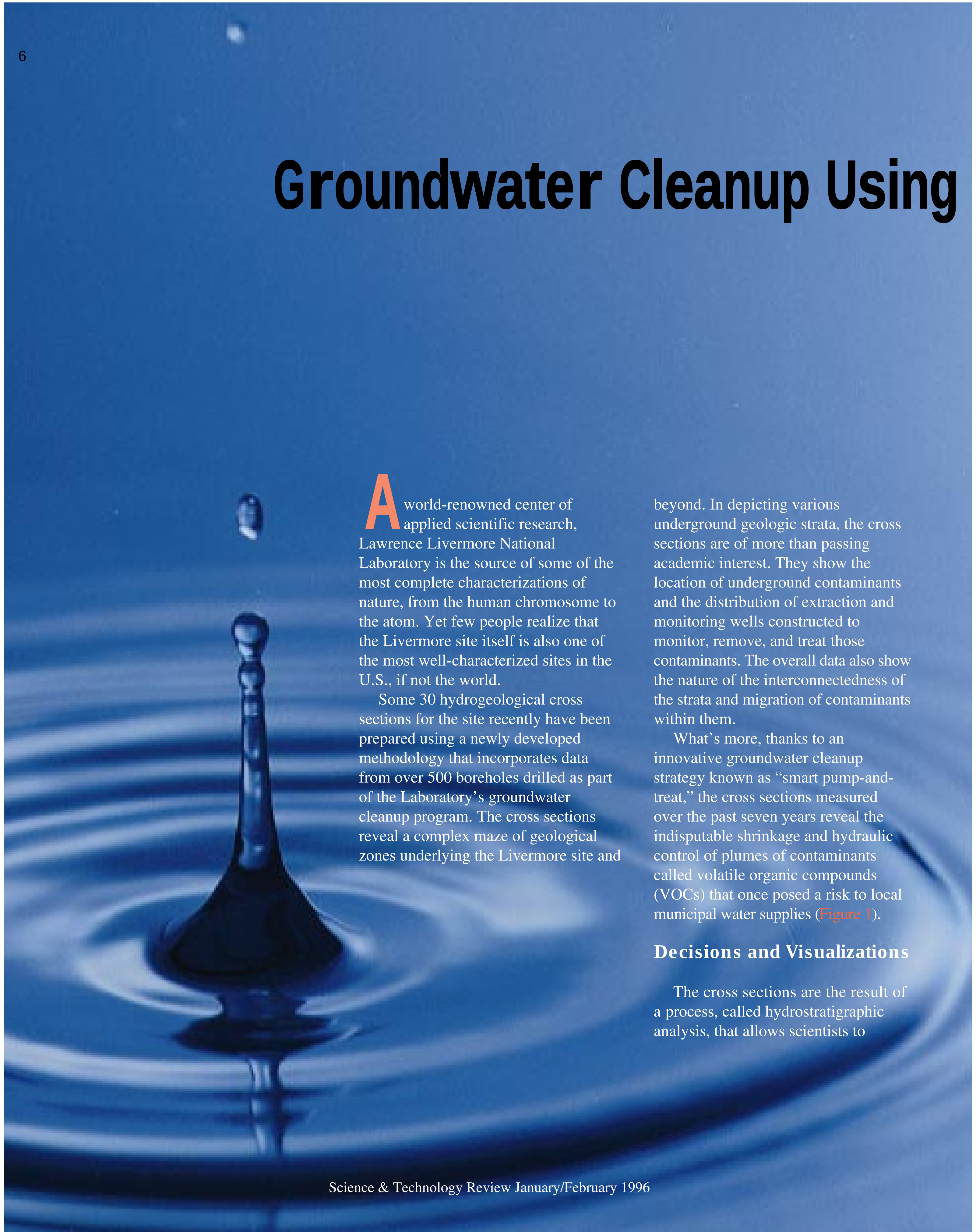
Groundwater Cleanup Using Hydrostratigraphic Analysis

Individual contaminant plumes are effectively targeted for hydraulic capture and cleanup by a Livermore team of researchers. Their use of hydrostratigraphic analysis integrates chemical, hydraulic, geologic, and geophysical data, which results in a three-dimensional conceptual model of the subsurface area.



A world-renowned center of applied scientific research, Lawrence Livermore National Laboratory is the source of some of the most complete characterizations of nature, from the human chromosome to the atom. Yet few people realize that the Livermore site itself is also one of the most well-characterized sites in the U.S., if not the world.

Some 30 hydrogeological cross sections for the site recently have been prepared using a newly developed methodology that incorporates data from over 500 boreholes drilled as part of the Laboratory's groundwater cleanup program. The cross sections reveal a complex maze of geological zones underlying the Livermore site and beyond. In depicting various underground geologic strata, the cross sections are of more than passing academic interest. They show the location of underground contaminants and the distribution of extraction and monitoring wells constructed to monitor, remove, and treat those contaminants. The overall data also show the nature of the interconnectedness of the strata and migration of contaminants within them.

What's more, thanks to an innovative groundwater cleanup strategy known as "smart pump-and-treat," the cross sections measured over the past seven years reveal the indisputable shrinkage and hydraulic control of plumes of contaminants called volatile organic compounds (VOCs) that once posed a risk to local municipal water supplies (Figure 1).

Decisions and Visualizations

The cross sections are the result of a process, called hydrostratigraphic analysis, that allows scientists to integrate chemical, hydraulic, and geologic data into a detailed, three-dimensional model of the subsurface environment.[1] As an integral part of smart pump-and-treat for the past two years, the process demonstrates that the Livermore groundwater cleanup efforts are being conducted in a comprehensive and cost-effective manner. The success of the process is drawing inquiries from federal agencies and other national laboratories eager for more information on better ways to characterize, monitor, and clean up groundwater contamination at Superfund sites across the U.S.

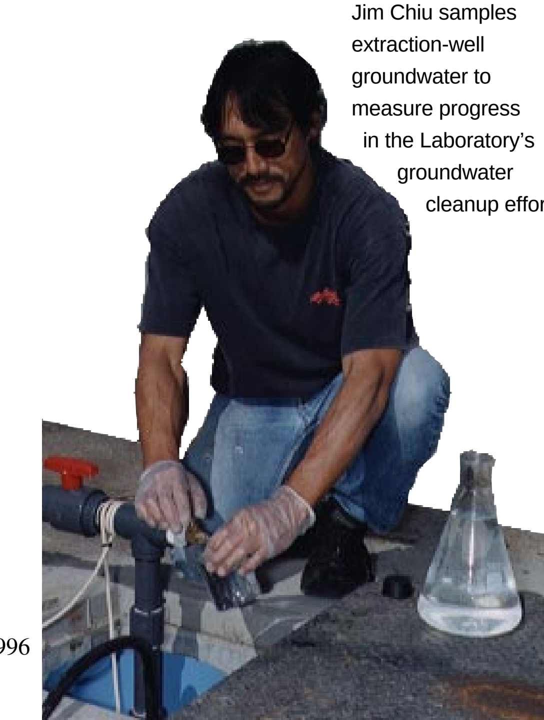
Hydrostratigraphic analysis is proving to be an effective management tool for making better-informed and more timely decisions regarding groundwater cleanup. These decisions include positioning and designing extraction and monitoring wells, prioritizing the construction and phased startup of remediation systems, managing the extraction of subsurface contaminants, finding the sources of past contaminant releases, and evaluating the effectiveness of the remediation systems.

The technique is also an effective visualization tool for presenting complex geologic and groundwater remediation issues to the Department of Energy, federal and state regulatory agencies, and the local Tri-Valley community. In addition, hydrostratigraphic analysis forms the basis of two- and three-dimensional computer simulations of groundwater contaminant transport using advanced physics codes to estimate cleanup times, costs, and design parameters. Finally, it should prove to be a valuable method to evaluate the effectiveness of innovative cleanup technologies, such as dynamic underground stripping.

Before implementing hydrostratigraphic analysis in early 1994, Laboratory environmental experts had constructed numerous maps and cross sections showing the distribution of hazardous materials known to be residing in some of the complex geological strata underlying the site[2,3] (see sidebar on p. 10). Although these maps formed a solid basis for planning the groundwater cleanup at LLNL, they could not be directly used to implement cleanup because the subsurface contaminant pathways were not shown or well understood. Hydrostratigraphic analysis is an extension of this previous hydrogeologic work performed at LLNL.[4,5] The contaminants of greatest concern are two VOCs dissolved in water some 50 to 200 feet* below the ground. They are primarily the industrial solvents perchloroethylene (PCE) and trichloroethylene (TCE).

Pump-and-Treat

Although the estimated volume of the solvents in the subsurface is only about 200 gallons, the concentrations in groundwater range up to about 10 parts per million in some areas (state and



Jim Chiu samples extraction-well groundwater to measure progress in the Laboratory's groundwater cleanup efforts.

*Hydrogeologic measurements use U.S. units rather than metric.

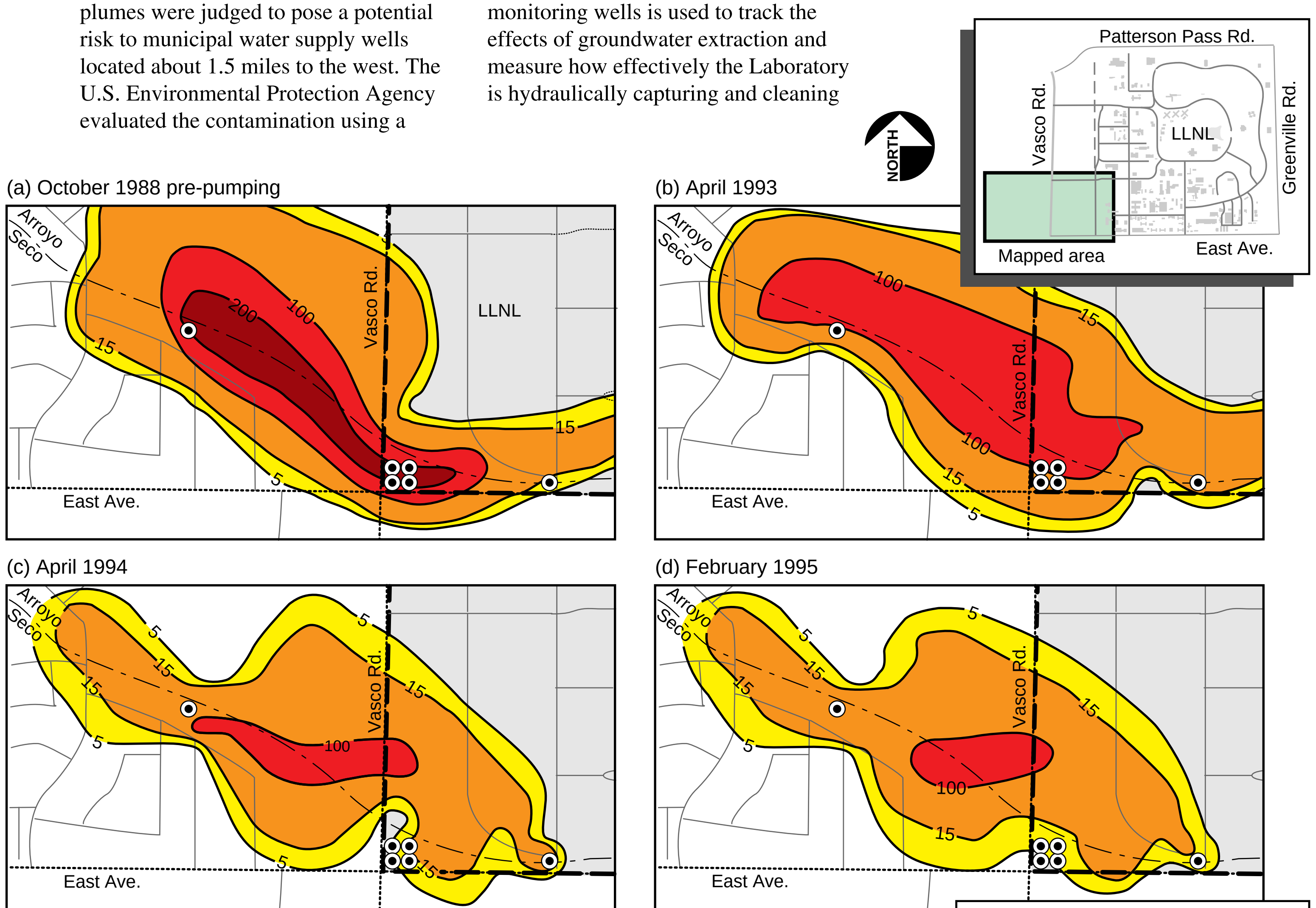
federal maximum contaminant levels for the two compounds are 5 parts per billion). All together, past discharges of these materials from a number of areas at the site have contaminated approximately 3 billion gallons of groundwater below the Laboratory and immediate vicinity covering approximately a square mile.

The VOCs formed several underground plumes below the Laboratory, some of which have traveled slowly off site underneath Vasco Road and beyond the Laboratory's western boundary. Because of estimated migration paths and flow rates, the plumes were judged to pose a potential risk to municipal water supply wells located about 1.5 miles to the west. The U.S. Environmental Protection Agency evaluated the contamination using a Hazard Ranking Scoring System and decided to list the site on the National Priorities List (Superfund). As a result, the Laboratory was charged by state and federal environmental regulatory agencies with cleaning up the contaminated groundwater and stopping the westward migration of the plumes.

The primary remediation technology in use at the Livermore site is groundwater pump-and-treat. This technique uses a network of extraction wells that pump contaminated groundwater to the surface for treatment to remove contaminants. A network of monitoring wells is used to track the effects of groundwater extraction and measure how effectively the Laboratory is hydraulically capturing and cleaning up the plumes. Minimizing the cost of groundwater cleanup using pump-and-treat technology requires a thorough understanding of the hydrogeologic factors that control the flow and transport of contaminants in the heterogeneous subsurface.[6]

Improving the Maps

"In the early years of the environmental restoration program, emphasis was placed on locating source areas and identifying strata that needed



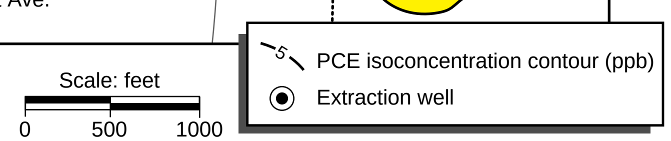


Figure 1. Concentration maps of the western edge of LLNL illustrate the decrease in PCE concentrations over six and a half years resulting from hydraulic capture and PCE mass removal at extraction well locations.

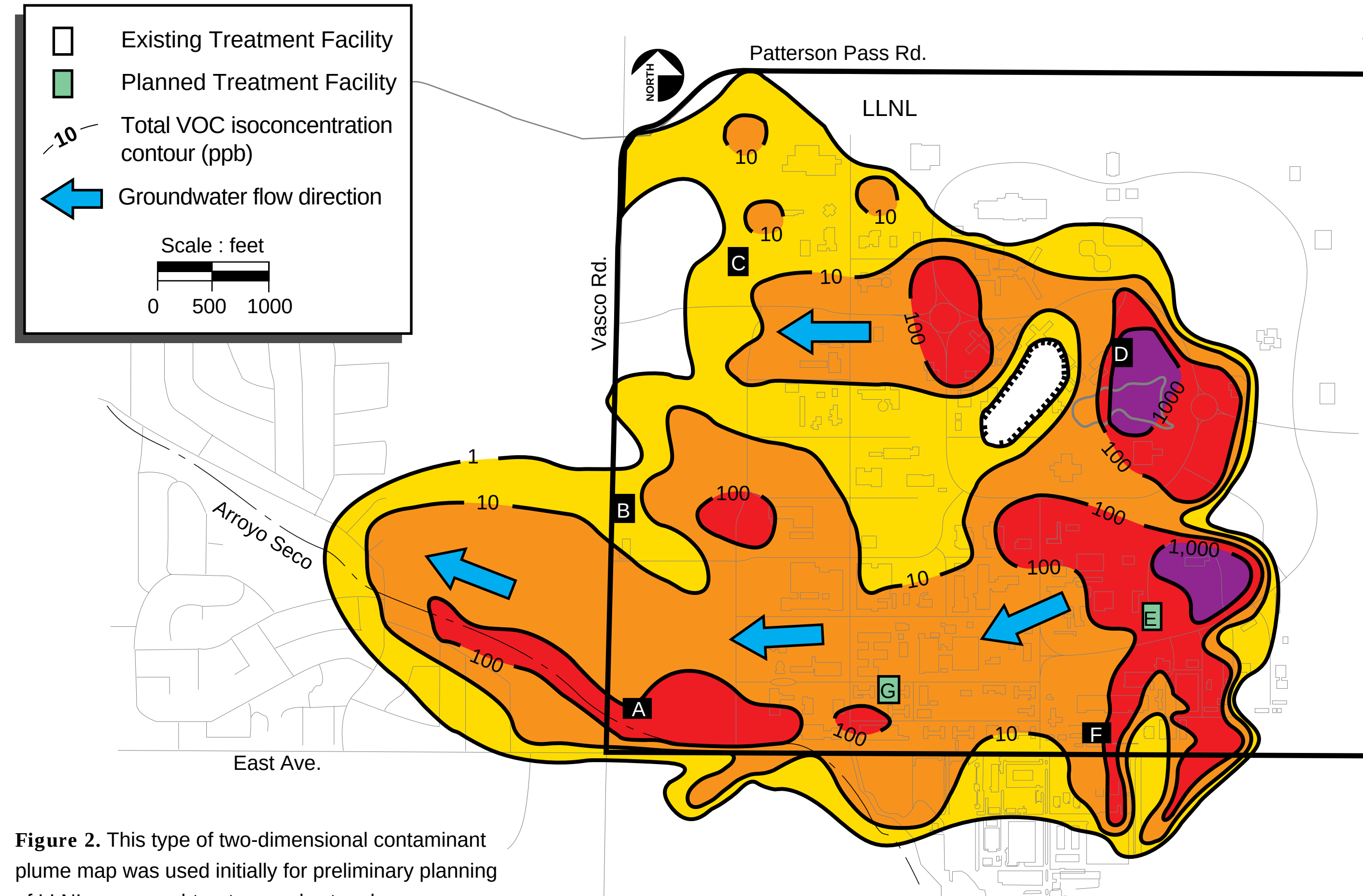


Figure 2. This type of two-dimensional contaminant plume map was used initially for preliminary planning of LLNL pump-and-treat groundwater cleanup.

to be cleaned up, not necessarily on the logistics of how to clean them up," notes LLNL hydrogeology team leader Rick Blake. "As we planned cleanup and began implementation, we realized that more needed to be understood about how the contaminated strata are interconnected. What we lacked was a site-wide road map of the subsurface, which would allow us to target specific contaminated zones and enable us to place our extraction wells at optimum locations to meet our cleanup objectives."

In the initial phases of the cleanup project, Livermore experts used two-dimensional maps and cross sections plus scientific and engineering estimates as they placed wells throughout the site and off site (Figure 2). Although these hydrogeologic cross sections showed individual permeable zones in detail (see Figure 3), "we realized that if we could group these zones into units that are hydraulically interconnected, we could simplify implementation," explained Blake.

The Livermore site and surrounding vicinity are underlain by a complex network of alluvial silts, clays, sands, and gravels that are tens to hundreds of feet thick. Known as the Upper and Lower Livermore Formations, these formations were deposited by multiple streams within the past 2 million years. The sand and gravel channels within these formations serve as migration pathways for various contaminants. Compounding this complexity, the shifting of tectonic plates underlying California has tilted the geological strata, causing groundwater and any dissolved contaminants to travel westward at a rate of about 70 feet per year.

Multidisciplinary Approach

Because of its complexity, the Livermore subsurface cannot be fully characterized using geology alone. "We knew we had to take a more multidisciplinary approach to get the job done," notes Blake.

Together with Weiss Associates hydrogeologists Michael Maley and Charles Noyes, Blake developed the hydrostratigraphic framework for the site. A geologist with 15 years of experience in the oil and gas industry, Blake was familiar with stratigraphic analysis used by oil and gas companies for decades in their search for new accumulations of petroleum and natural gas. "The key to unlocking the details of the strata underneath the Laboratory

Origins of Cleanup Efforts

Much of the groundwater contamination underlying the Livermore site originated in the early 1940s when the U.S. Navy converted some 640 acres from agricultural use into a flight-training base and aircraft assembly and repair facility. Most of the contaminant releases from this time are believed to have been solvents used to clean airplanes, their engines, and associated parts. Smaller releases of gasoline, diesel fuel, and other compounds are also known to have occurred.

From 1950 to 1954, California Research and Development Co., a subsidiary of Standard Oil, occupied the southeastern portion of the site. This marked the beginning of testing with radioactive materials at the site and probably the first releases of small amounts of tritium (a radioactive isotope of hydrogen) to the environment.

Since the Laboratory's founding in 1952, additional releases are attributed to localized spills, landfills, disposal pits, broken sewer lines and pipes, and leaking tanks. Releases of solvents were the most prevalent, although small releases of polychlorinated biphenyls (PCBs), metals, radionuclides (primarily tritium), gasoline, and pesticides also occurred.

In 1983, LLNL personnel detected VOCs (volatile organic compounds) on site and in domestic water supply wells just west of the site that were in concentrations above maximum contaminant levels (MCLs). The Laboratory immediately informed the regulatory agencies and owners of private wells nearby and provided city water hookups to affected residences. The State of California issued a regulatory order in 1984 to investigate groundwater quality underlying LLNL and off site, ultimately leading to investigation of more than 350 potential release sites.

Because the VOC concentrations exceed drinking water standards and are in groundwater within 1.5 miles of a municipal water supply, the U.S. Environmental Protection Agency placed LLNL on the National Priorities List (Superfund) in 1987 for cleanup. Other environmental problems, such as leaking underground tanks and closure of hazardous waste management facilities, are managed under this program, too. In response, the Laboratory drew up a comprehensive remedial action plan, which was reviewed by regulatory agencies, the DOE, and the public. Where MCLs vary between state and federal regulations, the Laboratory must observe the stricter level.

Pilot groundwater cleanup began in fiscal year 1989. To date, more than 200 million gallons of VOC-contaminated groundwater have been extracted, treated, and then either put into a recharge basin or reused.

The Laboratory's Environmental Restoration Division, part of the Environmental Protection Department, is the focal point for the development of restoration and waste treatment techniques needed for environmental cleanup on site and off site. For efficient soil and groundwater cleanup, program scientists and engineers have developed and are using advanced sampling, monitoring, and two- and three-dimensional modeling techniques for underground cleanup operations. Hydrostratigraphic analysis provides the necessary framework to successfully carry out this effort. This so-called "smart" approach saves time and money compared to conventional pump-and-treat groundwater cleanup programs. The Laboratory also has evaluated treatment methods for VOCs in groundwater, including ultraviolet light/hydrogen peroxide oxidation, air stripping, and solar detoxification. Steam flooding and soil heating were conducted to remediate a gasoline spill from the 1970s.

was to integrate the oil and gas industry technology with hydrogeologic approaches used in the environmental cleanup industry," he says.

Hydrostratigraphic analysis accomplishes this task by linking data on physical properties of the sediments, groundwater, and contaminants from extraction and monitoring wells. This information includes:

- Descriptions of geologic formations and their physical properties, including borehole geophysical logs, in which electrical currents and gamma radiation detectors create distinct signatures revealing the nature of subsurface rock and sediment types and their contained fluids.
- Hydraulic test data, including evaluation of the response of observation wells during aquifer pumping tests to determine the extent of hydraulic communication, or water movement, from one geologic stratum to another.
- Groundwater elevation data measured in monitoring wells for evaluating groundwater flow directions.
- VOC concentrations in soil and groundwater for mapping contaminant distributions.[7]
- Plume "signatures" based on the ratios of VOC concentrations, which can be used to trace an individual contaminant plume back to its source area.

Since 1984, these data have been collected at LLNL by staff and environmental consultants using rigorous standard operating procedures as well as quality assurance and control protocols. Strict adherence to these procedures has resulted in an enormous database of high-quality environmental data concerning the site.

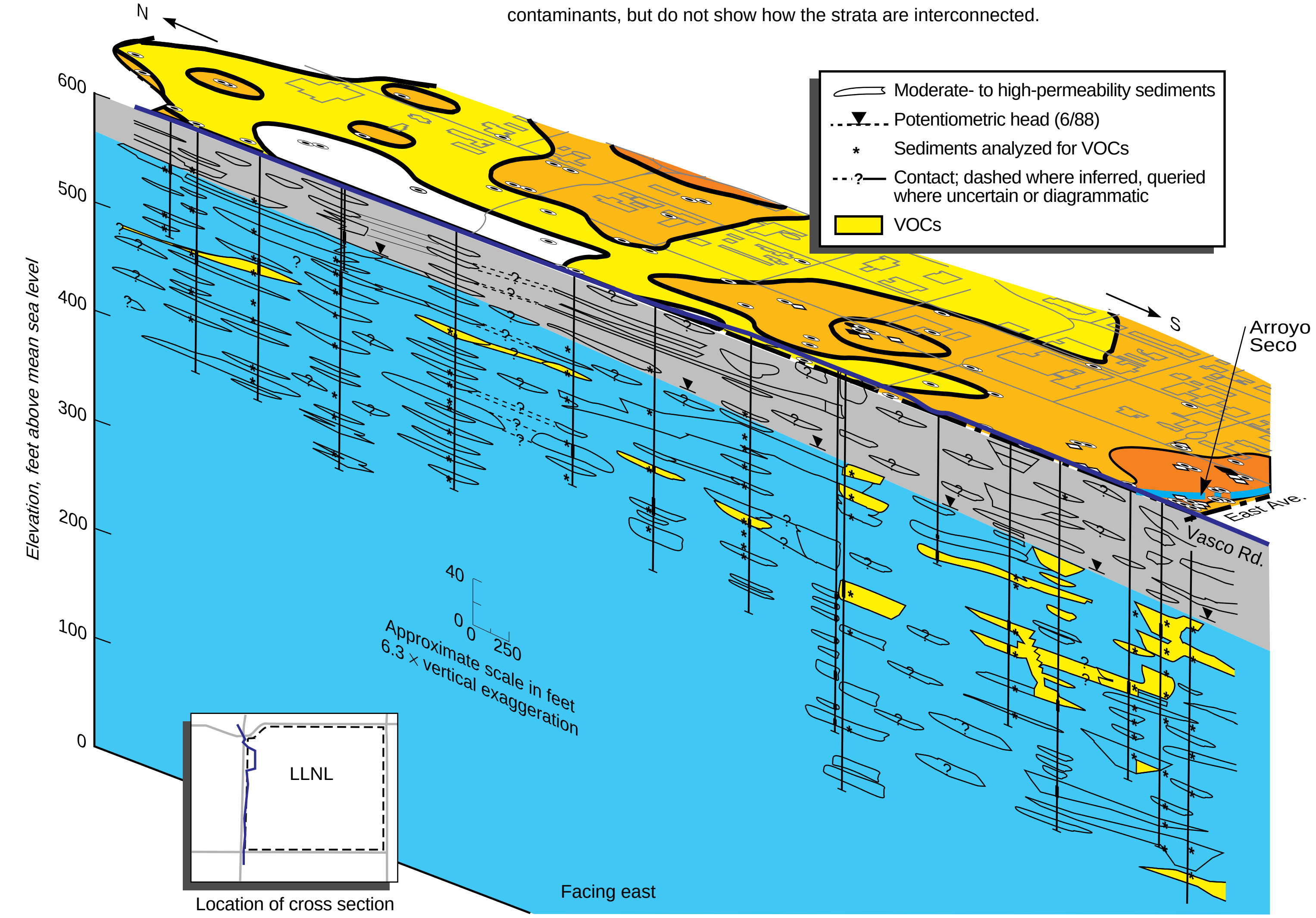
Although Livermore-developed software is used to display much of this subsurface data on maps and cross sections (Figure 3), the actual process of data integration is performed manually by the geologists and hydrogeologists. During this process, subsequent revisions of the working maps and cross sections ensure that they honor all of the independent data sets used to develop the final interpretation. "This is the most laborious and tedious part of the process, but one that is absolutely critical for developing a technically defensible, comprehensive interpretation," says Blake. "As you can imagine, with 30 interconnected cross sections, once you change interpretations on one cross section, changes cascade through most of the others, requiring many hours of careful, painstaking revisions."

Pathways Revealed

Careful analysis of hydraulic data from monitoring wells revealed that many of the underlying strata, once believed to be geologically and hydraulically separate, are actually interconnected. This interconnectedness became evident when active pumping at one well resulted in the water level being drawn down in other wells around the site. These wells, although drilled to varying depths in what appear to be separate permeable zones, as shown in Figure 4, actually tap into a single hydraulically interconnected unit.

Using data and observations such as these, Blake and coworkers found that the underlying Livermore site and neighboring area just west of the Laboratory are divided into seven layers, called hydrostratigraphic units (HSUs), each stacked on top of the other with low-permeability sediments separating one HSU from another. Figure 5 is a cross section showing VOCs above cleanup levels in each hydrostratigraphic unit. Because low-permeability boundaries limit water moving between HSUs, contaminants mostly travel within individual HSUs during their slow migration westward.

Figure 3. Hydrogeologic cross sections like this one show the detailed geology and contaminants, but do not show how the strata are interconnected.



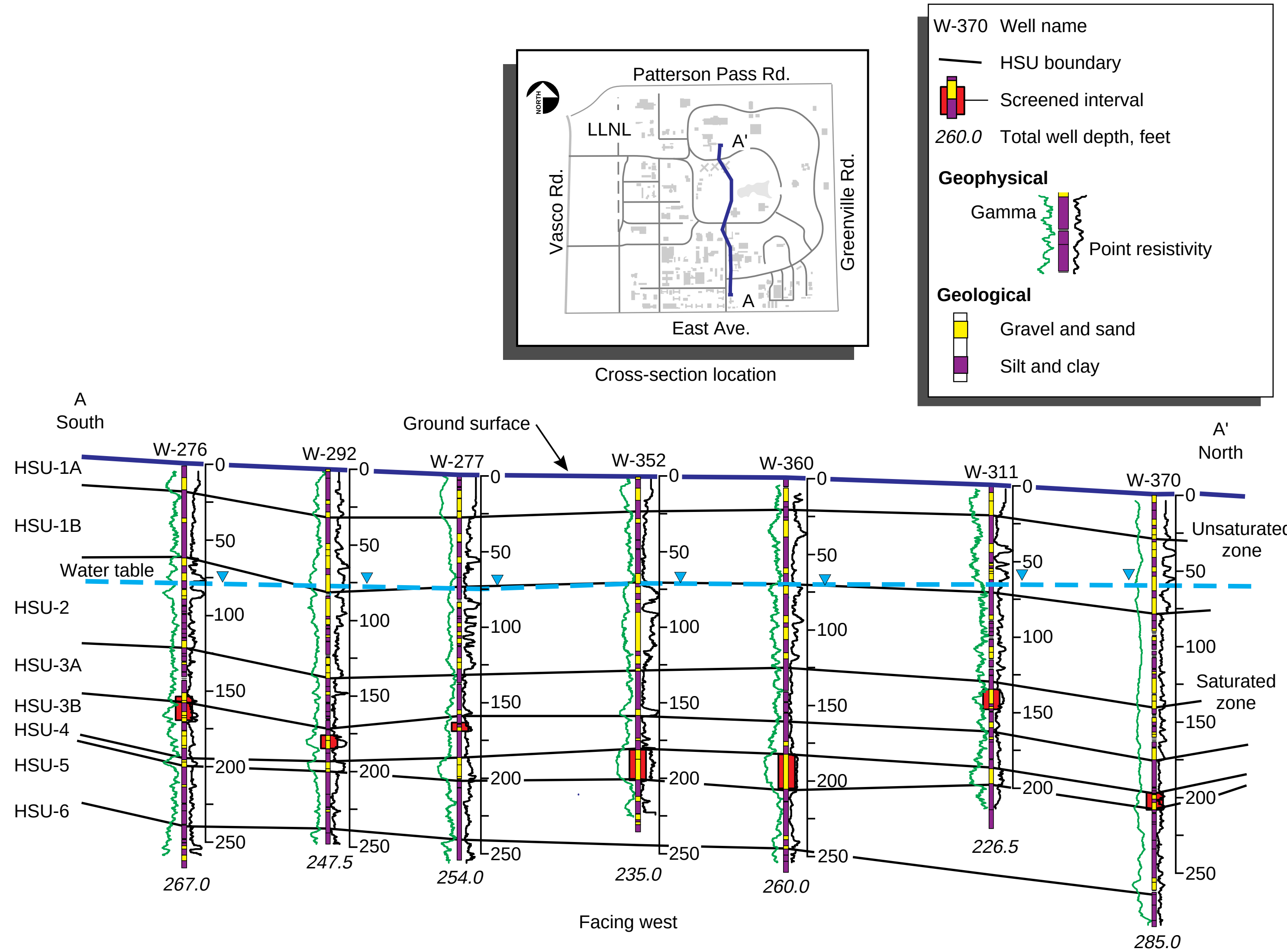


Figure 4. This hydrostratigraphic cross section shows geologic and geophysical borehole data that researchers gathered for correlating subsurface hydrogeology. Hydrostratigraphic unit (HSU) interpretations were cross checked and refined using hydraulic and chemical data.

The seven HSUs that form the hydrostratigraphic framework are the key feature of 30 cross sections the team developed to cover the site and surrounding areas. The cross sections represent a working hypothesis of the subsurface structure that continues to gain definition as more field data are gathered and analyzed.

Together the HSUs contain information on the geology of the site, the present location of contaminants and their migration pathways, the three-dimensional geometries of individual plumes, and the relationship between plumes and their sources at the surface.

These cross sections and maps are used to optimize the locations of extraction and monitor wells, to ensure adequate hydraulic control of plumes, and to maximize contaminant removal. They also show the relationship between contaminant source areas and VOC plumes within HSUs.

Controlling Migration

Figure 5 also shows that VOCs tend to migrate within the confines of individual HSUs. Transport between HSUs, however, may occur where the low-permeability sediments separating the units are indistinct or missing. Thus, it may be necessary to redefine HSU boundaries as new field data are collected. Because of the general westward dip of the geological strata, VOCs initially present near the surface are found at increasing depths from east to west within a unit. In addition, once VOCs migrate vertically downward from source areas through the vadose zone (the area above the water table) and encounter the saturated zone, their transport becomes primarily lateral and follows the groundwater flow direction within the HSU.

HSU-5, in the eastern portion of Figure 5, shows this relationship. A source near an old salvage yard in the southeastern quadrant of the site introduced VOCs into HSU-5 several decades ago. Once the VOCs migrated into the saturated zone, groundwater carried them laterally westward within HSU-5. Figure 5 shows how extraction wells have been placed to target VOCs in HSU-5 close to the source area as well as near the higher concentrations on the western edge of the plume.

Figure 6 is a north–south cross section along the western edge of the site, looking eastward. Similar to Figure 5, Figure 6 shows that VOCs originating from sources to the east in this area are found mainly in HSUs 1B and 2, with minor contamination in HSU-3A. Plumes in these three units are being remediated by extraction wells located at two treatment facilities in the Laboratory's southwest corner.

Making Steady Progress

Maps such as Figures 5 and 6 are allowing the Laboratory to minimize the number of wells needed for site cleanup and compliance monitoring, and in turn reduce expenditures for wells and pipelines. At Treatment Facility A alone, the number of extraction and monitor wells necessary for cleanup was decreased by about 20% by using hydrostratigraphic analysis. Together with accompanying pipelines and other infrastructure, that reduction translates into significant cost savings, on the order of $500,000 per treatment facility.

HSU methodology also is allowing overall cleanup to progress faster than expected because Laboratory staff now

Figure 5. The relationship is shown between source areas and VOC groundwater plumes within HSUs. Extraction wells are positioned to target individual VOC plumes.

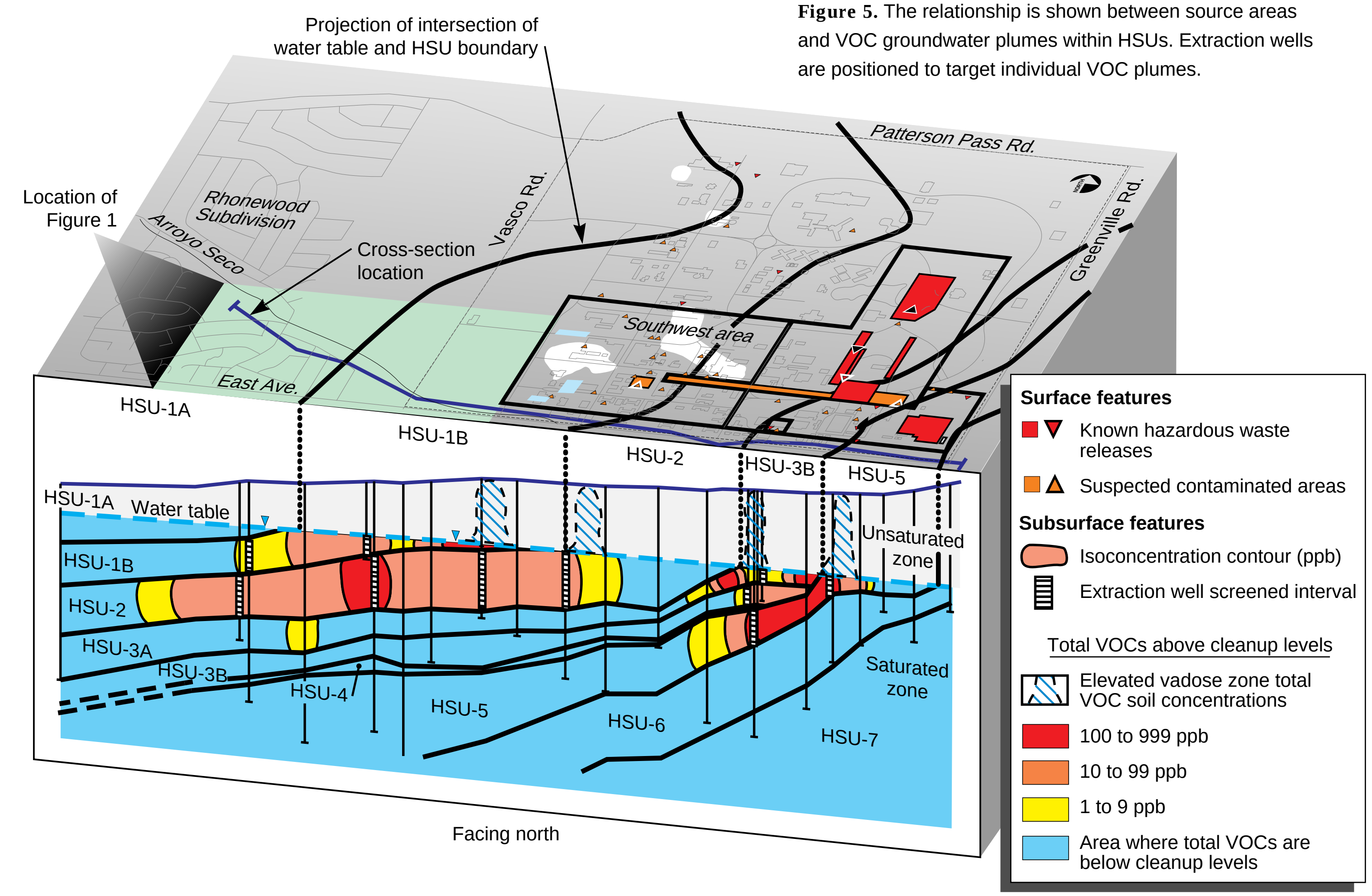
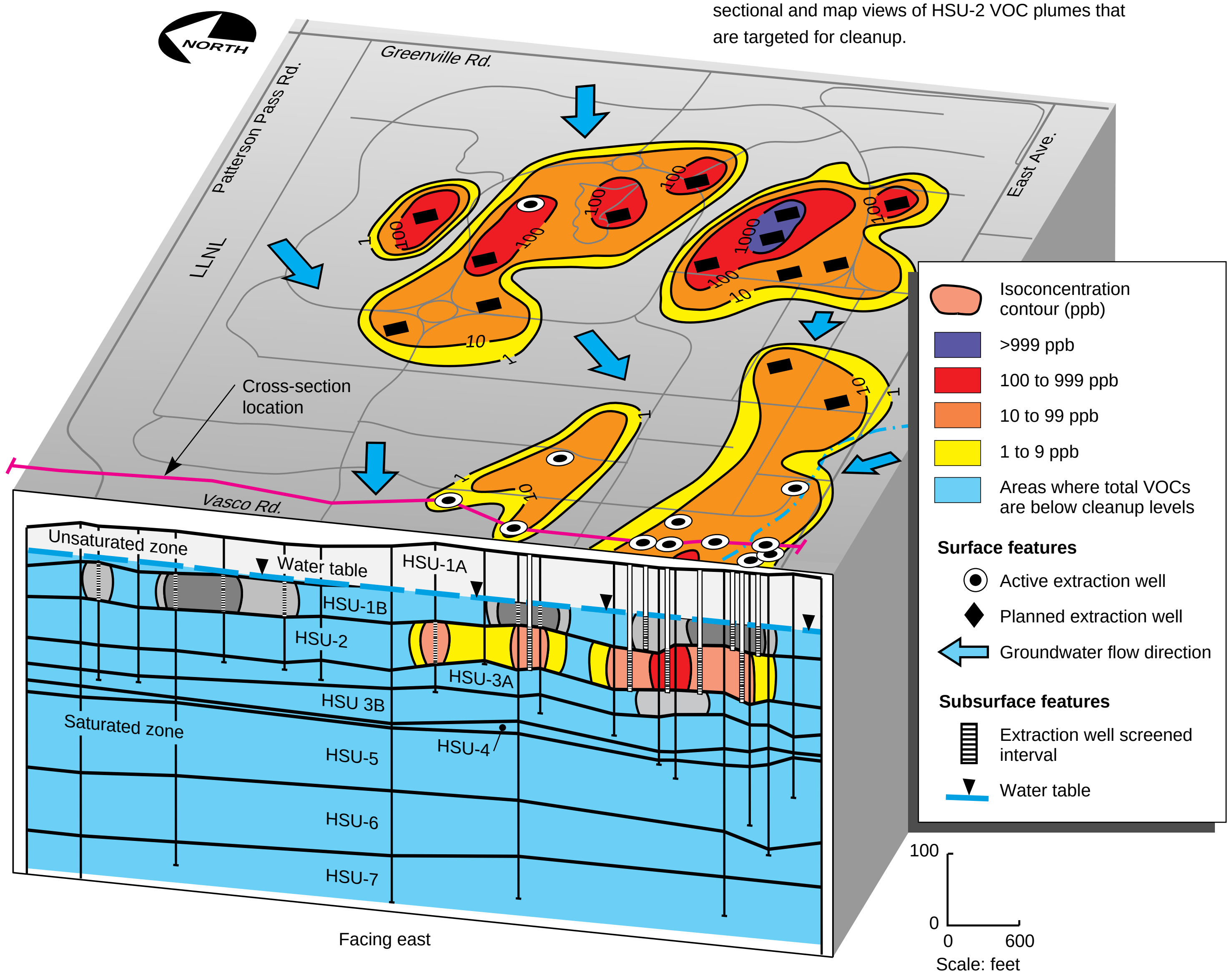


Figure 6. This block diagram shows both cross-sectional and map views of HSU-2 VOC plumes that are targeted for cleanup.



have even better information for placing the extraction wells for maximum effect. Through smart pump-and-treat, PCE concentrations in HSU-2 along the western margin of the site have been reduced from over 1,000 parts per billion to less than 100 parts per billion over the last seven years. The newly installed extraction wells and associated pipelines that were designed using the HSU methodology have accelerated the cleanup and may allow cleanup objectives to be reached in another 10 to 15 years rather than the Laboratory's original estimate of 50 years.

The steady progress of the Lab's groundwater cleanup effort can be seen back in Figure 1, the sequence of four maps covering the time period October 1988 to February 1995. Together the maps show a dramatic decrease in VOC concentrations in HSU-2, illustrating the capacity of hydrostratigraphic analysis to effectively monitor plume changes as remediation work proceeds.

The maps have proven to be an effective communication tool with the public as well as with regulators. In community and regulatory-agency meetings, researchers have used graphics depicting hydrostratigraphic analysis to clearly convey the extent of the Laboratory's commitment to clean up contaminated groundwater and to illustrate the success of the efforts to decrease VOC concentrations and thereby reduce any potential dangers to municipal water supplies.

In a time of shrinking federal budgets, a very important goal is to use hydrostratigraphic analysis to demonstrate that the Laboratory's groundwater cleanup efforts are being conducted in the best, most cost-effective manner possible. Stresses Blake, "Our ultimate goals are to accelerate the VOC plume cleanup process, demonstrate that the plumes no longer pose an environmental threat, and be the first federal environmental site in the U.S. to be removed from the Superfund list."

Key Words: hydrostratigraphic analysis, groundwater, groundwater restoration and remediation, hydrostratigraphic unit (HSU), pump-and-treat.

References

1. R. G. Blake, M. P. Maley, and C. M. Noyes, *Hydrostratigraphic Analysis: The Key to Cost-Effective Ground Water Cleanup at LLNL,* LLNL, Livermore, CA, UCRL-JC-120614 (1995).
2. W. F. Isherwood, C. H. Hall, and M. D. Dresen (Eds.), *CERCLA Feasibility Study for the LLNL Livermore Site,* LLNL, Livermore, CA, UCRL-AR-104040 (1990).
3. R. K. Thorpe, W. F. Isherwood, M. D. Dresen, and C. P. Webster-Scholten (Eds.), *CERCLA Remedial Investigations Report for the LLNL Livermore Site,* LLNL, Livermore, CA, UCAR-10299 (1990).
4. M. D. Dresen, J. P. Ziagos, A. J. Boegel, and E. M. Nichols (Eds.), *Remedial Action Implementation Plan for the LLNL Livermore Site,* LLNL, Livermore, CA, UCRL-AR-110532 (1993).
5. U.S. Department of Energy, *Record of Decision for the Lawrence Livermore National Laboratory, Livermore Site,* LLNL, Livermore, CA, UCRL-AR-109105 (1992).
6. F. Hoffman, "Ground-Water Remediation Using 'Smart Pump and Treat,'" *Ground Water* **31** (1), pp. 98–106 (1993).
7. F. Hoffman and M. D. Dresen, "A Method to Evaluate the Vertical Distribution of VOCs in Ground Water in a Single Borehole," *Ground Water Monitoring Review* **10** (2) (1990).

For further information contact Richard G. Blake (510) 422-9910 (blake2@llnl.gov); or Charles Noyes or Michael Maley (510) 422-8820.

About the Scientist

RICHARD G. BLAKE joined the Laboratory in 1992 as an environmental scientist/hydrogeologist. He graduated with a B.S. (1977) and an M.S. (1983) in geology from California State University, Los Angeles. He is currently the Hydrogeology Team Leader in the Environmental Restoration Division of the Environmental Protection Department. Blake also spent twelve years in the California oil and gas exploration industry: seven years for PG&E's subsidiary Natural Gas Corporation of California, and five years as Fleet Oil Co.'s vice president. His publications include papers about California oil and gas exploration, stratigraphy and sedimentation, engineering geology and geologic hazards, hydrogeology, and environmental restoration.