Defining Hydrostratigraphic Units within the Heterogeneous Alluvial Sediments at Lawrence Livermore National Laboratory

by Charles M. Noyes[a], Michael P. Maley[b], Richard G. Blake[c]

Abstract

At Lawrence Livermore National Laboratory (LLNL) Superfund site, the properties of ground water flow were used to define a series of hydrostratigraphic units (HSUs) within a thick sequence of previously-undivided, heterogeneous alluvial sediments. A methodology using multiple independent data sets was used to define the hydrostratigraphic unit boundaries. The methodology employs an iterative process to minimize uncertainty in the correlations. Monitoring of the ground water system under stressed conditions during extraction well pumping and long-term pumping tests provided the most effective data set for identifying and verifying HSU boundaries. Hydrostratigraphic analysis identified low-permeability horizons within the alluvial sequence that exert significant control over ground-water flow and contaminant transport. These geologic features, which inhibit vertical hydraulic communication and contaminant migration, form the boundaries of the HSUs. At LLNL, the HSUs generally consist of a hydraulically-interconnected network of higher-permeability deposits set within finer-grained, lower-permeability sediments.

By identifying the primary hydraulic controls within the LLNL alluvial sequence, a hydrostratigraphic framework consistent with ground water flow and contaminant transport processes was established. The HSU framework has allowed for the mapping of a complex network of co-mingled plumes, each of which can be traced back to their respective source areas. Ground water cleanup systems at the site have been designed to treat and capture individual contaminant plumes, and are optimized with respect to their location, geometry, and mobility.

[a]Lawrence Livermore National Laboratory, P.O. Box 808, L-530, Livermore, CA 94550, 925-422-8820, noyes2@llnl.gov
[b]Weiss Associates, 5801 Christie Ave, Suite 600 Emeryville, CA 94608, 925-422-8945, maley,1@llnl.gov
[c]Lawrence Livermore National Laboratory P.O. Box 808, L-530, Livermore, CA 94550, 925-422-9910, blake2@llnl.gov

This has proven a successful strategy for implementing the ground water cleanup based on the site remediation history.

Introduction

The design and implementation of an effective ground water remediation system requires a thorough understanding of the hydrogeologic factors that control site-specific flow and transport in the subsurface. However, at sites underlain by a heterogeneous geological environment, understanding contaminant transport at the necessary scale is a difficult task (Narasimhan 1998; Koltermann and Gorelick 1996; Anderson 1989; Fogg 1986). Yet, until this basic hydrogeologic framework has been established, planning and designing an effective remedial strategy can be problematic (LeGrand and Rosen 1998). For example, extraction wells may not be located and designed for maximum mass removal and optimal hydraulic capture, leading to ineffective, or prolonged and costly remediation. At many sites, attention has been focused on identifying individual high-permeability paleochannels. However, the relatively limited areal extent of individual paleochannels requires a high density of data for proper definition (Fogg et al. 1998; Koltermann and Gorelick 1996). This type of characterization is not feasible for many environmental sites.

At Lawrence Livermore National Laboratory (LLNL), the characterization objective was to define a practical set of subsurface units to provide a framework for planning a large ground water remediation system. These units needed to accurately represent ground water flow and contaminant transport at the site, and group together sets of hydraulically-interconnected, high-permeability sediments. The primary characteristics used to define hydrostratigraphic units (HSUs) at LLNL include:

- a high degree of hydraulic interconnectivity within an HSU;
- a low degree of hydraulic interconnectivity with adjacent HSUs; and

- boundaries that significantly limit vertical hydraulic communication and contaminant migration.

To identify and correlate the HSUs, a methodology that integrated the evaluation of geologic, geophysical, pumping test, ground water elevation, and soil and ground water chemistry data was employed. During this process, efforts were focused on identifying and correlating low-permeability layers because they proved to be more laterally continuous than the higher-permeability layers. It was found that certain low-permeability layers did significantly limit hydraulic communication and contaminant transport within the alluvial sediments across the entire site. These layers were used to define the HSU boundaries. However, there was no unique feature from the analysis of core or geophysical logs that distinguished layers that formed boundaries from those that did not. Therefore, it was necessary to integrate multiple data sets with a strong reliance on ground water data to define the HSUs at LLNL.

Background

Lawrence Livermore National Laboratory (LLNL) is located in Livermore, California, about 65 kilometers east of San Francisco (Figure 1). The LLNL facility is a highly-developed research and industrial facility that covers about 2.5 square kilometers. The site was converted from agricultural use into a Navy Air Field in 1942. In 1951, the site became a weapons design and basic physics research laboratory. In 1982, multiple plumes of volatile organic compounds (VOCs), predominantly trichloroethene (TCE) and tetrachloroethene (PCE), were discovered in ground water beneath LLNL (Dreicer 1985). Prior to the start of remediation, the plumes situated on the western margin of the site extended up to 1,200 meters (m) off site toward municipal supply wells in the city of Livermore. In 1987, LLNL was placed on the U.S. Environmental Protection Agency's National Priorities List. To comply with federal regulations, LLNL has completed a Remedial Investigation (Thorpe et al. 1990), Feasibility Study (Isherwood et al.

1990), and Record of Decision (U.S. DOE 1992). These investigations identified 14 major areas of concern that include landfills, impoundments, leaking tanks, and localized spills. The environmental investigation now covers an area of about 4 square kilometers to depths up to 100 m.

LLNL is located on the eastern margin of the fault-bounded Livermore Basin, considered to be a Late Tertiary pull-apart basin within the Coastal Range Province of California (DWR 1966; Carpenter et al. 1984). The basin is bounded on the east by the Greenville Fault and to the west by the Calaveras Fault. Previous geologic and structural studies of the area include DWR (1966), Herd (1977), Dibblee (1980), Springer (1983), and Carpenter et al. (1984). The sedimentary sequence consists of interbedded sands, gravels, silts, and clays within the Quaternary alluvium, Plio-Pleistocene alluvial fan, fluvial, and lacustrine deposits of the Upper and Lower Members of the Livermore Formation (Carpenter 1984; Thorpe et al. 1990). A facies analysis at the site (Noyes 1991; Fogg et al. 1998) identified fluvial channel deposits, debris and mud flow deposits, crevasse-splay deposits, and overbank/floodplain deposits within the Upper Member of the Livermore Formation.

Data Available

The primary data sets used to define HSUs at LLNL include: (1) lithologic core descriptions, (2) borehole geophysical logs, (3) pumping test data, 4) ground water elevation data, (5) VOC concentrations in sediments and ground water, and (6) plume signatures of chemical constituents. The data was collected from approximately 500 wells and boreholes which average 30 to 75 m in depth and are laterally separated by about 30 to 150 m. Table 1 summarizes the amount of each data set available at LLNL.

At LLNL, many boreholes have been continuously cored. The detailed lithologic logs from these boreholes include descriptions of color, texture, grain size, sedimentary structures, sorting, cementation, and a qualitative estimate of hydraulic conductivity. Geophysical logs are acquired at most boreholes, and include short, long, and point resistivity, gamma ray, spontaneous potential, induction, and caliper logs. Hydraulic data from the site includes both monthly monitor well water levels, collected since 1984, and pumping test data. The pumping tests range in duration from one hour to several days. An analysis of hydraulic response in observation wells to pumping is used to evaluate horizontal and vertical hydraulic communication within the vicinity of the pumping well.

Unsaturated soil, saturated soil, and ground water samples are collected from boreholes and monitor wells to provide chemical data for determining the nature and extent of contaminants in the subsurface. Hoffman and Dresen (1990) described the method used at LLNL to collect soil samples at multiple depths, while minimizing potential cross-contamination in boreholes drilled using the mud-rotary method. Since 1984, ground water samples at LLNL have been routinely collected for analysis of VOCs. To improve cost-effectiveness while maintaining data integrity, LLNL has applied a statistical algorithm (Johnson et al. 1995) to optimize ground water sampling. This algorithm increases or decreases sampling frequency based on the rate of change in VOC concentrations at a well. The VOC ground water data was screened for recognizable suites and ratios of VOCs that constitute a signature for specific plumes. These analyses accounted for possible chemical transformations based on a natural attenuation study of the site (McNab and Narasimhan 1994). Differences in inorganic constituents were not found to vary enough to serve as a useful discriminator at LLNL.

Methodology

As employed at LLNL, hydrostratigraphic analysis is a systematic method to integrate independent data sets to define and verify the HSU correlations. The methodology consists of the following seven steps:

1. Select appropriate data sets, evaluate data quality, and construct cross-section grid,
2. Define HSU boundaries at specific boreholes using multiple, independent data sets,
3. Correlate HSU boundaries across the study area using the cross-section grid,
4. Resolve discrepancies in HSU correlations on the cross-section grid,
5. Construct structure, potentiometric, isopach, and isoconcentration maps for each HSU,
6. Review maps to identify anomalies and inconsistencies in correlations, and
7. Revise correlations and repeat steps 2 through 6 in an iterative manner.

Locations with high-density or high-quality data were analyzed first to define initial HSU boundaries. These high-density or high-quality data locations became the anchor points for subsequent analyses. The HSU boundaries at the anchor points were defined based on pumping test data, lithology, and borehole geophysical logs. These interpretations were further constrained by chemical and ground water elevation data. Monitoring changes in ground water elevations due to long-term pumping from extraction wells or pumping tests was considered the most direct means for evaluating the hydraulic connection between areas. In many cases, it was very difficult to resolve the different HSUs under natural hydrologic conditions. However, under pumping conditions, significant differences in response to the hydraulic stress were observed, thus becoming the basis for identifying HSU boundaries.

The HSU boundaries were then correlated into sparse data areas primarily using the geophysical log cross sections and supplemented with other available data. A comprehensive cross-section grid was constructed for the site (Figure 2). The grid was designed to link together all the wells at the site. Having a large, dense grid helped ensure that a consistent, three-dimensional interpretation was developed, since correlations on all intersecting, site-wide cross-sections had to be resolved.

Once the correlations were developed, a set of structure, isopach, VOC concentration, and ground water elevation maps were constructed for each HSU. These maps were used to identify anomalies and inconsistencies in the HSU correlations in the horizontal view. Inconsistencies were examined on both the cross sections and maps in order to revise questionable correlations. As each successive set of HSU correlations was completed, a new series of structure, VOC isoconcentration, ground water elevations, and isopach maps was constructed for each HSU. This process was repeated in an iterative manner until all remaining inconsistencies could be resolved. The validity of each HSU was tested by constructing ground-water elevation maps under both unstressed and stressed conditions, using all wells completed within the HSU. If correctly defined, these maps demonstrated that a single ground water flow field existed within the HSU, and that this flow field was distinct from the flow fields of adjacent HSUs.

These maps, constructed to verify the HSU correlations, were also immediately useful for ensuring that the design and location of extraction wells were optimized for hydraulic capture and contaminant mass removal. These maps were also used to identify key locations at LLNL where additional hydrogeologic information was needed to resolve the hydrostratigraphy, and therefore were used to guide ongoing drilling activities.

Results

The following examples illustrate the use of hydrostratigraphic analysis to identify subsurface features that control vertical hydraulic communication and contaminant transport in alluvial sediments beneath LLNL, and are representative of how the methodology was used to define the HSUs at LLNL.

Treatment Facility A

Treatment Facility A (TFA) is located at the southwestern corner of LLNL (Figure 1) and was designed for the ground water remediation of VOC plumes that initially extended up to 1,200 m beyond the LLNL site boundary. Figure 3 presents the geophysical logs from a cluster of eight TFA extraction wells with a well-spacing of less than 15 m. Hydrostratigraphic analysis of this area was required to help define the geometry and mobility of the offsite plumes and to evaluate the effectiveness of the extraction wells to hydraulically contain them. Figure 3 shows these logs both with and without the interpreted HSU boundaries. The considerable lithologic variability shown on the logs is representative of the scale of geologic heterogeneity present at the site. Based solely on geology and geophysical data, no distinct features that could represent an HSU boundary can be identified. In addition, the degree of vertical interconnection between higher-permeability layers within the section is not evident from the logs. Additional data sets were needed to determine whether any HSU boundaries were present in the area.

A series of multi-day pumping tests were performed to test the application of HSUs in this area. Figure 4 shows a hydrograph of a three-week pumping test performed on wells W-520, W-602, and W-522. The wells were pumped sequentially starting with W-520, and water levels were monitored continuously in all eight wells. Once pumping began, the wells were pumped at a constant flow rate until the end of the test. The water levels in wells W-521, W-601, and W-602 show an immediate response to the W-520 pumping, whereas the other wells do not show any significant change in water level. Similarly, the same set of wells respond to pumping of W-602, whereas the other wells remain relatively unchanged. Finally, when W-522 begins pumping, the wells W-518, W-603, and W-609 show a significant water level response, whereas water levels in wells W-520, W-521, W-601, and W-602 remain relatively unchanged. Clearly, wells W-520, W-521, W-601, and W-602 can be considered to be hydraulically-interconnected, but are hydraulically separated from wells W-518, W-522, W-603, and W-609.

The location of an HSU boundary between these two sets of wells was verified using VOC data from soil samples collected during drilling (Figure 5). The average PCE concentration changes from about 35 _g/L to about 5 _g/L across the boundary indicating that the low-permeability zone is inhibiting the vertical movement of VOCs as well as ground water. Figure 3 shows the same TFA profile with the HSU boundary added. The low-permeability layer at the HSU boundary is a subtle feature, less than 1 m thick, that does not show any unique characteristics on the logs. However, based on a series of overlapping pumping tests, ground water chemistry, soil chemistry, lithologic descriptions, and geophysical data, this low-permeability zone was found to be a significant flow-controlling feature at this location. Subsequently, this hydrogeologic feature was determined to be laterally continuous across the LLNL site, and was used to define the boundary between HSU-1B and HSU-2. These two HSUs are distinct ground water units that contain multiple, higher-permeability sand and gravel zones. The higher-permeability zones within these HSUs can be demonstrated to be hydraulically-interconnected using the pumping test data, despite appearing separate on lithologic and geophysical logs.

T-5475 Area

The T-5475 area is located in the east-central portion of LLNL (Figure 1). Figure 6 shows a cross section through the T5475 area both with and without the HSU interpretation. A series of small landfills were used in this area to dispose of laboratory waste products that included both

VOCs and tritium. Total VOC concentrations as high as 25,000 _g/L, and tritium activities as high as 40,000 picocuries per liter (pCi/L) have been measured in the T-5475 area. The regulatory maximum contaminant level (MCL) for tritium is 20,000 pCi/L. Because of the regulatory concerns regarding mixed-waste, a detailed understanding of the hydrostratigraphic framework was required prior to the implementation of remediation. The primary objective was to determine whether the proposed ground water extraction from surrounding areas would induce tritium migration to surrounding areas.

The HSUs were first defined by identifying subsurface intervals with distinct differences in ground water elevations, VOC concentrations, tritium activities, and the ratios of individual constituents. For example, in 1996 a distinct difference in ground water elevations was noted between HSU-2 and 3A of 30 to 60 cm, and between HSU-3A and 5 of 80 to 100 cm. Subsequent ground water extraction in the area has further exaggerated these differences and provided additional verification of these correlations. By 1999, the difference in ground water elevations between HSU-2 and 3A had increased to about 180 cm, and that between HSU-3A and 5 was about 330 cm. In addition, distinct differences in the vertical distribution of VOCs and tritium were observed. Figure 7 shows tritium activity maps for HSUs 2, 3A, and 5 in the T-5475 area. In 1996, tritium activities were observed as high as 30,000 pCi/L in HSU-3A, whereas tritium activities in HSU-2 and 5 are generally below 1,000 pCi/L. These distinct variations in tritium activity, along with tritium being an excellent ground water tracer (Freeze and Cherry 1979), imply that these HSUs are separate ground water flow units.

To verify the initial HSU correlations, a series of multi-day pumping tests were conducted in the T-5475 area. For example, a 72-hour pumping test was conducted using HSU-5 well W-1108 which is screened underneath the tritium plume in HSU-3A. During this test, hydraulic responses of 20 to 70 cm were observed in HSU-5 wells up to 100 to 300 m from the pumping well (Figure 8). In general, however, the HSU-3A wells showed changes in water levels of less than 10 cm during pumping. Since these HSU-3A changes did not vary with respect to distance from the pumping well (Figure 8), these water level fluctuations were interpreted to be unrelated to pumping at W-1108. An exception was noted in two HSU-3A wells that showed a weak response to pumping. This response is interpreted to indicate the location of a limited area of vertical leakage between HSU-3A and 5.

In the T-5475 area, HSU-3A was interpreted to lie directly upon HSU-5, with HSUs 3B and 4 absent at this location. This interpretation was based primarily on ground water rather than geologic data. Pumping tests were used to confirm that wells W-1108 and W-566 were completed within the same HSU despite W-566 being 15 m deeper than W-1108 (Figure 6). A similar analysis of pumping tests of wells completed in HSU 2 established that HSU 2 varied by less than 3 m across the same area. Based on this interpretation, the sedimentary interval between the base of HSU 2 and the top of HSU 5 thinned from about 13 m at W-566 to about 5 m at W-1108. Furthermore, the westward structural dip on the base of HSU 2 was estimated to be about 1 degree in contrast to 5 degrees for the top of HSU 5. By incorporating these interpretations into the site-wide correlations, HSUs 3B and 4 were determined to pinch out in the subsurface in the western part of the T-5475 area (Figure 6).

Once the hydrostratigraphic relationships were determined, it became clear that the plumes were residing within distinct flow systems. The analysis also indicated that the tritium was effectively contained within HSU-3A, and that controlled pumping in adjacent HSUs could be accomplished without spreading the tritium plume outside of the T-5475 area. The HSU analysis proved to be a key element for developing the remediation plan for the T-5475 area and obtaining approval for the design from the regulatory agencies.

Site-Wide Application

Once the hydrostratigraphy of data-rich areas such as TFA and T5475 was established, a large cross-section grid was used to develop the site-wide HSU framework by correlating the HSUs into areas with limited data. Initially, a grid of 29 east-west, north-south, and diagonal cross sections (Figure 2) was constructed for the site. The grid has an average spacing of about 200 m, and contains over 165 tie points. Figures 9 and 10 provide examples of an east-west and north-south cross-section, respectively. These cross sections depict the general westward dip and thickening of the sedimentary sequence towards the depositional center of the basin. HSUs 3A, 3B, and 4 are interpreted to pinch-out in the eastern section of LLNL. The geophysical logs in the two figures also show the nature and scale of heterogeneity present in the sediments beneath the site.

The transport of VOCs in the subsurface is influenced by the structural configuration of the HSUs. The westward dip of the sedimentary sequence (Figure 9) causes HSUs located at depth in the western portion of the site to become unsaturated in the eastern portion of the site. In the eastern portion of LLNL, HSU 5 is the first saturated HSU (Figure 11). In this area, HSU 5 is overlain by multiple source areas that contain both VOC and fuel hydrocarbon source areas. Because vertical hydraulic communication and contaminant migration is restricted at the HSU boundaries, VOCs from the overlying source areas preferentially migrate downgradient within this first saturated HSU rather than crossing HSU boundaries. Because of this relationship, VOCs occur at higher concentrations and are found further downgradient in HSU-5 than in the overlying HSUs. In contrast, in the western part of LLNL, HSUs 1B or 2 are the first saturated

HSUs. Accordingly, VOCs originating from local source areas in this part of LLNL are generally confined to these upper two HSUs. The relationship between source areas and the VOC ground water plumes within the HSUs is shown on the block diagram in Figure 11. The geometry shown is consistent with the VOC plume signature distributions in the area, which are shown in Figure 12. This conceptual hydrogeologic model has been essential to installing extraction wells to appropriately intercept and remediate VOC plumes at LLNL.

The ability to make reliable ground water elevation maps under a variety of pumping conditions serves as one of the principal tools to verify that an HSU has been correctly defined. Prior to the definition of HSUs in 1994, ground water elevation maps were constructed with limited regard to depth. However, as more ground water extraction wells were put into operation, significant differences in response to pumping were observed at different depth intervals, suggesting that additional vertical refinement of the conceptual hydrogeologic model was needed. Currently, a separate map is constructed for each HSU. Figure 13 shows three separate ground water elevation maps for HSUs 1B, 2, and 3A at LLNL. The overall ground water flow direction in these HSUs is similar. In areas without ground water extraction, the difference in ground water elevations between HSUs is typically less than 30 cm. However, in areas of active ground water extraction, drawdown on the order of 300 cm or greater is observed in monitor wells completed within the HSU, whereas little to no drawdown is observed in nearby monitor wells that are completed in adjacent HSUs. This relationship exists even in areas where extraction wells have been in continuous operation for months to years, suggesting limited leakage occurs across HSU boundaries across much of the site.

Similarly, mapping of ground water contaminants is another method to verify that an HSU has been correctly defined. Figure 14 shows three separate isoconcentration maps for total

VOCs for HSUs 1B, 2 and 3A. The VOC plume geometry in each HSU consists of a concentration distribution that is distinct from those in the other two HSUs. This would indicate that minimal mixing is occurring between the HSUs and is additional evidence that VOC transport occurs primarily within an HSU. VOC transport across HSU boundaries is most likely limited to isolated areas that represent holes in the HSU boundary.

Hydrostratigraphic Unit

Hydrogeologists have long noted that ground water flow often does not conform to the boundaries of recognized stratigraphic units. Two hydrogeologic terms, “aquifer” and “hydrostratigraphic unit,” are commonly employed to subdivide the subsurface into units more relevant to ground water hydrology. However, the term “aquifer” is commonly defined for water supply usage in economic terms. In many areas, “aquifer” is defined by local laws and regulations which makes it difficult to use ‘aquifer’ as a technical term. The term “hydrostratigraphic unit” has been defined in a variety of ways in the literature, and does not currently have a formal definition within the North American Code of Stratigraphic Nomenclature (North American Commission on Stratigraphic Nomenclature 1983). The term hydrostratigraphic unit was first proposed by Maxey (1964) for “bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system.” Maxey (1964) identified the need to define ground water units that are based not solely on specific lithologic characteristics but also included parameters “that apply especially to water movement, occurrence, and storage.”

Seaber (1988) noted the disagreement among hydrogeologists whether to “map and name the flow system and the rock body separately, or to find a means to combine the two concepts into one system of mapping and nomenclature.” Much of this disagreement in classifying and naming hydrostratigraphic units occurs because “the nature of the boundaries of the unit have not been defined before mapping the unit.” Seaber (1982; 1986; 1988) proposed a definition of hydrostratigraphic unit as “a body of rock distinguished by its porosity and permeability,” which he considered more consistent with established stratigraphic nomenclature. With this definition, Seaber intended to accommodate the observation that a “hydrostratigraphic unit may occur in one or more lithostratigraphic, allostratigraphic, pedostratigraphic, or lithodemic units.” Seaber (1988) attempted to define a hydrostratigraphic unit that applied to all geological environments by focusing on the material properties of the rock or sediment.

For this paper, we defined a hydrostratigraphic unit (HSU) as a body of sediment and/or rock characterized by ground water flow that can be demonstrated to be distinct under both unstressed (natural) and stressed (pumping) conditions, and is distinguishable from flow in other HSUs. Using this definition, an HSU is not restricted to any particular geologic setting, which was the intent of Seaber (1988), but is principally based on the properties of ground water flow, which is consistent with Maxey (1964). For our use, we consider an aquifer to be composed of one or more HSUs. Thick aquitards or aquicludes may be defined as HSUs based on their distinct ground water flow characteristics. Thin aquitards or aquicludes that form significant, laterally-continuous layers that limit hydraulic communication may be used to define HSU boundaries.

Discussion

The HSUs have proven a useful management tool for implementing site-wide remediation at LLNL by improving our ability to identify and target contaminant migration pathways, delineate individual plume geometries, identify the relationship between plumes and source areas, and better define hydraulic capture areas. The HSU analysis provides an effective format to communicate technical issues regarding the complex geology and contaminant distribution found at LLNL.

Site Characterization and Remediation Management

Prior to the application of the HSU concept, the alluvial sequence beneath LLNL was considered so heterogeneous that it could not be correlated or subdivided into ground water units, on a site-wide basis, that were relevant to the proposed ground water remediation. Figure 15 presents a north-south cross section along the western site boundary constructed for the Remedial Investigation (Thorpe et al. 1990) prior to the use of HSUs. Although this early characterization clearly defined the nature and extent of contamination, a more comprehensive understanding of the hydraulic interconnectivity was necessary to implement a ground water remediation program. Figure 16 presents the current interpretation, showing the VOC plume distribution in HSU 1B and 2, and the locations of the extraction wells, which have been optimized with respect to mass removal and hydraulic capture. Active LLNL ground water extraction systems now serve as a means of testing the validity of the HSUs through the hydraulic monitoring of facility startups and shutdowns. Although the HSU correlations have been updated, revised, and refined since they were first defined, the overall framework has continued to provide a viable structure for site operations.

An improved understanding of the subsurface has allowed for more effective remediation plans to be designed and implemented (Hoffman 1993). By incorporating the HSUs into remediation management, LLNL has strengthened the role of hydrogeology in engineering and management decisions. One measure of improved remediation performance is the increasing rate of mass removal at LLNL. Through 1999, about 510 kg of VOCs have been removed from ground water at LLNL as compared to an estimated 280 kg based on earlier ground water model results (Tompson et al. 1995).

The HSU approach has proven to be an effective tool for communicating the complex geology and contaminant distribution found at LLNL to managers, technical staff, regulatory agencies, and the community. For example, hydrostratigraphic analysis provided an effective means of demonstrating to the regulatory agencies that certain sets of permeable layers are hydraulically interconnected, and should, therefore, be considered a single unit with respect to ground water cleanup. Through the acceptance of the HSU approach, LLNL was allowed to install ground water extraction and monitor well systems on an HSU basis rather than in each of these permeable layers. This decision allowed LLNL to reduce the number of wells and treatment systems in specific areas from the number originally planned.

Nature of HSU Boundaries

In applying the HSU methodology at LLNL, emphasis was placed on defining the separate ground water flow systems, and little attention was placed on determining the nature and origin of the HSU boundaries. Since the application of the HSU approach to site characterization and remediation management did not require a full understanding of the nature of these boundaries, the genesis of the lower-permeability deposits that form the HSU boundaries at LLNL has not been carefully examined, nor is it well understood.

Despite their significance in controlling flow and transport, these features cannot be readily identified in core or on geophysical logs. These horizons are commonly described as consisting of fine-grained, low-permeability sediments that contain caliche cementation. Subsequent sedimentologic analysis of the core does indicate textural evidence of paleosol development in these intervals (Gary Weissman, oral communication, 1999). Evidence of paleosol development includes the presence of caliche, clay coatings, root traces, and red coloration (Retallack 1990, 1997). However, paleosol development is also commonly found within HSUs as well. What appears to distinguish an HSU boundary at LLNL is the lateral persistence of these geologic features rather than their mere presence. Accordingly, the HSU boundaries are considered to occur at depositional or paleosol horizons within the alluvial fan complex.

Geological Understanding

Although the HSUs are defined in terms of ground water, the controlling features are geological. These horizons have been used to define the structural geometry within the alluvial sequence, which is observed to be gently folded with a general westward dip towards the center of the depositional basin (Figure 9). As described in the T5475 example, the alluvial sequence becomes thinner with sequence pinch-outs in the eastern portion of the site (Figure 6), perhaps due to lower subsidence rates at the basin margin or incisement of paleochannels. In addition, several distinct depositional gradients can be recognized within the section. The LLNL example suggests that detailed analyses of ground water flow have the potential for providing insights into the depositional and structural geology of certain sites.

Conclusions

At LLNL, a methodology using multiple independent data sets was used to define the hydrostratigraphy of the site. As discussed, a hydrostratigraphic unit (HSU) is defined as a body of sediment and/or rock characterized by ground water flow that can be demonstrated to be distinct under both unstressed (natural) and stressed (pumping) conditions, and is distinguishable from flow in other HSUs. The methodology employs an iterative process that integrates independent data sets to minimize uncertainty in HSU boundary correlations. Using this methodology, we recognized several distinct hydrostratigraphic units within a previously undifferentiated sequence of alluvial sediments. The HSU boundaries were located at subtle, laterally-persistent, low-permeability horizons that could only be distinguished from other low-permeability layers within the interval by using an analysis that incorporated ground water flow. The process of defining the HSUs also contributed to the overall understanding of the site geology.

The identification of these primary hydrogeologic controls within the alluvial sediments established a hydrostratigraphic framework consistent with ground water flow and contaminant transport processes. This framework allowed for the mapping of a complex network of co-mingled plumes, each of which can be traced back to their respective source areas. Ground water cleanup systems at the site have been designed to treat and capture individual contaminant plumes, and are optimized with respect to their location, geometry, and mobility. This has proven a successful strategy for implementing the ground water cleanup based on the site remediation history.

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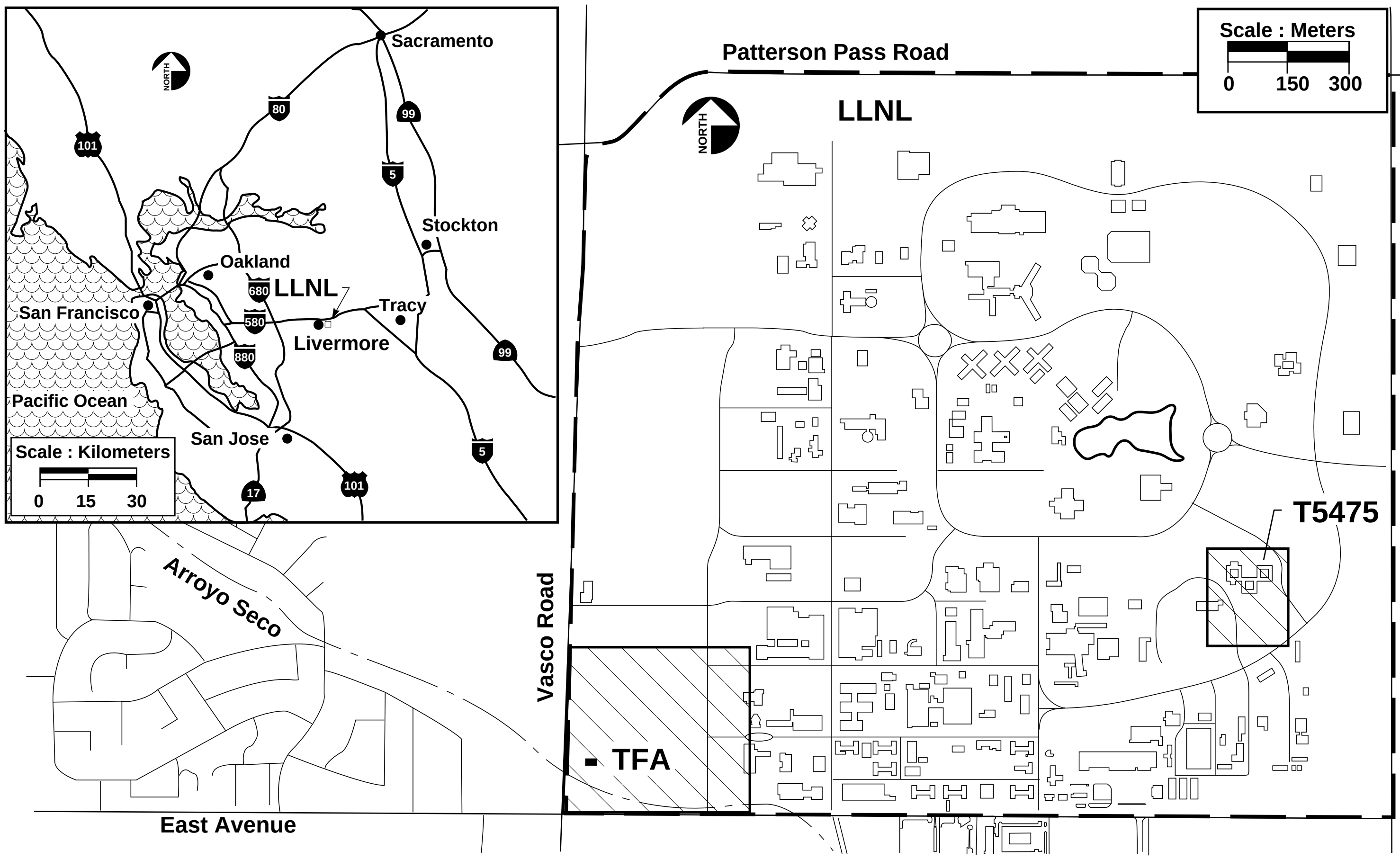
Table 1

List of Lawrence Livermore National Laboratory Data Sets.

Data set	**Description**
Lithologic core	Over 20,000 m of described core from 561 boreholes
Geophysical logs	406 boreholes
Pumping tests	61 multi-well tests
Ground water elevations	Monthly data from 556 wells dating back to 1984
Ground water chemistry	Over 13,500 samples from 556 wells dating back to 1983
Sediment chemistry	Over 4,600 samples from 670 boreholes



ERD-LSR-00-0104

Figure 1. LLNL site map showing the location of the TFA and T5475 study areas.

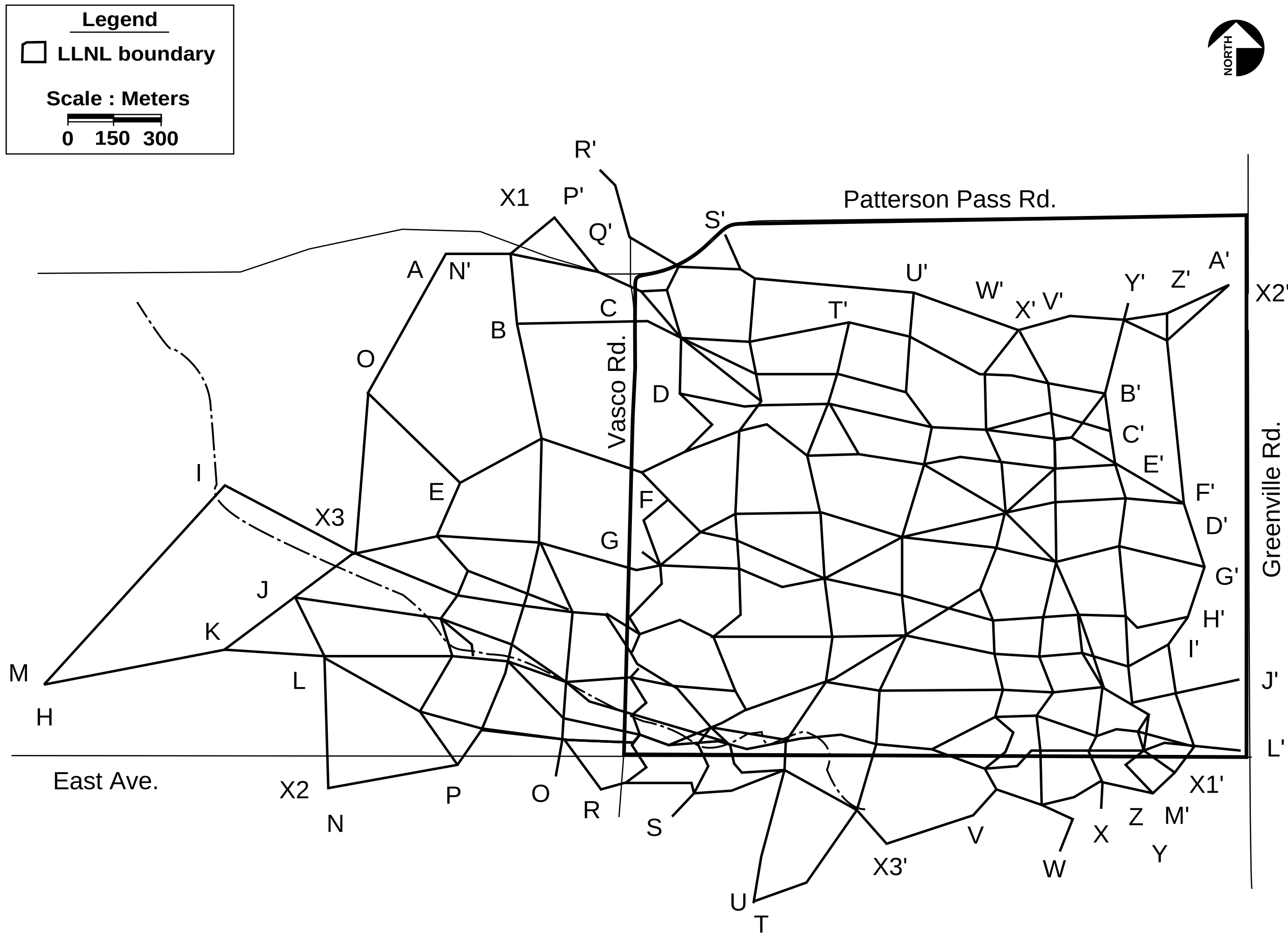


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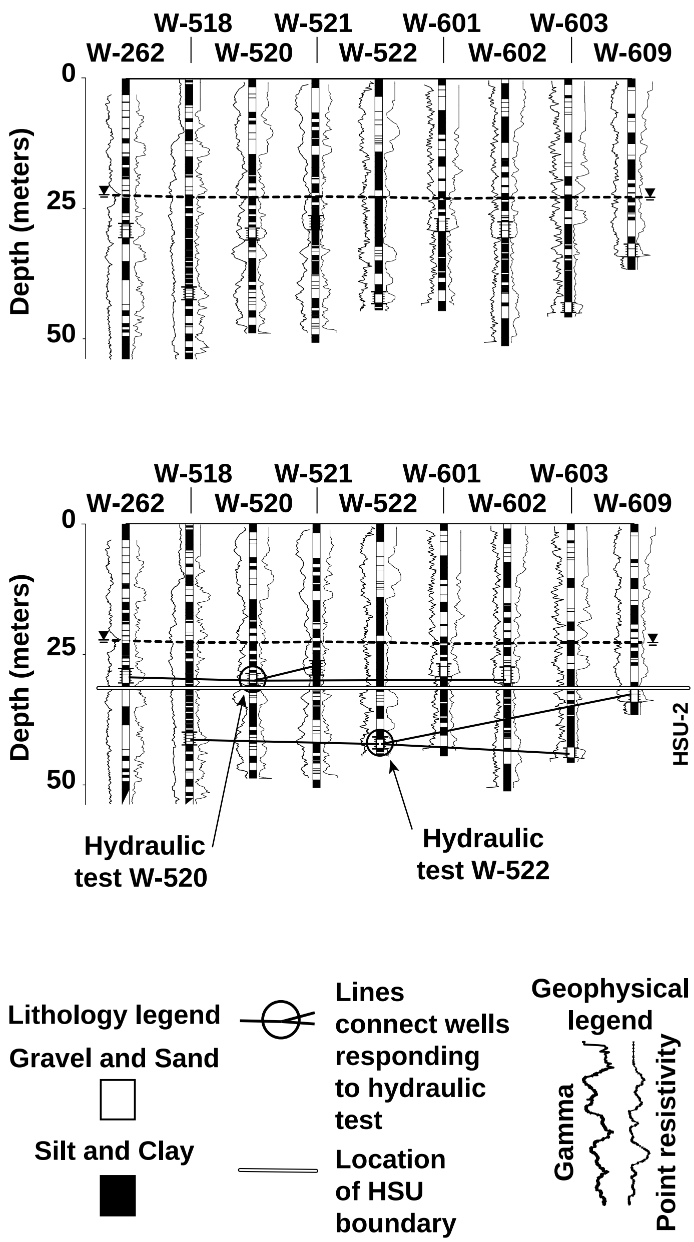
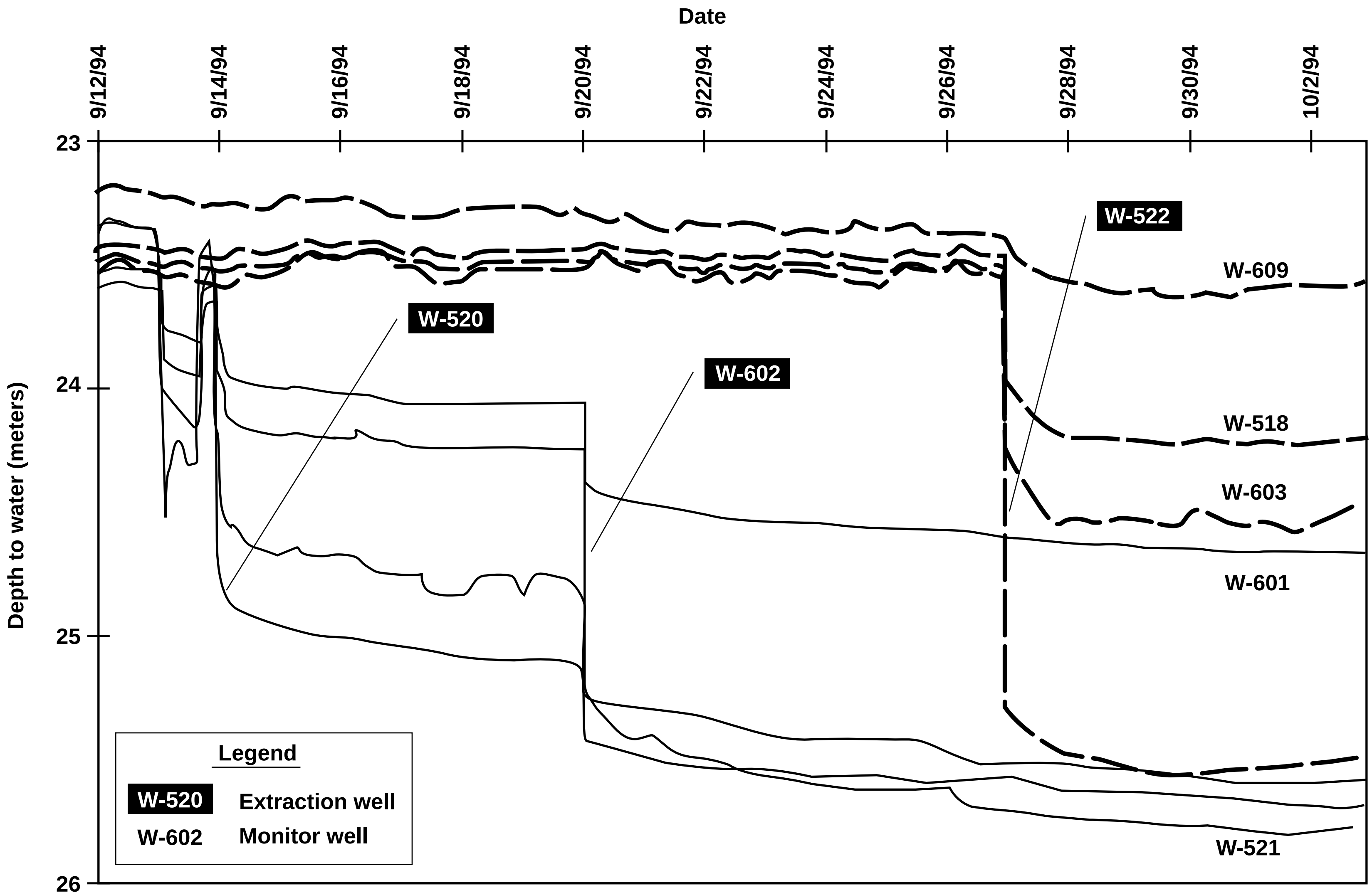
Figure 2. Cross section grid used to define HSUs at LLNL.



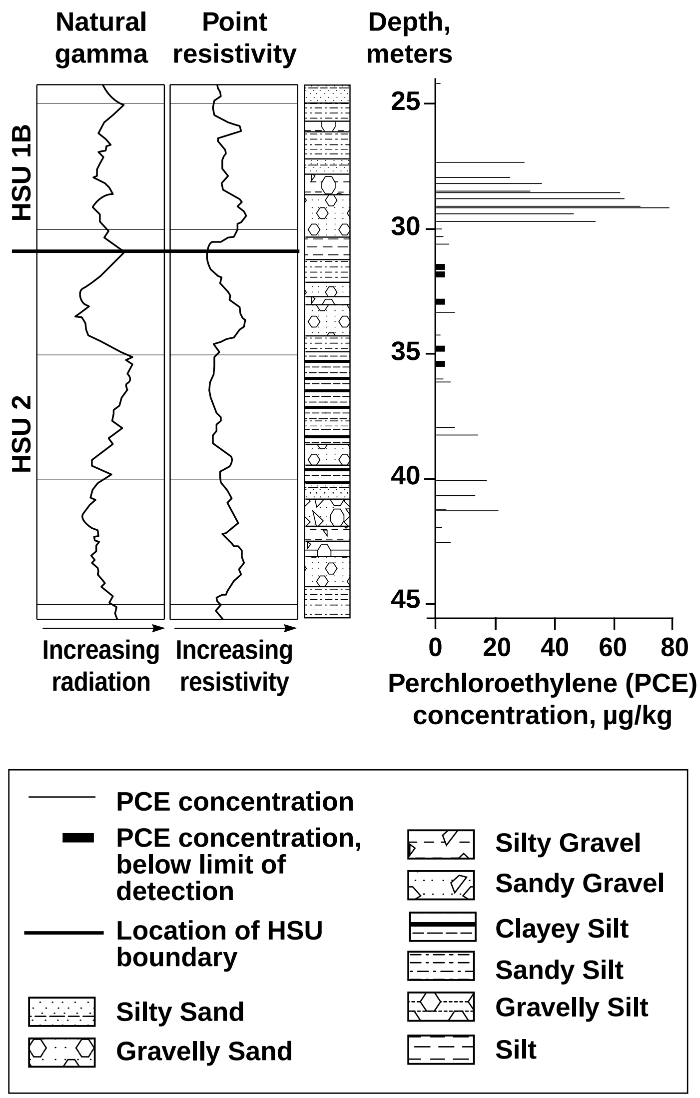
ERD-LSR-00-0106

Figure 3. TFA area well geophysical logs with and without HSU interpretations. The HSU boundary shown was identified using pumping tests (Figure 4) and confirmed using borehole soil chemistry (Figure 5).



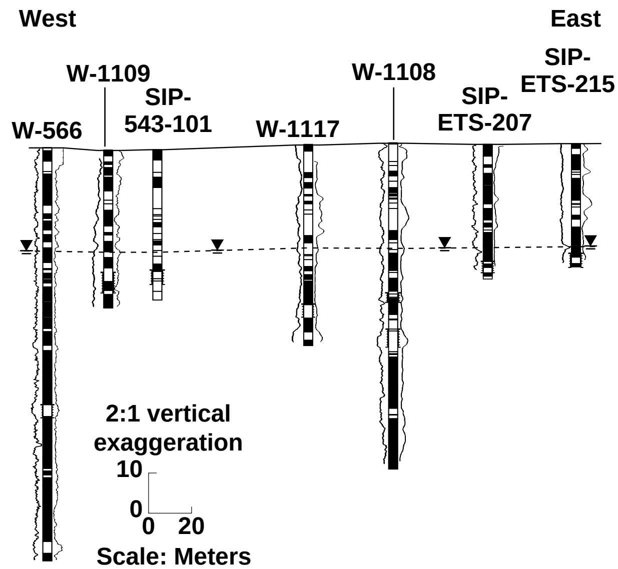
ERD-LSR-00-0107

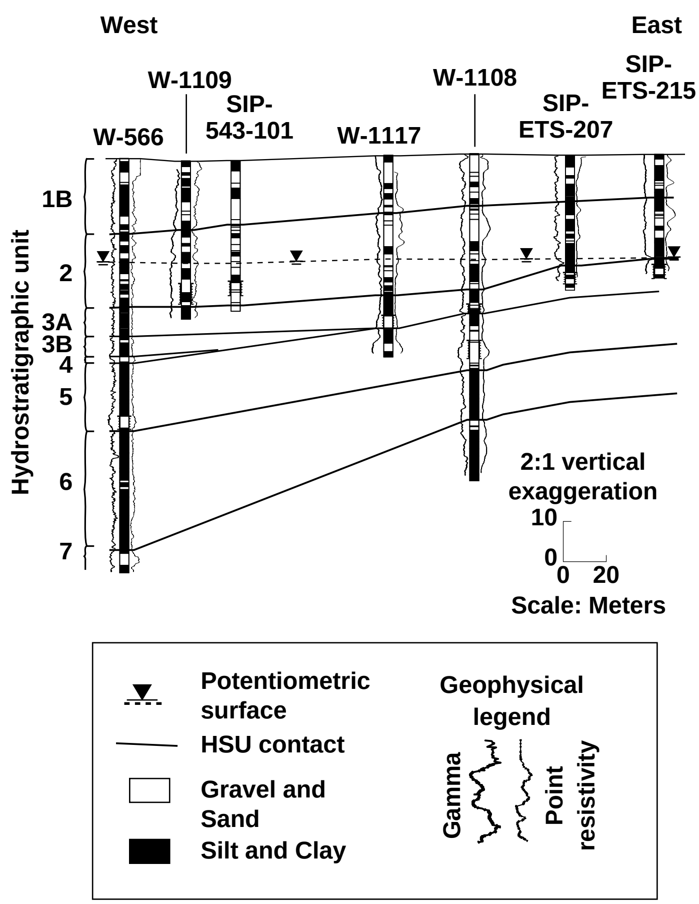
Figure 4. Hydrographs from 8 closely-spaced wells monitored during a TFA pumping test. The hydraulic response shown on the well hydrographs helped define the location of the boundary between HSU 1B and 2 in the TFA area (solid-line wells are screened in HSU 2, dashed-line wells are screened in HSU 1B).



ERD-LSR-00-0108

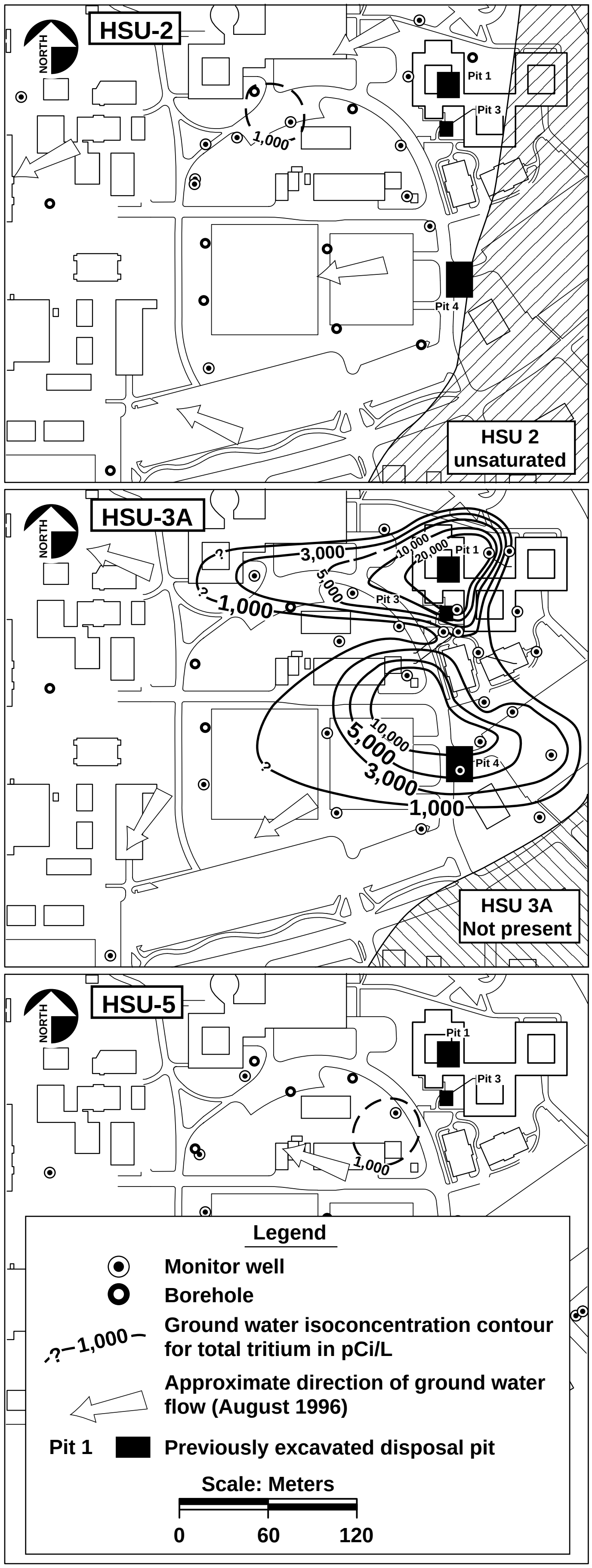
Figure 5. Saturated sediment sample results from W-520. The decrease in PCE concentrations below the 30m depth confirmed the location of the boundary between HSU 1B and 2, initially identified using TFA area pumping tests (Figure 4).





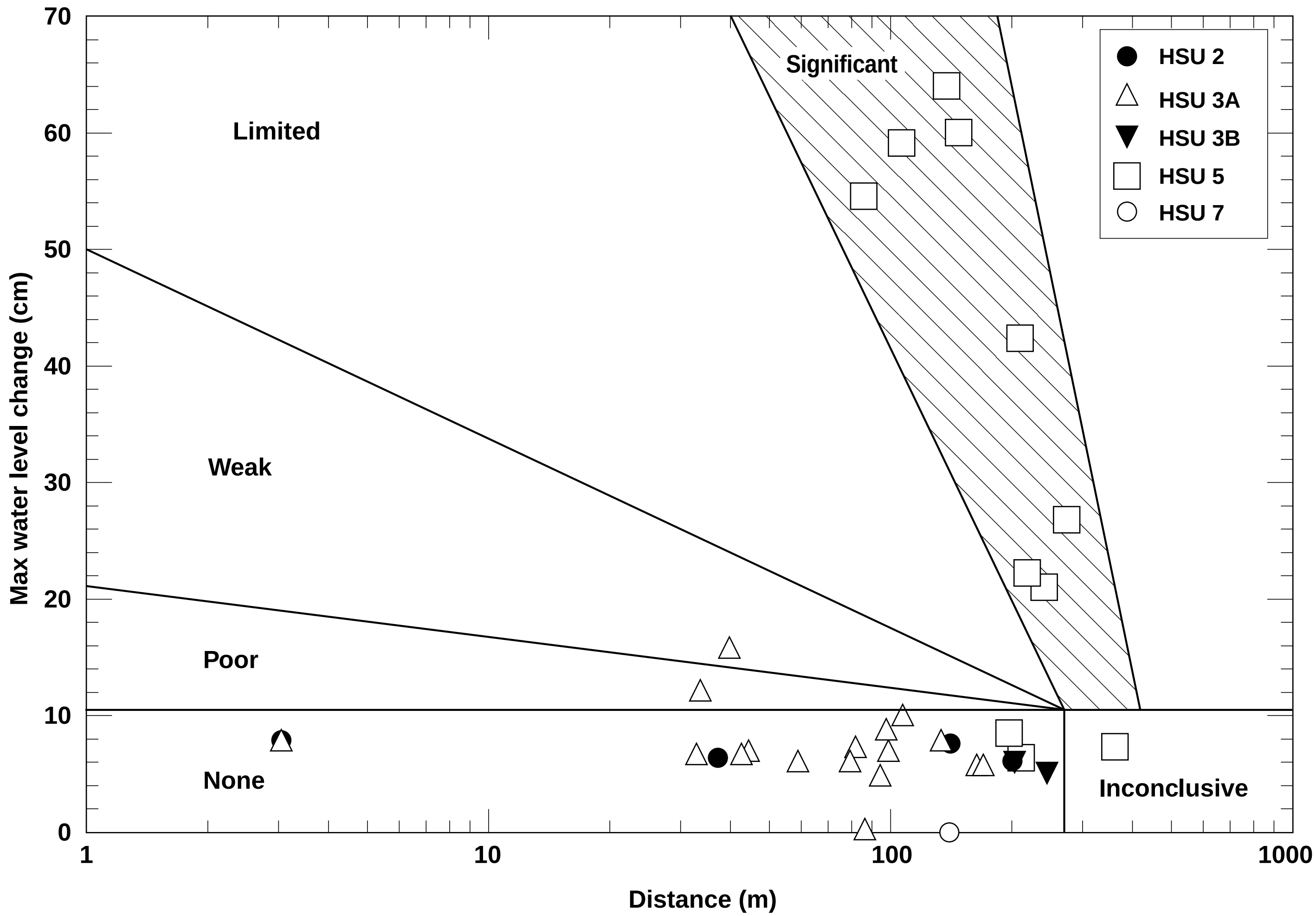
ERD-LSR-00-0109

Figure 6. East-west cross section through T5475 area with and without HSU correlations. The eastward pinchout of HSUs 3B and 4 was identified primarily using ground water data.



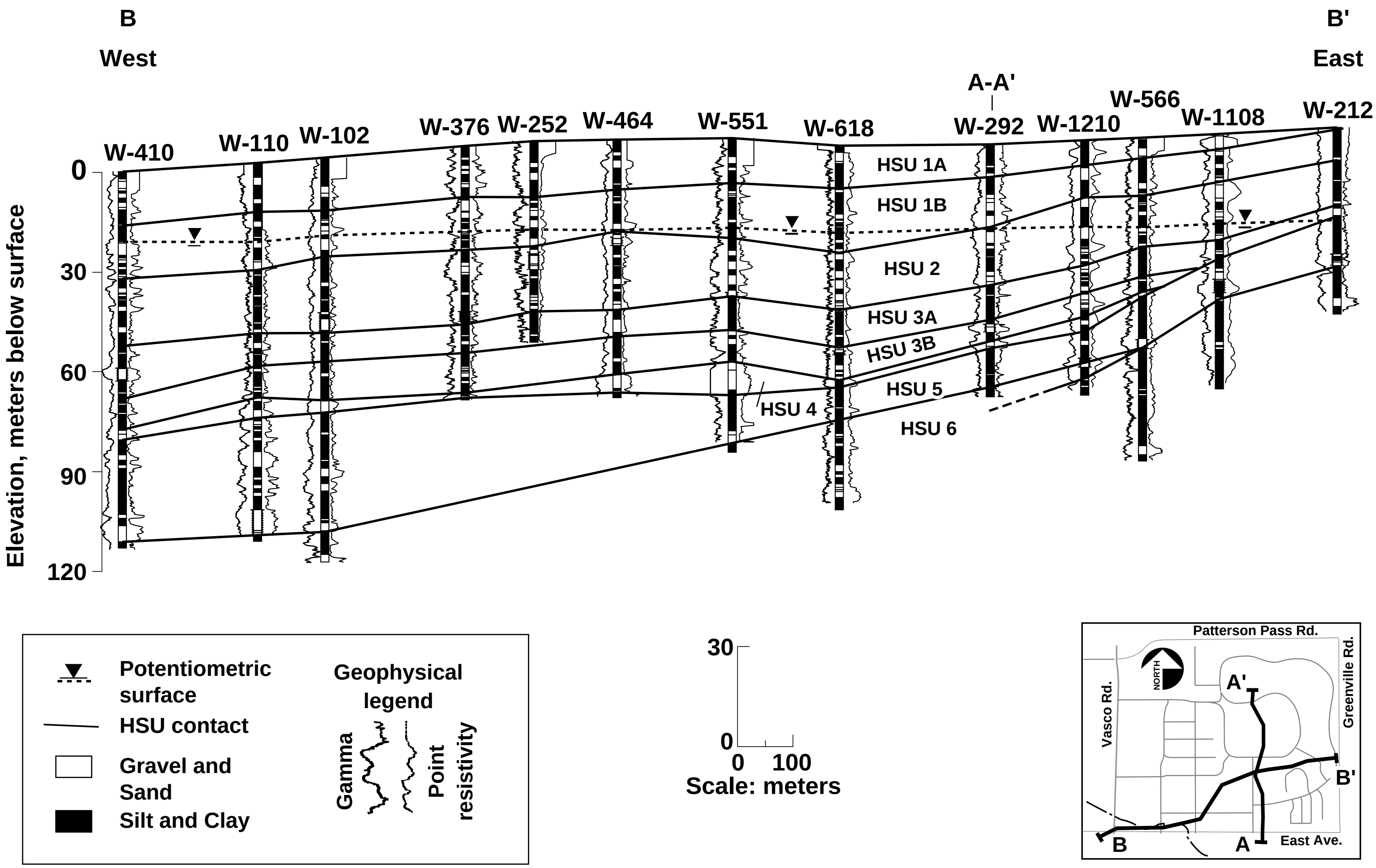
ERD-LSR-00-0110

Figure 7. Tritium activity maps for HSUs 2, 3A, and 5 showing the distinct difference in tritium activities in these three HSUs.



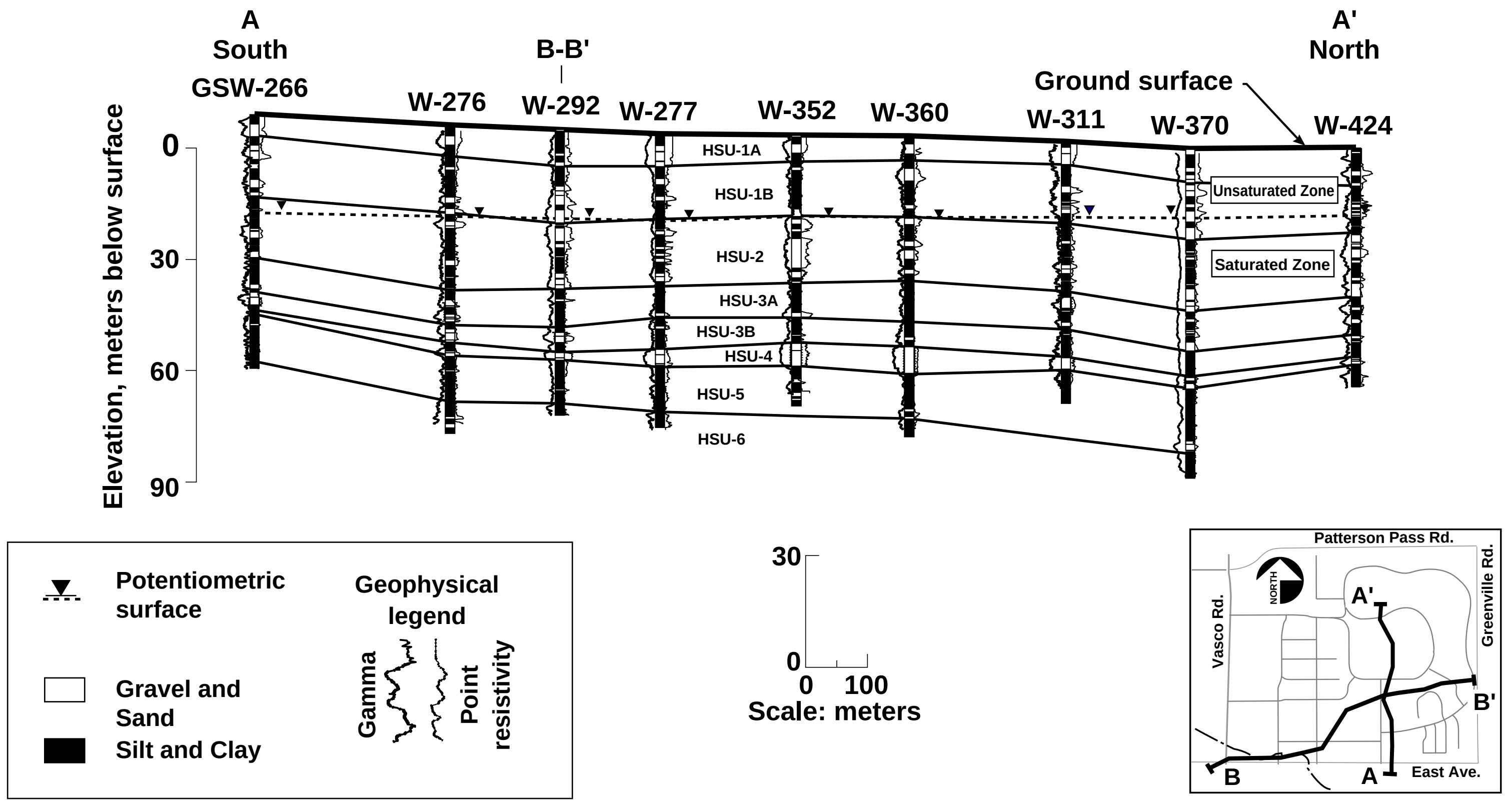
ERD-LSR-00-0111

Figure 8. Drawdown graph for well W-1108 pumping test indicating signifcant response in HSU-5 wells and little to no response in nearby wells screened in other HSUs.



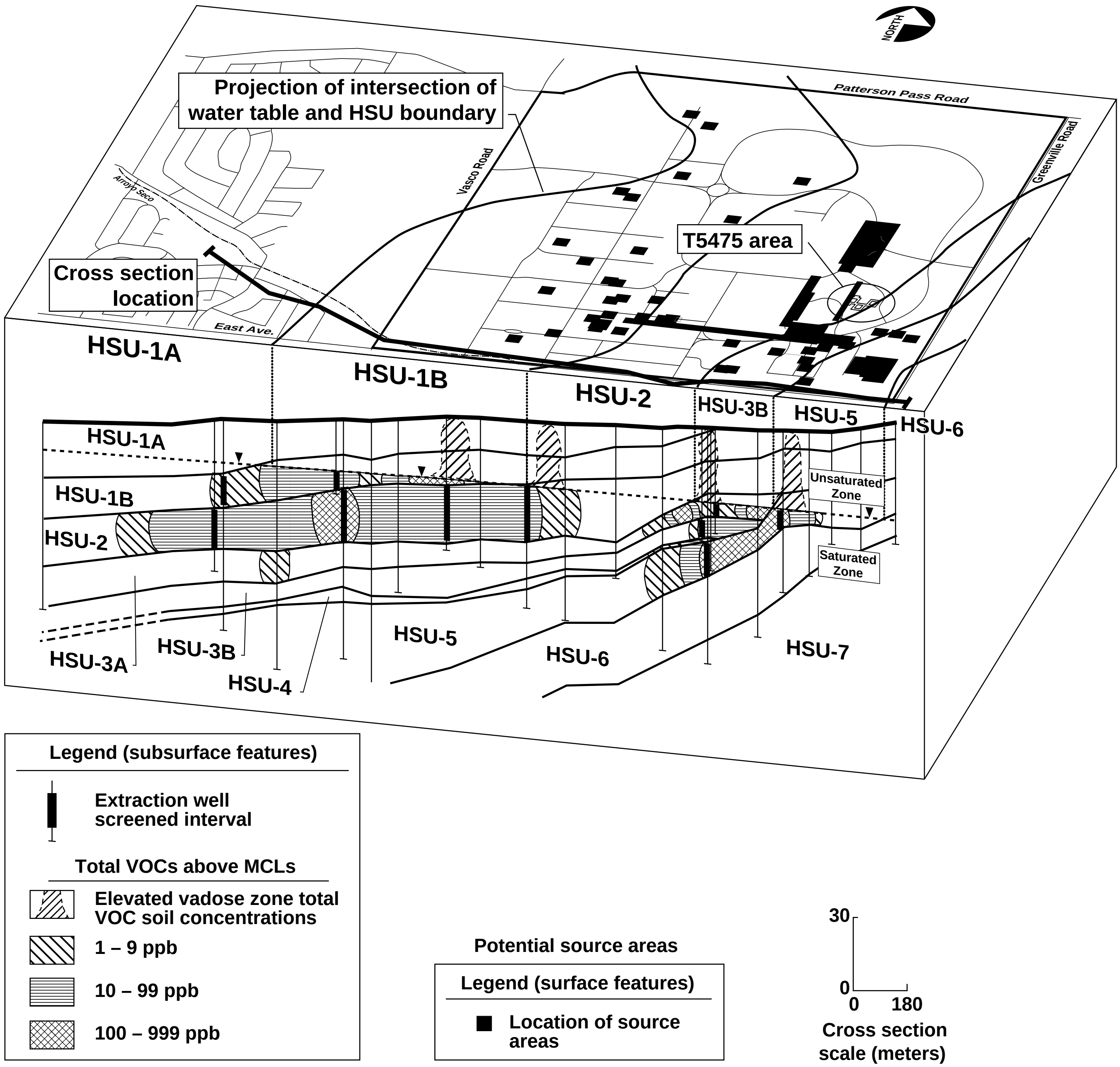
ERD-LSR-00-0112

Figure 9. East-west hydrostratigraphic cross section through southern LLNL showing borehole lithology and geophysical logs.



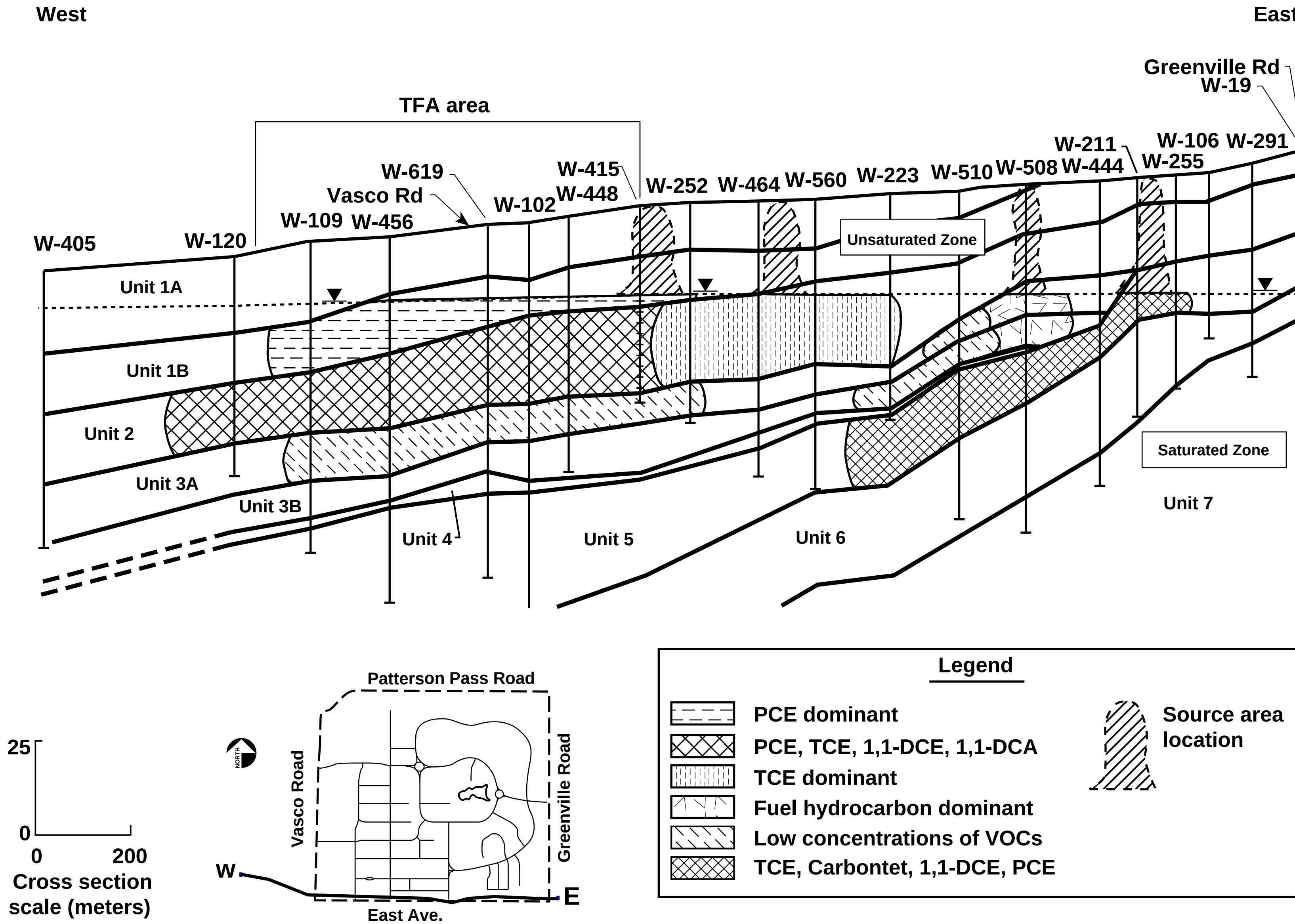
ERD-LSR-00-0113

Figure 10. North-south hydrostratigraphic cross section through central LLNL showing borehole lithology and geophysical logs.



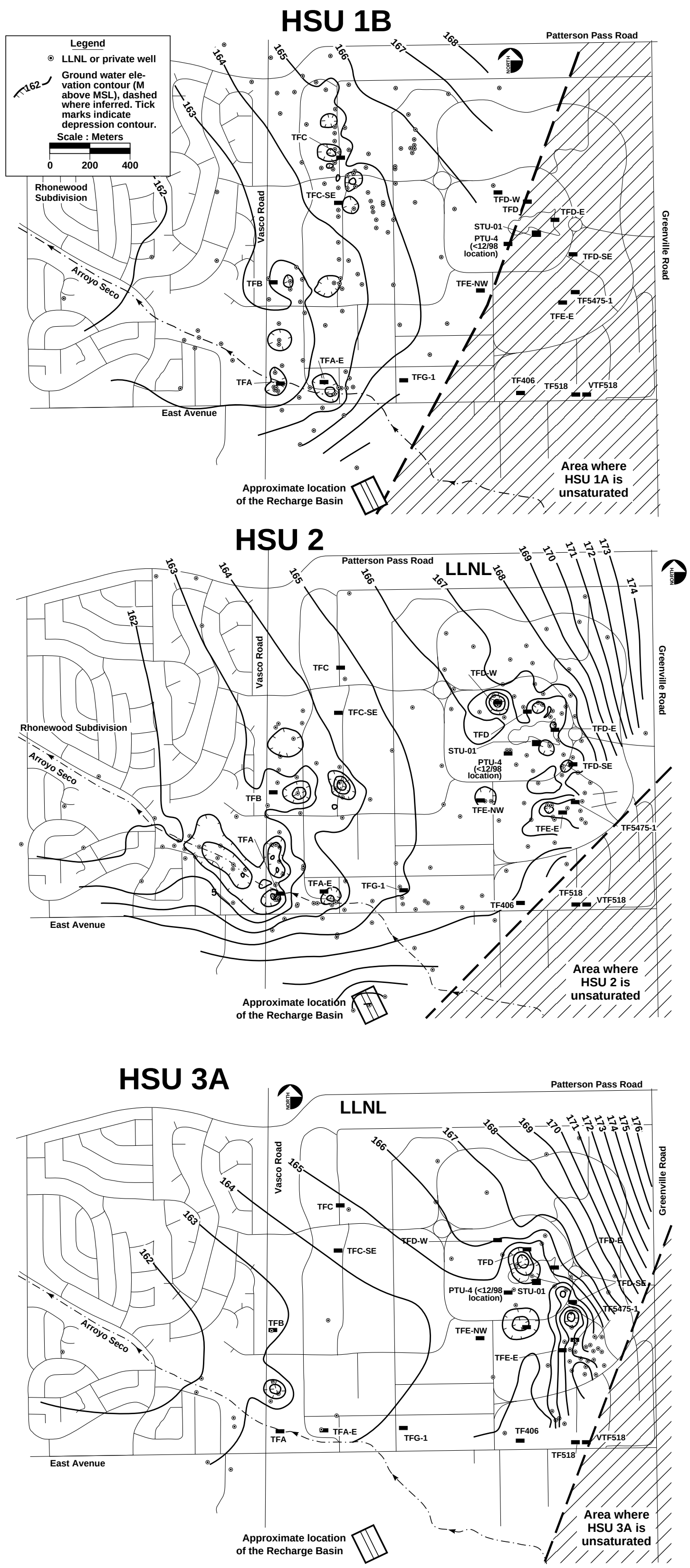
ERD-LSR-00-0114

Figure 11. Block diagram showing the relationship between source areas and VOC plumes contained within the HSUs. The LLNL ground water cleanup is being implemented using this hydrogeologic conceptual model.



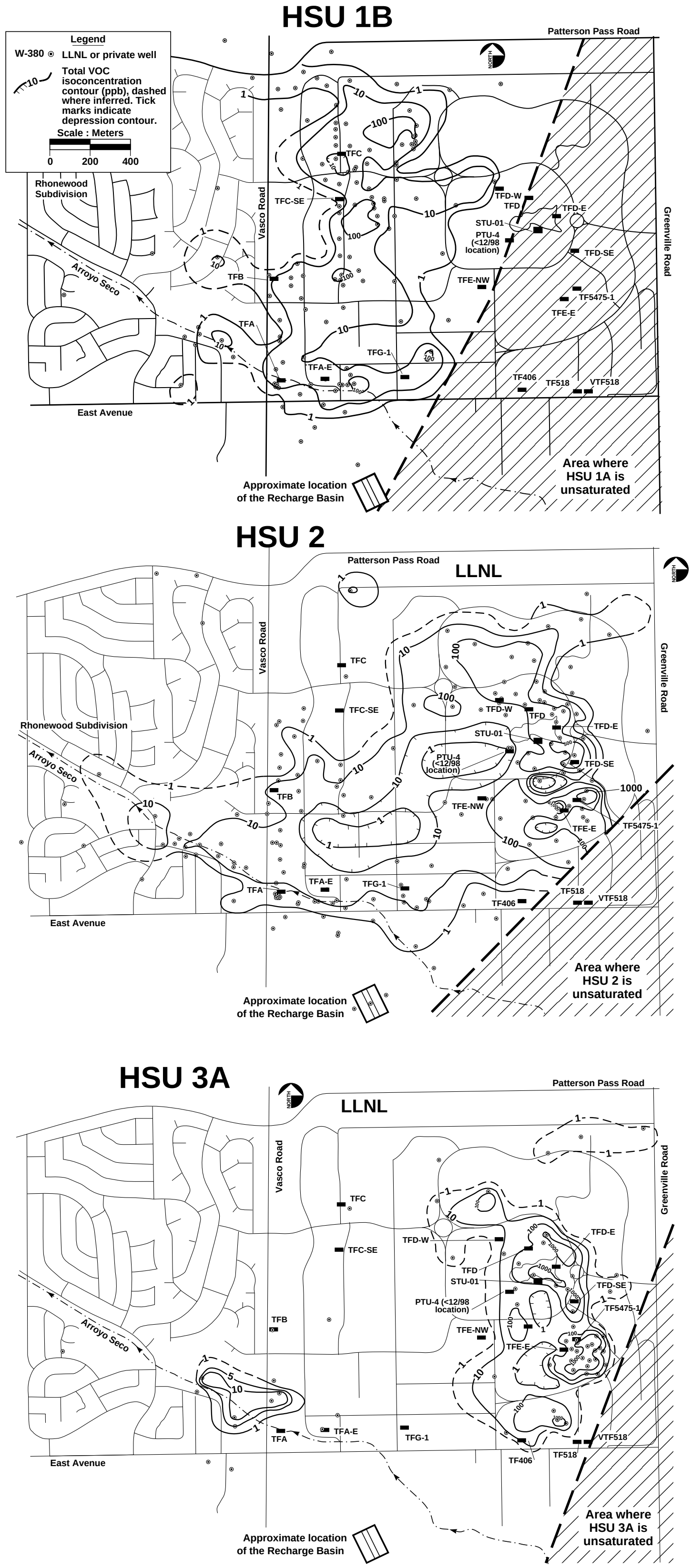
ERD-LSR-00-0115

Figure 12. LLNL site hydrostratigraphic cross section showing VOC plume signature distributions within the HSUs. The plume signature distributions were used to validate the LLNL hydrogeologic conceptual model presented on Figure 11.



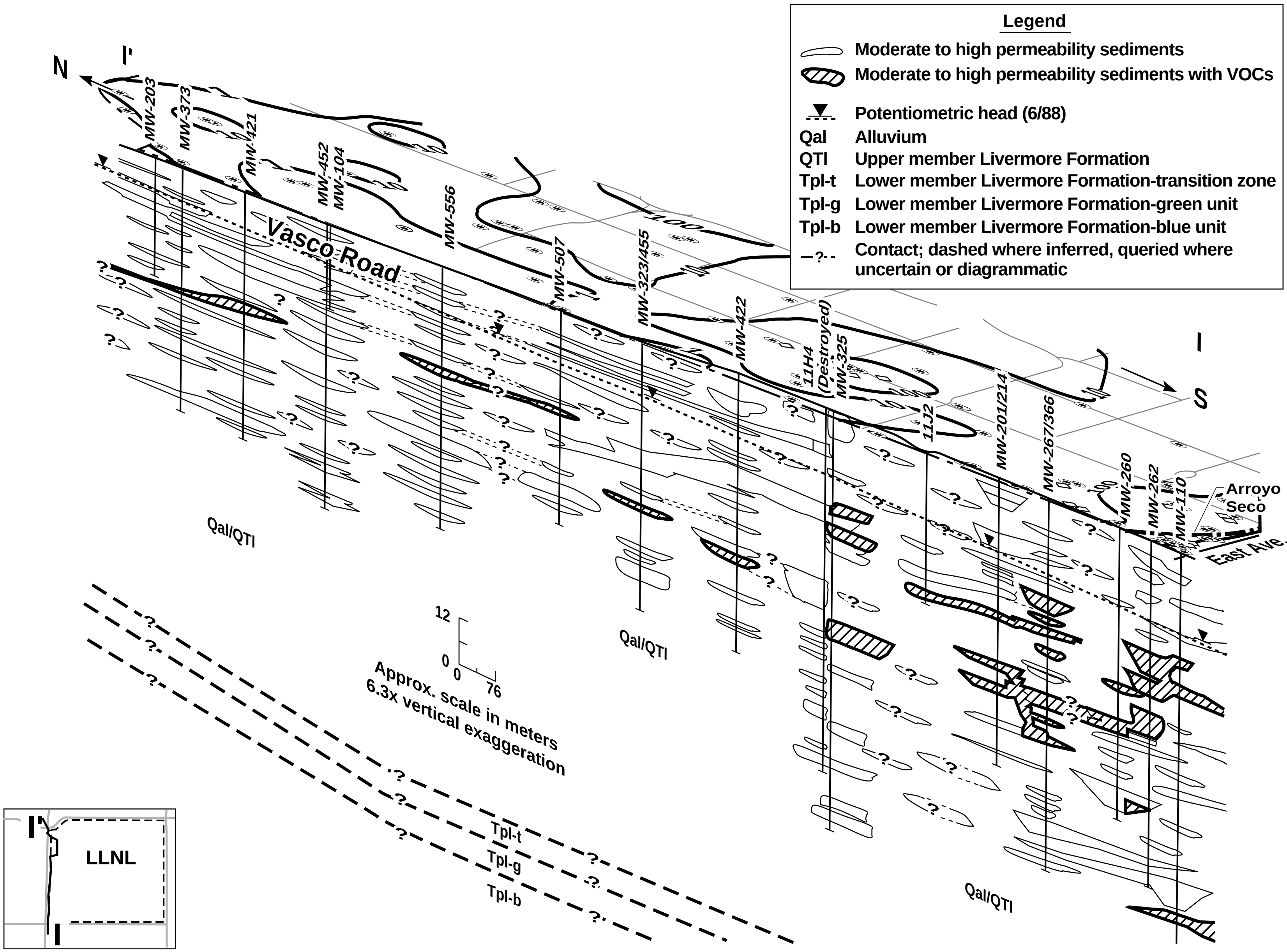
ERD-LSR-00-0116

Figure 13. Ground water elevation maps for HSUs 1B, 2, and 3A. Differences in ground water elevations between the three HSUs are particularly evident in areas of active pumping.



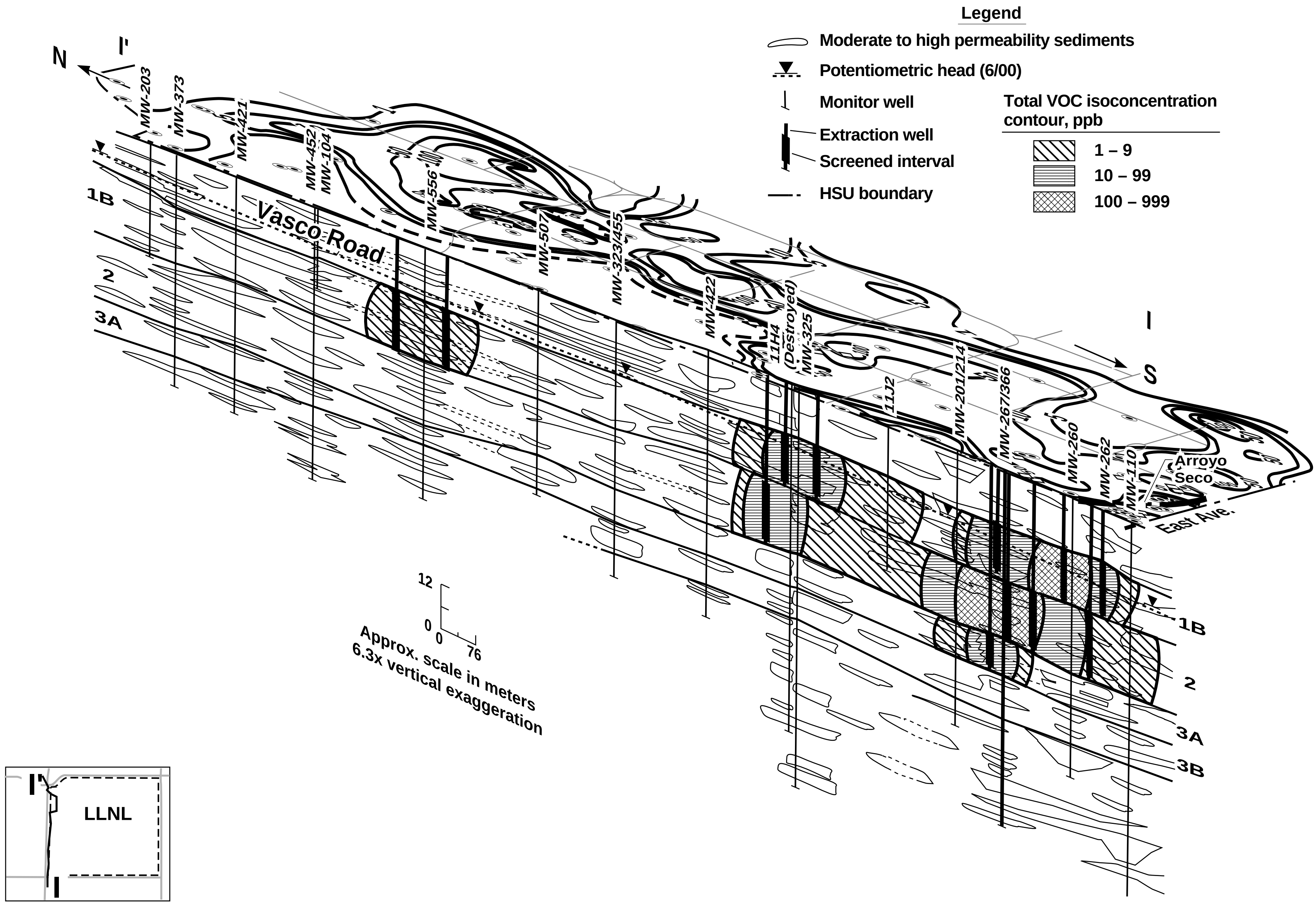
ERD-LSR-00-0117

Figure 14. Total VOC isoconcentration contour maps for HSUs 1B, 2, and 3A. Differences in VOC concentrations and distribution are evidence that VOC transport occurs primarily within HSUs rather than across HSU boundaries.



ERD-LSR-00-0118

Figure 15. Remedial investigation cross section depicting the nature and extent of contamination but not the hydraulic interconnectivity of permeable units required to implement ground water cleanup.



ERD-LSR-00-0118b

Figure 16. Current hydrostratigraphic interpretation showing the VOC plume distributions in HSUs 1B, 2, and 3A and the extraction well locations optimized with respect to mass removal and hydraulic capture.