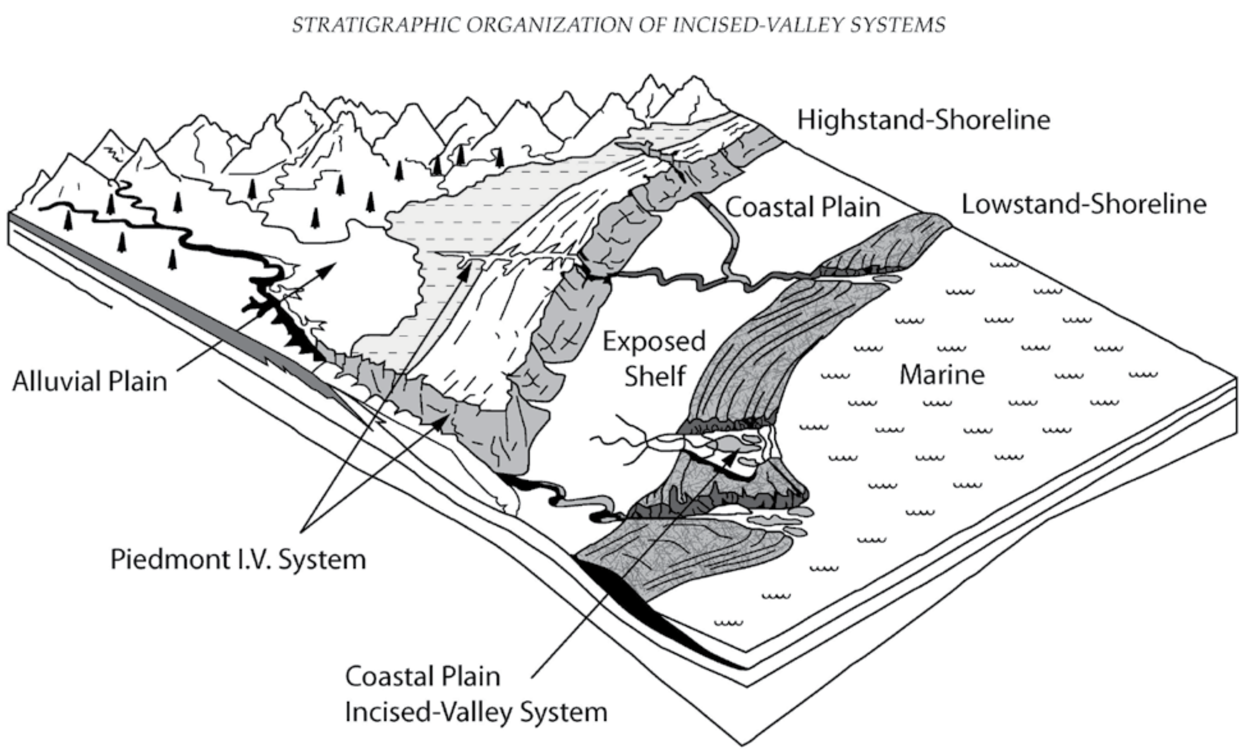

Figure A29. Block diagram depicting development of incised valleys during relative lowstand of sea level (glacial periods) modified from Zaitlin et al. (1994).

Due to the relatively flat topography of terrace deposits located within incised valleys, and proximity to major shipping and commerce areas (*e.g.,* Mobile Bay), the flooded incised valleys are preferential sites of industrial development and related groundwater contamination. This case study shows how an incised-valley depositional model can be used as a tool for interpretation of site data and a predictor of subsurface heterogeneity in incised valleys, and highlights the need for stratigraphic characterization prior to an in-situ injection program.

Site data consist of lithologic descriptions of borings and a suite of gamma-ray logs run through casing (Figure A30).

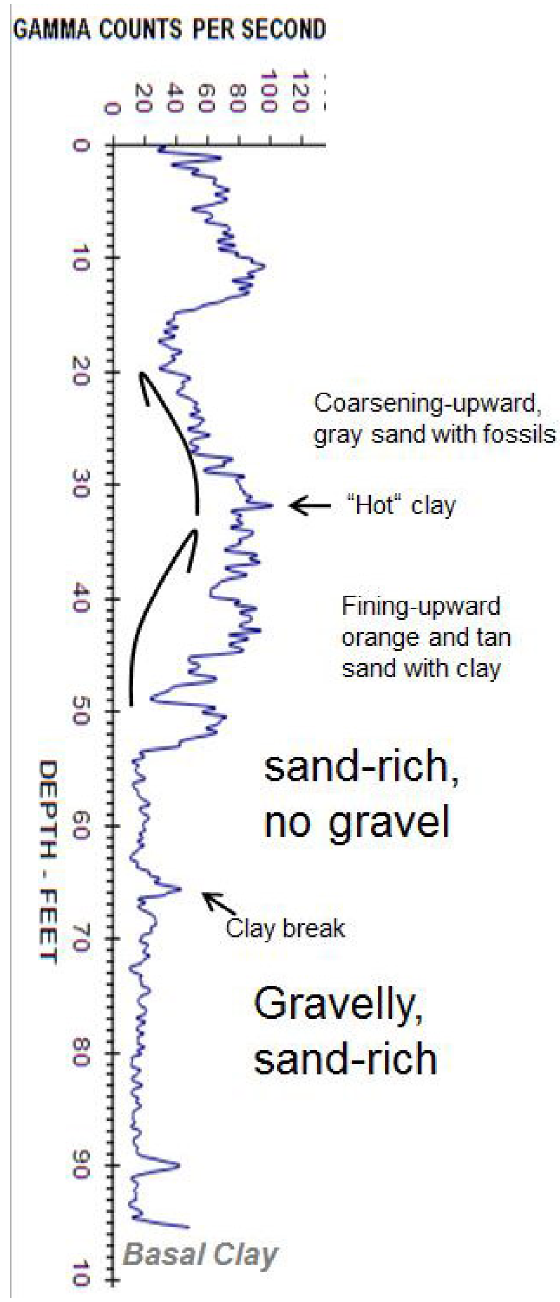

Figure A30. Gamma ray log representing grain size trends and significant clay spikes.

An analog depositional model from a well-studied estuary shows similar vertical facies trends and associations to the site (Figure A31).

Gamma-ray and lithologic data from the site were interpreted in the context of the incised valley fill sequences (Figure A32).

- Initially, an erosional surface (sequence boundary) was developed during sea-level lowstand at approximately -70’ msl (mean sea level) (see IV-1 on Figure A32). Fluvial gravels overlying the sequence boundary were deposited by braided type rivers occupying the incised valley floor (compare to Figure A31a). Injection treatments in this interval were very effective at reducing contaminant concentrations due to the well-connected, highly permeable nature of these deposits (lowstand systems tract in sequence stratigraphic terminology).

- As sea level rose, marine waters flooded the valley and a marine transgressive clay was deposited at approximately -25’ msl (compare to Figure A31b). A series of channelized, clay-rich estuarine sediments then accumulated (compare to Figure A31b). Injection treatments in this interval have been ineffective in reducing contaminant concentrations due to difficulty in achieving distribution of reagent due to the isolated, disconnected nature of estuarine channels in this interval and the effects of back-diffusion of contaminants out of estuarine clays.

- These deposits are overlain by a “hot clay” at 5’ msl characterized by high gamma counts representing the “maximum flooding surface”, or deposits of the relatively highest sea level (compare to Figure A31c, note that the micro-tidal setting of the gulf coast precluded development of a tidal ravinement surface such as shown in Figure A31c). This clay is widespread and likely forms an effective hydrogeologic barrier.

- After this, a bay-head delta prograded across the site producing the coarsening-upward, relatively sheet-like “upper zone” at 0 to 10’ msl (compare to Figure A31d).

- A second lowering of sea-level resulted in a second erosional event and another incised valley system (IV-2 on Figure A32). This second valley system is filled with coarse fluvial gravels at its base. The contact between this second incised valley and the older sediments provides a barrier to groundwater flow and contaminant transport.

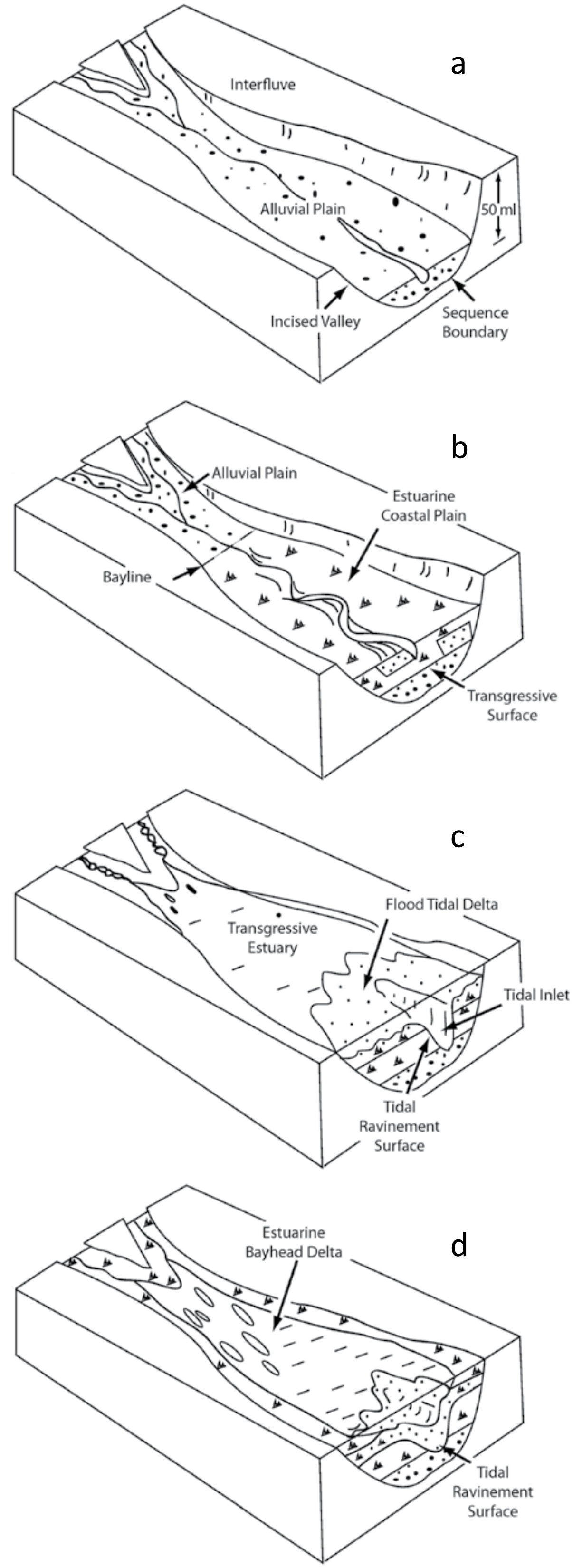

Figure A31. Block diagrams illustrating sequential phases of fill of the incised valley during sea-level lowstand and rise. (redrawn from Posamentier and Allen, 1999)

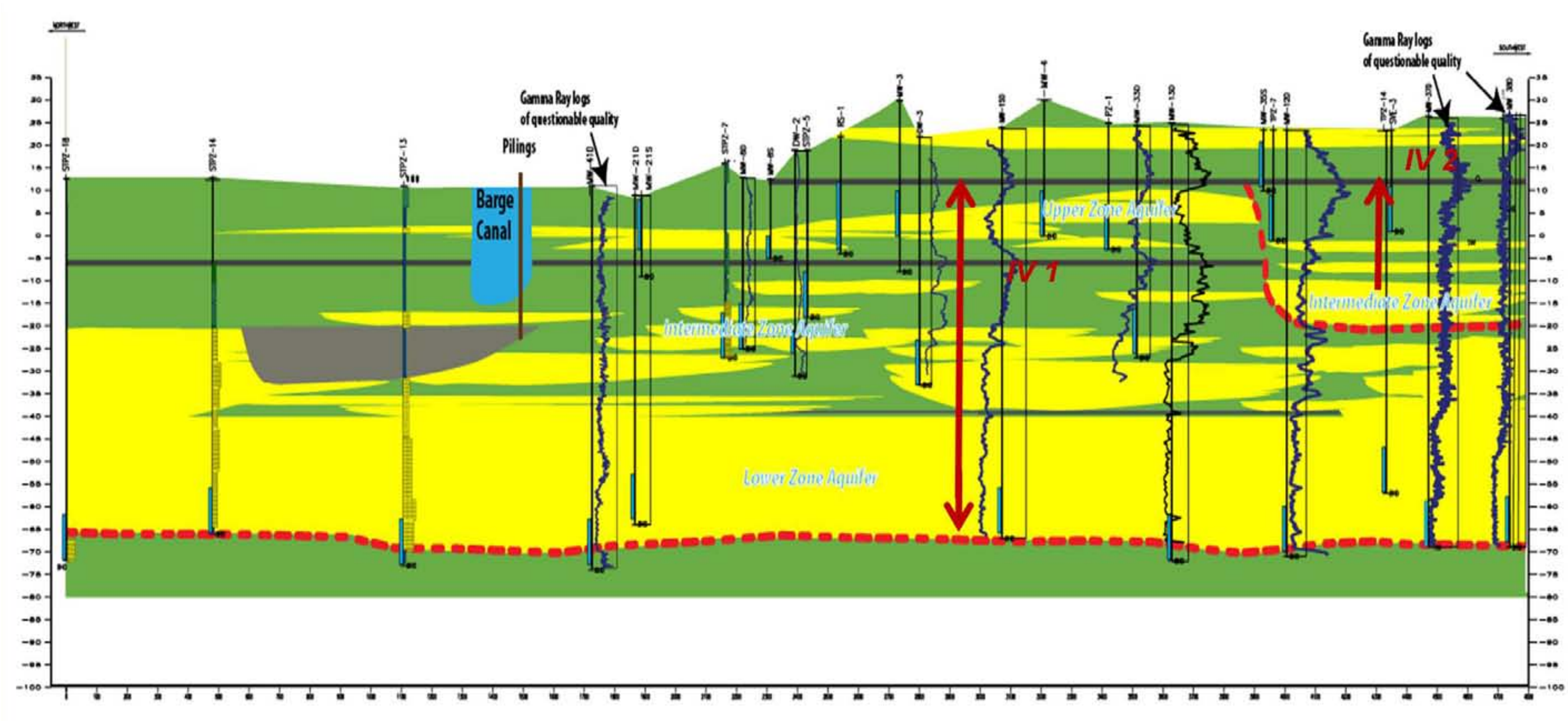

Figure A32. Cross section depicting the two incised valley sequences (IV-1 and IV-2).

The Intermediate Zone is depicted on Figure A33 and shows how the original CSM, based primarily on the mapped groundwater gradient and on the assumption of homogeneous, isotropic conditions (A33a and A33b), does not take into account the permeability architecture resulting from the incised valley depositional system. The Groundwater Gradient map (Figure A33a) and PCE Plume map (Figure A33b) are both constructed without consideration of the underlying heterogeneous geology. Figures A33c and A33d show that the heterogeneous Intermediate Zone is composed of high-permeability sand channels that trend almost perpendicular to regional groundwater gradient, which creates a northwest/southeast preferential pathway that was not identified before the stratigraphic evaluation. This makes a strong case that with heterogenic geology the regional groundwater gradient data alone cannot be used to identify preferential flow pathways. The details of the geology should be defined to assess the potential impact of the geology on groundwater flow and contaminant migration. In this example, defining the channel features helped to understand some of the issues encountered during the initial in-situ injection for the bioremediation program. The injection program was very successful in the more homogeneous Lower Zone where there was good distribution of the injectant. However, in the Intermediate Zone there was poor distribution and "daylighting" of injectant occurred due to the heterogeneous nature of the channel deposits. Understanding these inherent geologic permeability pathways proved important to optimize future groundwater containment and in-situ injection design.

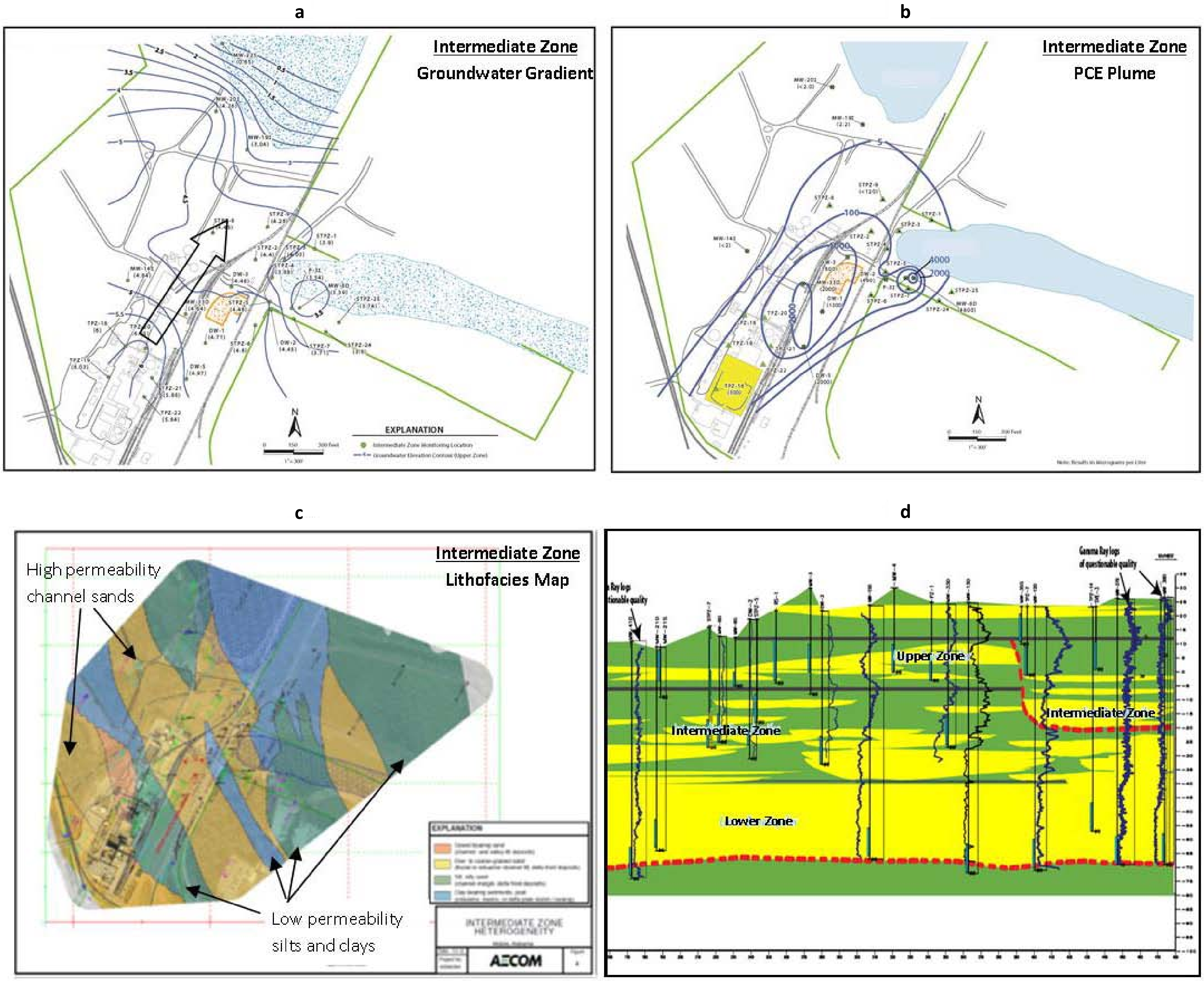

Figure A33. Original CSM (prior to ESS evaluation) is based on the following: A33a shows groundwater elevation contours for the Intermediate Zone with a northeast groundwater flow direction, and A33b shows PCE concentration contours interpreted prior to the lithofacies interpretation and based on this northeast flow direction alone. This interpretation of the contaminant distribution did not take into account the underlying geology. However, as a result of the ESS evaluation, A33c is a lithofacies map of the Intermediate Zone (depicted on the cross section A33d) that shows higher permeability sand channels trend almost perpendicular to the groundwater gradient, bringing to question the chemistry concentration contours interpreted in Figure A33b. Potential action would be to collect groundwater data along the high permeability zones to better define contaminant extent.

APPENDIX B

Glossary of Terms

Aeolian (or Eolian): Of, relating to, or derived from the action of the wind. Generally refers to sand dunes and interdune deposits either in coastal or desert environments.

Alluvial: Pertaining to or composed of clay, silt, sand, gravel or similar unconsolidated detrital material deposited by a stream or running water.

Alluvial fan: A fan- or cone-shaped deposit of sediment built up by streams which shift laterally across its surface. Alluvial fans typically form at the topographic change in slope where high-gradient mountain streams exit their confined canyons onto a relatively broad, flat basin floor where they become unconfined and can spread laterally. If a fan is built up by debris flows it is properly called a debris cone or colluvial fan.

Anastomosing: River system consisting of multiple interweaving channels. Anastomosing rivers typically consist of a network of low-gradient, narrow, deep channels with stable banks, in contrast to braided rivers, which form on steeper gradients and display less bank stability.

Aquifer architecture: Three-dimensional organization of permeable and relatively impermeable aquifer units.

Aquifer characteristics: Characteristics such as hydraulic conductivity, recharge, and aquifer boundaries.

Architectural elements: Component parts of sedimentary deposits with characteristic dimensions and properties, such as channel fills, overbank splays, and floodplain clays.

Avulsion: Rapid abandonment of a river channel and the formation of a new river channel in a different location.

Braided river: One of a number of channel types that consists of a network of small channels separated by small and often temporary islands (called braid bars). Braided streams occur in rivers with high slope and/or large sediment load, are typically only a few feet deep.

Clastic sedimentary aquifer: Aquifer that consists of accumulations of transported and redeposited detrital material (*e.g.,* clay, silt, sand, gravel).

Clay plug: A clay- and organic matter-rich deposit which forms after an avulsion or "cut-off" of a meander loop in a meandering stream. Clay plugs are arcuate (crescent-shaped) in map view, filling "oxbow lakes".

Deltaic: Of, or pertaining to, a delta environment where sediment load from a river is discharged into a body of standing water. Deltas typically form a protuberance in the shoreline and can be dominated by fluvial processes, tidal processes, or wave processes.

Depositional elements: Basic mappable components of both modern and ancient depositional systems and stages that can be recognized in modern depositional environments, outcrops, and the subsurface.

Depositional models: See Facies Models

Depositional processes: Natural processes which transport, deposit, and preserve sediment, such as a stream shifting across an alluvial plain.

Depositional System: A three-dimensional association or assemblage of facies (depositional environments) genetically linked by active (modern) or inferred (ancient) environmental and sedimentary processes.

Facies: Bodies of sediment recognizably different from adjacent sediment deposited in a different depositional environment or sub-environment (*e.g.,* upper shoreface and lower shoreface facies of a barrier island environment).

Facies models: Conceptual construct summarizing the processes acting to erode, transport, deposit, and preserve sediments in particular depositional environment. Also known as Depositional Models, they typically are represented as a three dimensional block diagram showing component parts of buried strata (architectural elements), how they fit together, and a map view showing the active depositional system and its key features.

Fining (or coarsening) upward: Vertical trend in grain size related to a change in energy level within the depositional system with time as the deposit accumulates.

Flooding surface: A general term that refers to surface that separates older rocks/sediments from younger rocks/sediments and is marked by deeper-water strata resting on shallower-water strata.

Geomorphology: The scientific study of the origin and evolution of topographic and bathymetric features created by physical, chemical, or biological processes operating at or near the earth's surface.

Glacial: Of, relating to, or derived from ice.

Hydrostratigraphic unit: A body of sediment saturated with groundwater with limited connectivity to adjacent sediments. Clastic (sedimentary) aquifers typically are composed of multiple hydrostratigraphic units due to heterogeneous geology.

Immobile porosity: The portion of pore space (porosity) that does not allow for groundwater movement; contains stagnant groundwater that serves as a reservoir for contamination; mainly in fine-grained sediments.

Lithology: A description of physical characteristics of a rock (or unconsolidated sediments) such as color, texture, grain size, or composition.

Lithofacies: Lateral, mappable subdivision of a designated stratigraphic unit formed under common environmental conditions of deposition, distinguished from adjacent subdivisions on the basis of lithology.

Loop-tied correlations: Using 2D information to aid in the construction of a valid 3D interpretation is called "tying" the cross section interpretations together. To "tie the loop" (or loop tied) is to ensure that *all geologic surfaces* that affect an interpretation have been tied around a loop along the cross section lines being constructed and are thus consistent in 3D.

Mobile porosity: Corresponds to portion of porosity where groundwater flow occurs; includes interconnected pore space that acts as conduits for contaminant transport; mainly in coarse-grained sediments. (total porosity = mobile + immobile)

Outwash: Glacial sediments deposited by meltwater at the terminus of a glacier.

Overbank: An alluvial deposit consisting of sediment that has been deposited on the floodplain of a river or stream by flood waters that have broken through or overtopped the banks.

Permeability heterogeneity: Diversity in a rock's ability to transmit fluids.

Point bar: An arcuate deposit of sediment, usually sand, that occurs along the convex inner edges of the meanders of channels and builds outward as the stream channel migrates.

Sedimentary depositional environments: Specific depositional settings that are unique in terms of physical, chemical, and biological characteristics (*e.g.,* lake, stream, deep marine, glacier, etc.).

Sedimentary unit: Layers that are laid down by deposition of sediment associated with weathering processes, decaying organic matters or through chemical precipitation.

Strata: Layers of sedimentary rocks or sediments.

Stratigraphic architecture: Structure of sediment/rock layers and layering.

Stratigraphic heterogeneity: Diversity in sediment/rock layers and layering.

Transgression: The migration of a shoreline onto land that can result in sediments characteristic of shallow water being overlain by deeper water sediments.

Udden – Wentworth classification: A grade scale for classifying the diameters of sediments is widely used as the standard for geology and the objective description of sediment.

USCS- Unified Soil Classification System: A soil classification system used in engineering and historically the environmental industry to describe the texture and grain size of a soil to aid in the evaluation of its significant properties for engineering use.

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