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# The efficacy of soil vapor extraction in remediation of a gasoline spill

George Edward Cook  
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**THE EFFICACY OF SOIL VAPOR EXTRACTION  
IN REMEDIATION OF A GASOLINE SPILL**

**A Thesis**

**Presented to**

**The Faculty of the Department of Geology  
San Jose State University**

**In Partial Fulfillment**

**of the Requirements for the Degree  
Master of Science**

**by**

**George Edward Cook II**

**December, 1996**

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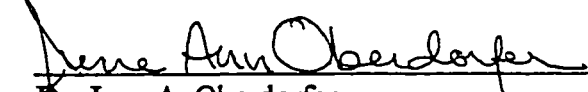
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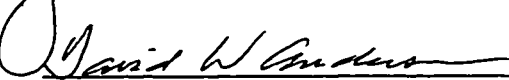
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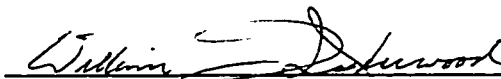
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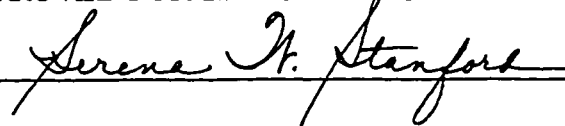
  
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THE EFFICACY OF SOIL VAPOR EXTRACTION  
IN REMEDIATION OF A GASOLINE SPILL

by George Edward Cook II

The study, performed at Lawrence Livermore National Laboratory in Livermore, California, assessed the physical characteristics of geologic materials, the soil and vapor contaminant distribution, and the efficacy of soil vapor extraction (SVE) in removing gasoline compounds from the subsurface to depths of approximately 100 feet. The study included installation of three, multi-level vadose-zone monitoring devices adjacent to the SVE well and a series of SVE tests monitoring pressure and vapor contaminant response.

Results indicate that SVE effectively removes gasoline compounds in sediments unaffected by the presence of free product. The air flow pattern in this study was spherical in shape as opposed to the cylindrical flow typically assumed by SVE models. The distribution of vapor contaminants reflects the distribution of residual soil contaminants during and immediately following extraction. After a period of no extraction, diffusion of contaminants causes the vapor distribution to become more uniform.



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## INTRODUCTION

At Lawrence Livermore National Laboratory (Fig. 1), a leaking underground storage tank released an estimated 17,000 gallons of gasoline to the subsurface. The gasoline has migrated through more than 100 feet of sediment and has impacted groundwater. A Soil Vapor Extraction (SVE) system was installed to remediate the vadose zone.

SVE commonly is used to remediate vadose-zone soils at sites contaminated by volatile organic compounds (VOCs; Johnson *et al.*, 1990). The most common usage is at gasoline stations with leaking underground storage tanks. Many laboratory and bench scale tests have shown SVE to be both efficient and cost-effective. There have been very few large scale field tests of SVE, particularly in heterogeneous areas (Johnson *et al.*, 1990). This investigation constitutes such a field test.

This study was conducted between October 1990 and October 1991. The vadose-zone monitoring system was installed during the first five months of the study. This portion of the study included soil sampling to assess the contaminant distribution following the initial 179 days of SVE operation, installation of three vadose-zone monitoring devices, and refining the test methodology. A series of SVE tests was conducted during the following five months. The vadose zone was monitored to observe recovery of the subsurface to equilibrium conditions during the final two months. The vadose-zone monitoring system also allows future monitoring of the vadose zone contamination in the vicinity of the gasoline spill.

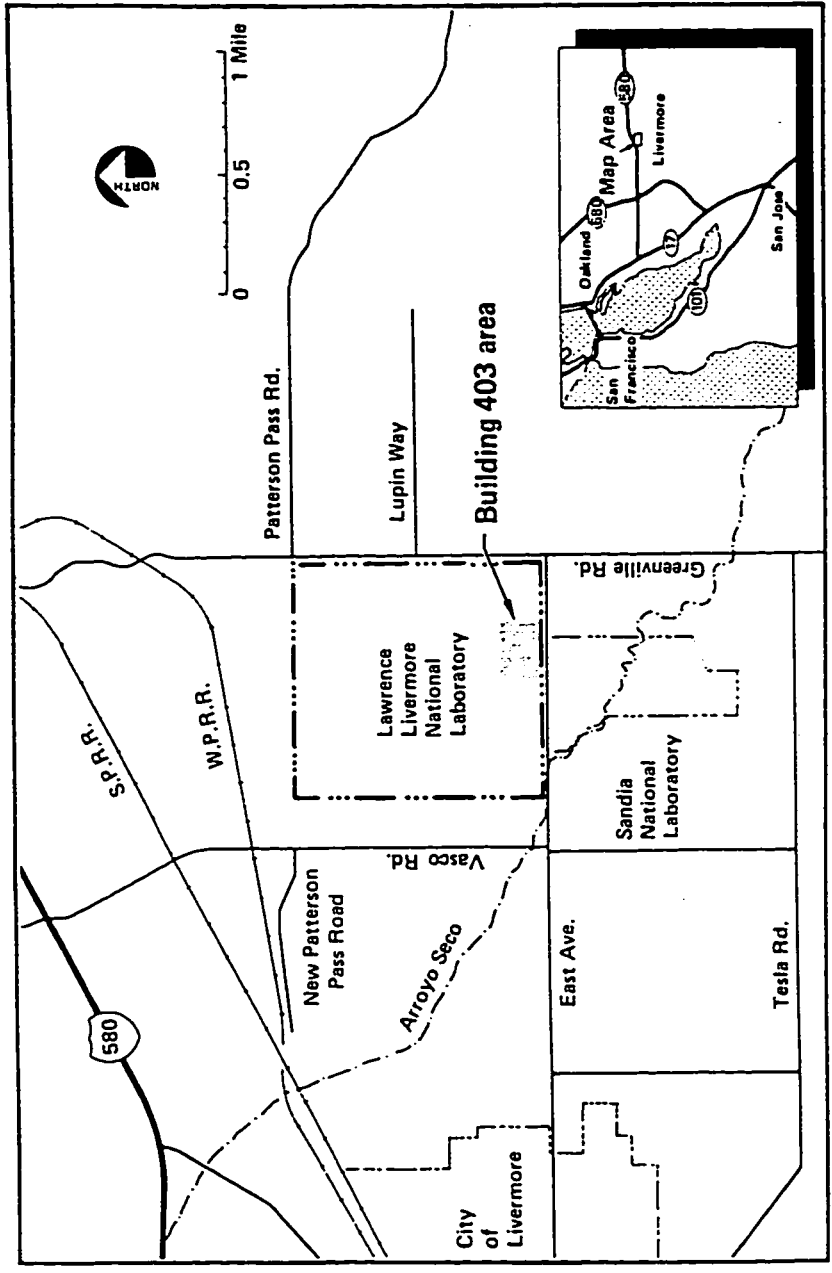


Figure 1. Location of Lawrence Livermore National Laboratory (Dresen *et al.*, 1986).

### Purpose

The goal of this investigation was to assess the effectiveness of SVE in the remediation of heterogeneous deposits contaminated by gasoline. To complete this investigation, it was necessary to design a vadose-zone monitoring system that allowed three-dimensional observation of vacuum response and vapor-contaminant response. The effectiveness of the monitoring system will also be discussed.

### Previous Studies

Two areas of investigation that are pertinent to this study are contaminant migration through the subsurface and the processes that control the use of SVE. The following subsections present the findings of previous studies of these two areas.

#### Gasoline Migration in the Vadose Zone

Gasoline is a light non-aqueous phase liquid (LNAPL), i.e., less dense than water. LNAPLs released to the subsurface above the water table migrate vertically because of gravitational and capillary forces. When groundwater is encountered, the LNAPL will spread laterally until it reaches equilibrium (Fig. 2). The LNAPL may be retained in the capillary fringe due to surface tension (Ostendorf *et al.*, 1993).

Soil heterogeneity also has a significant impact on the migration of LNAPLs (Butts, 1991). Coarse sediment facilitates vertical migration of gasoline in the vadose zone. Gasoline will migrate laterally along a layer of lower-permeability material (e.g.

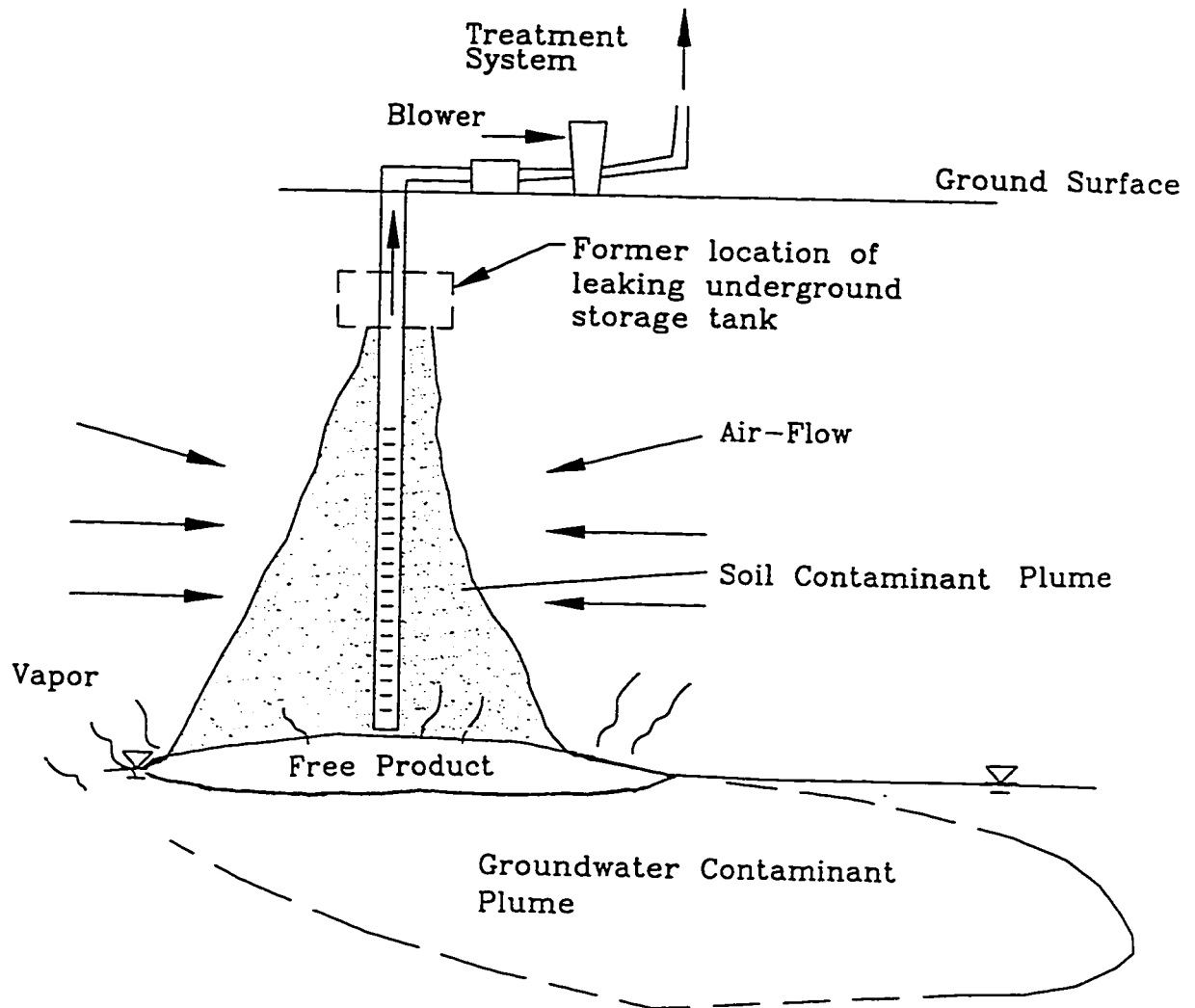


Figure 2. Cross-section of typical SVE system and gasoline migration from a leaking underground storage tank.

clay) until the edge of the layer is reached. Vertical migration may then resume until another fine-grained unit or the water table is encountered.

Further migration of gasoline continues through the processes of capillary action, advection, dissolution, and volatilization. Capillary action draws gasoline into the lenses of fine-grained sediment. Advection is the flow of the free product along the surface of the fine-grained units or along the surface of the groundwater table. Components of gasoline will slowly dissolve into and migrate with groundwater.

Volatilization occurs in the vadose zone from residually saturated sediment and at the free product surface. As the free product evaporates, vapors migrate through the subsurface, further spreading the contaminants. Vapor flow may be caused by advection due to pressure, temperature, and density gradients or through diffusion along concentration gradients. Vapor migrates from areas of high concentration to areas of low concentration.

### Soil Vapor Extraction

SVE is an increasingly utilized remedial method for soils contaminated by VOCs because it is more cost-effective than flushing, excavation, or incineration (Johnson *et al.*, 1990). Recent studies have provided evidence that SVE also enhances bioremediation and groundwater remediation (Blanchard and Dunlap, 1991).

The SVE system is constructed from the same basic components as a groundwater extraction system: an extraction well, a blower to withdraw vapors (equivalent to a pump in a groundwater extraction system), and a treatment system (Fig. 2). The difference is

that SVE works by pumping soil vapor from an extraction well completed within the vadose zone. The soil vapor is then treated at the surface. Treatment systems include granular-activated carbon units, thermal oxidation, and biologic media.

A pressure differential is created by inducing a vacuum within the extraction well. Vapor flows along the pressure differential from an area of high pressure to an area of low pressure. Vapor density, soil permeability, and vapor phase pressure affect the flow of vapors in porous media (Johnson *et al.*, 1990). Although vapor flow can occur under a density gradient, vapor density effects can be considered to be negligible because of the vacuum created by SVE (Beckett and Huntley, 1994).

The induced vapor flow results in the removal of contaminants from the subsurface. The vapor flow causes the contaminants to volatilize from the dissolved portion in pore water and desorb from the soil surfaces (Falta *et al.*, 1993). Additionally, volatilization will occur from free product, if present.

The effectiveness of SVE is determined by the vapor flow rate, contaminant composition, and the relation between the vapor flow path and the soil-contaminant distribution (Johnson *et al.*, 1990). VOCs are removed more rapidly with increased vapor flow rate. The vapor flow rate is dependent upon several factors. The surface equipment, including the vacuum pump and treatment system, have certain capabilities that cannot be exceeded for an extended period of extraction. The vapor flow rate also is controlled by the permeability of the sediment. Moisture affects the flow rate by decreasing the air permeability.

The permeability, air-filled porosity and grain-size distribution also influence the relation between the vapor-flow path and the soil-contaminant distribution. Vapor will flow through high-permeability sediment more easily than through low-permeability sediment. Typically, low-permeability deposits preclude the use of SVE. Thus, the high-permeability sediment will be more efficiently remediated and act as primary air-flow pathways. Gibson *et al.* (1993) reported that organic solvents may cause the formation of macropores and fractures in low-permeability deposits that may make the use of SVE feasible. Organic chemicals are more tightly bound in fine sediment, which may be bypassed by air-flow. Fine sediment will still be remediated by diffusion of contaminants into nearby coarse sediment, but the clean-up time will be much longer. VOCs that are strongly partitioned between the aqueous and solid phases may limit the removal due to low mass transfer rates (Falta *et al.*, 1993).

The composition of the contaminant also is important in determining the efficiency of SVE. The greater the vapor pressure of a compound, the more suited it is to remediation by SVE. In a mixture such as gasoline, which may contain over 100 individual compounds, compounds with the highest vapor pressures will be removed first, leaving the less volatile compounds behind. The compounds in gasoline with the greatest known toxicity are quite volatile.

The effectiveness of SVE decreases with time. The cause of the decrease is the decreasing mass removal rate. As the soil is remediated, the vapor concentrations decrease, and thus, the mass extraction rate decreases.



### Site Location

LLNL is located approximately 40 miles east of San Francisco, California, in the southeast corner of the Livermore Valley (Fig. 1). It is approximately 3 miles east of Livermore, California, on East Avenue, and occupies approximately 700 acres.

### Site History

LLNL is a research facility operated by the Department of Energy (DOE). The site currently occupied by LLNL was a Naval Air Station during World War II. The Gasoline Spill Area (GSA) was used as an Automotive Maintenance and Fuel Facility during this period. This use was continued by LLNL upon its formation in 1951 (O. H. Materials, 1985). Previous reports have referred to the GSA as the Building 403 Area. Building 403, the Automotive Garage, was demolished in the summer of 1988. The fuel dispensing facility was closed in 1980. The area continued to be used as a maintenance facility until 1984 (Nichols *et al.*, 1988). No work other than that associated with remedial activities was underway at the GSA in October 1991.

The leak in the GSA, first reported in March 1979, reportedly released 9,000 gallons of gasoline from the southernmost of four underground storage tanks located beneath the concrete pad (Fig. 3). This tank had been in use since 1942. A detailed review of inventory records revealed that up to 17,500 gallons of gasoline may have been lost to the subsurface in the six months preceding the leak's discovery (O. H. Materials, 1985).



The type of gasoline present in the subsurface is not known. The presence of ethylene dibromide indicates that at least some of the gasoline is leaded (Maureen Ridley, LLNL, personal communication, 1991). A low-lead tag was discovered when the southernmost tank was partially excavated in January 1991 (Gerald Duarte, LLNL, personal communication, 1991). Lindekin *et al.* (1986) reported the 9,000 gallons to be leaded. Bob Fornaciari (LLNL, personal communication, 1990), manager of the motor pool in 1979, thought the southernmost tank contained unleaded gasoline. Elevated levels of lead have not been detected in soil or groundwater samples taken in the area.

The source of the leak also is not known. The southernmost of the four underground storage tanks was leak tested in April 1980. The tank was half filled with water and allowed to sit for six days. No loss of water was observed. It was hypothesized that material shifted on the bottom of the tank and blocked the leak (O. H. Materials, 1985). A second possibility was a leak in the distribution lines. These lines were uncovered and pressure tested in January 1991. The lines still held 12 gallons of gasoline when they were exposed. The lines were pressurized with nitrogen for three days. No loss of pressure was observed during this test (Gerald Duarte, LLNL, personal communication, 1991).

### Previous Site Investigations

The GSA site characterization occurred in four phases. The goals of these investigations were as follows: 1) characterize the site geology and hydrogeology; 2) determine the soil-contaminant distribution in the vadose and saturated zones; and

3) determine the contaminant distribution in the groundwater. The subsurface characterization of the GSA is more complete than that found at many sites due to the large number of soil borings and monitoring wells installed in the vicinity (Fig. 3).

The initial characterization of the vadose zone hydrocarbon distribution was completed in 1984 by LLNL. Ten soil borings (403-1 through 403-10) and two monitoring wells (GSW-403-6 and GSW-20) were installed during this phase of the investigation (Dresen *et al.*, 1986).

The second phase of the site investigation was conducted by O. H. Materials (OHM). OHM conducted an aquifer test and a bench-scale study of in-situ biodegradation and further defined the subsurface hydrocarbon distribution. Six soil borings (GSB-1 through GSB-6) and five monitoring wells (GSW-1 through GSW-5) were installed in the winter of 1985 (O. H. Materials, 1985).

The third phase of the site investigation was initiated following a meeting between LLNL, the California Water Resources Control Board, and the California Department of Health Services. An agreement was reached that additional monitoring wells were necessary to assess the hydrocarbon distribution in the groundwater. The installation of 13 new monitoring wells (GSW-1A, GSW-6 through GSW-12, GSW-208, GSW-209, GSW-215, GSW-216, and GSW-266) was begun in November 1985 by LLNL and Weiss Associates. Additional soil samples were obtained from the vadose zone during the installation of these wells (Dresen *et al.*, 1986).

The final site investigation was conducted between July 1986 and July 1988. During this period, 10 new monitoring wells were installed (GSW-13, GSW-15, GSW-16,

GSW-326, GSW-367, and GSW-441 through GSW-445). Two additional soil borings, GSB-14 and GSB-374, also were completed. GSW-15 and GSW-16 were completed with multiple screens within the vadose and saturated zones. GSW-16 was designed to be used as the extraction well for both soil vapor and groundwater extraction.

Subsequent discussions rely on combining data from each of the four investigative periods with data collected specifically for this investigation. Several factors that may cause variability of the data should be noted. The first factor is the time that has passed over the course of the studies. It is assumed that natural processes causing the contaminants to degrade and migrate are acting relatively slowly to change the contaminant distribution, although these processes undoubtedly have had some effects. Secondly, improvement of analytical methods over time allows smaller contaminant concentrations to be detected. Thus, when comparing the results of this study with the past studies, only gross changes will be considered significant. Thirdly, the different investigations were also conducted by different individuals, resulting in different compounds being analyzed and different interpretations of the sediment types being encountered. The data sets were assumed to be comparable in order to develop a synthesized picture of site conditions.

### Regional Geology

The Livermore Valley is located in Alameda and Contra Costa counties approximately 30 miles east of San Francisco. The valley is oriented in an east-west direction, nearly perpendicular to the California Coast Range. It is bordered on the north

by the northern Diablo Range and the Altamont Hills and to the south by the central Diablo Range. The valley is bordered to the east by the Greenville fault, and the Calaveras fault forms the western boundary. The Livermore Valley is approximately 15 miles long and 11 miles wide. The elevation of the eastern side of the valley is approximately 1,000 feet [above mean sea level (MSL)] and rises to about 2,230 feet in the surrounding hills. The elevation of the valley is approximately 285 feet at its drainage exit (Wiggington and Carey, 1982).

Fluvial and lacustrine deposits underlie the Livermore Valley (Fig. 4). The thickness of these deposits may exceed 4,000 feet (Carpenter *et al.*, 1984). Near LLNL, in the southeastern corner of the valley, a hydrocarbon exploration well was drilled through 2,420 feet of alluvium before reaching Franciscan bedrock. The alluvium may be differentiated into the Plio-Pleistocene Livermore Formation and late Pleistocene to Holocene alluvial deposits. The underlying bedrock units will not be discussed in this paper.

#### Livermore Formation

The Livermore Formation is divided into two members by most workers (Barlock, 1989). The lower member of the Livermore Formation consists of clasts composed of Cenozoic sandstone, graywacke, and fine-grained quartz. Horizontally bedded gravel is surrounded by thick, planar cross-bedded sandstone and laterally extensive siltstone and mudstone. The interpretation of these deposits has been that of a mostly sandy-braided stream. The gravels and cross-beds indicate a southwesterly paleocurrent direction,



putting a source area to the northeast in the Altamont Hills. The exposed thickness of this unit is approximately 1,700 feet (Barlock, 1989). In the LLNL area, the upper contact of this unit is marked by a bluish-green clay layer interpreted to be lacustrine because of fresh-water mollusks recovered in borings (Robert Devaney, Weiss Associates, personal communication, 1990).

The upper member of the Livermore Formation consists of clasts composed of Franciscan graywacke, lithic sandstone, metamorphic rocks, chert, volcanic rocks, and traces of fine-grained quartz (Barlock, 1989). This member is characterized by thick, horizontally bedded, clast-supported, well-imbricated gravels interfingering with planar and trough cross-bedded sands. These deposits are interpreted to be those of a gravely braided stream on an alluvial fan. The imbrication and cross-bedding indicate a northeasterly paleocurrent direction, thus the source area was to the southwest in the Diablo Range.

#### Late Pleistocene to Holocene Deposits

Overlying the Livermore Formation are younger alluvial deposits that closely resemble the upper member of the Livermore Formation (Fig. 4). The thickness of these units ranges up to 400 feet (Stone *et al.*, 1982; California Department of Water Resources [1974] reported a thickness of 660 feet). There is an increase in thickness to the west (Stone *et al.*, 1982). These deposits have been studied by Huey (1948), Helley *et al.* (1972), Herd (1977), and Carpenter *et al.* (1984). These studies have revealed a complex



relation between deposits of varying ages. The work of Helley *et al.* (1972) will be used for this discussion of the LLNL area.

Older alluvial deposits range in age from late Pleistocene to Holocene. The deposits are highly-weathered, weakly-consolidated, poorly-sorted silty sand and gravel. The deposits in the northeast corner of the Livermore Valley generally are more fine-grained, possibly due to the composition of the rocks in the source area. Deposits of this unit generally are less permeable than younger deposits. Fossils found include those of continental vertebrates and invertebrates. Stream terraces are included in this unit (Helley *et al.*, 1972).

Interfluvial basin deposits were deposited in intermittent lakes that formed in the Livermore Valley. This unit is characterized by plastic, poorly-sorted, and organic-rich clay and silty-clay deposits. The interfluvial basin deposits are poorly drained due to their fine-grained nature. This unit typically is less than 10 feet thick (Helley *et al.*, 1972).

The younger fluvial deposits consist of unconsolidated material of varying grain sizes, primarily sand, silt, and silty clay. These are levee and overbank deposits. Freshwater gastropod and pelecypod fossils have been found. The thickness of this unit is typically less than 15 feet (Helley *et al.*, 1972).

Younger alluvial fan deposits are unconsolidated, moderately-sorted, permeable fine sand and silt with gravel. This unit is common in fan heads and within canyons. The deposits form well-drained levees that grade upward into terraces. Colluvium in narrow canyons is also included in this unit (Helley *et al.*, 1972).

## Site Geology

The 100 feet of sediment affected by the hydrocarbon plume in the GSA are within the upper member of the Livermore Formation and the late Pleistocene and Holocene alluvial deposits. The lower member of the Livermore Formation lies at a depth of approximately 200 feet below ground surface (bgs) in the GSA.

Four cross-sections were drawn using data obtained during the investigations prior to July 1986 (Dresen *et al.*, 1986). The locations of these cross-sections are presented in Figure 5. Sediments were divided into high, moderate, and low relative permeabilities for the purposes of constructing the cross-sections. Relative permeability estimates were based on grain size, percent fines, and interpretation of geophysical logs. Generally, sediments with more than 50 to 60 percent fines were considered to have relatively low permeability and those with less than 10 to 20 percent fines were considered to have relatively high permeability. Sediment not meeting these criteria was considered to have moderate relative permeability.

Figures 6 and 7 present cross-sections A-A' and B-B', respectively. These cross-sections trend northeast and east, respectively. High- and moderate-permeability sediments are observed as discontinuous lenses in a matrix of generally low-permeability sediments. The lenses generally are thin (5 to 10 feet thick) and parallel to the surface. A continuous lens of high-permeability sediment is located at a depth of approximately 70 to 80 feet bgs.

Cross-section C-C', trending southeast, is presented in Figure 8. This cross-section is similar to cross-sections A-A' and B-B', but the high- and moderate-

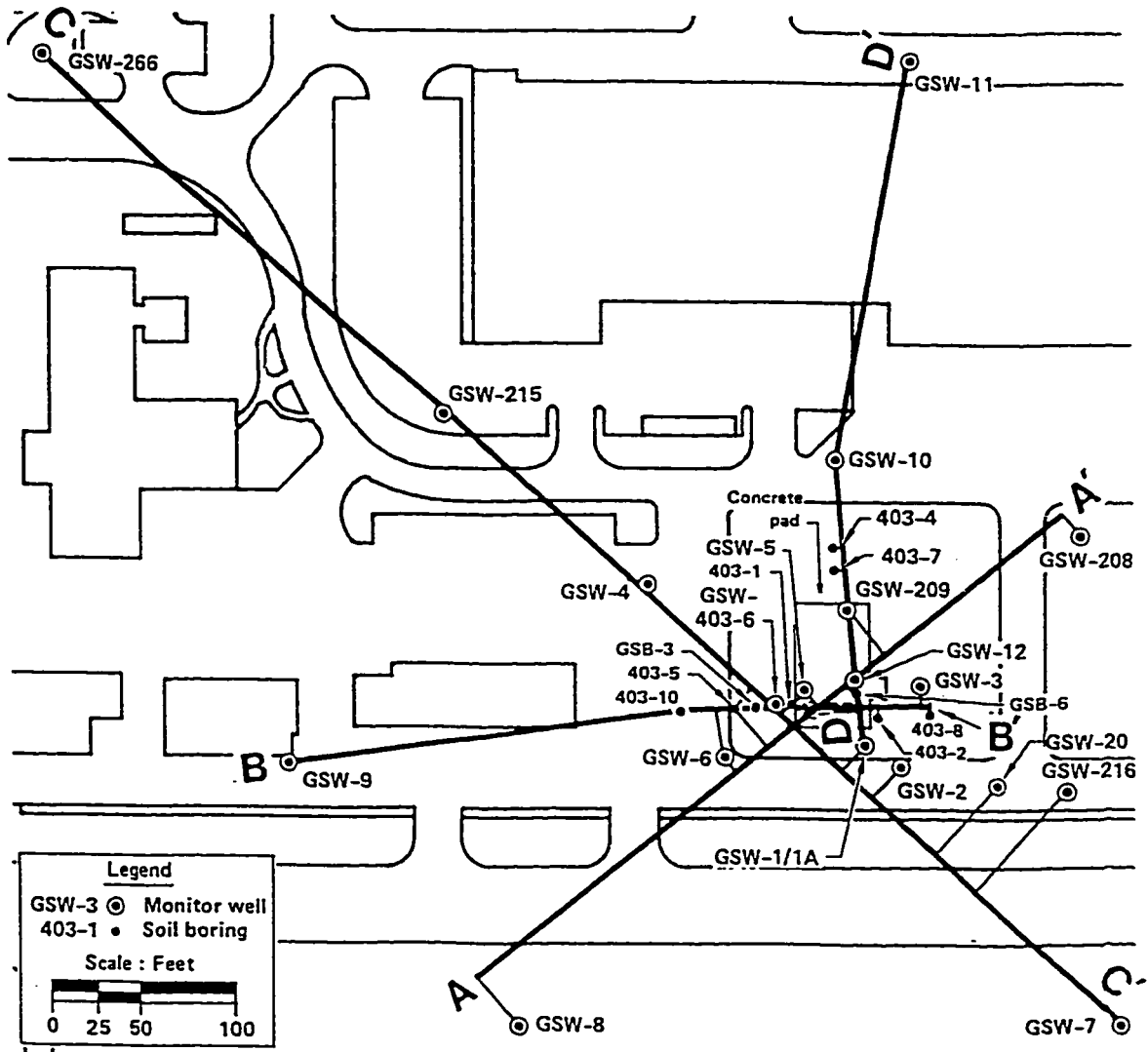


Figure 5. Location of cross-sections through the Gasoline Spill Area (Dresen *et al.*, 1986).

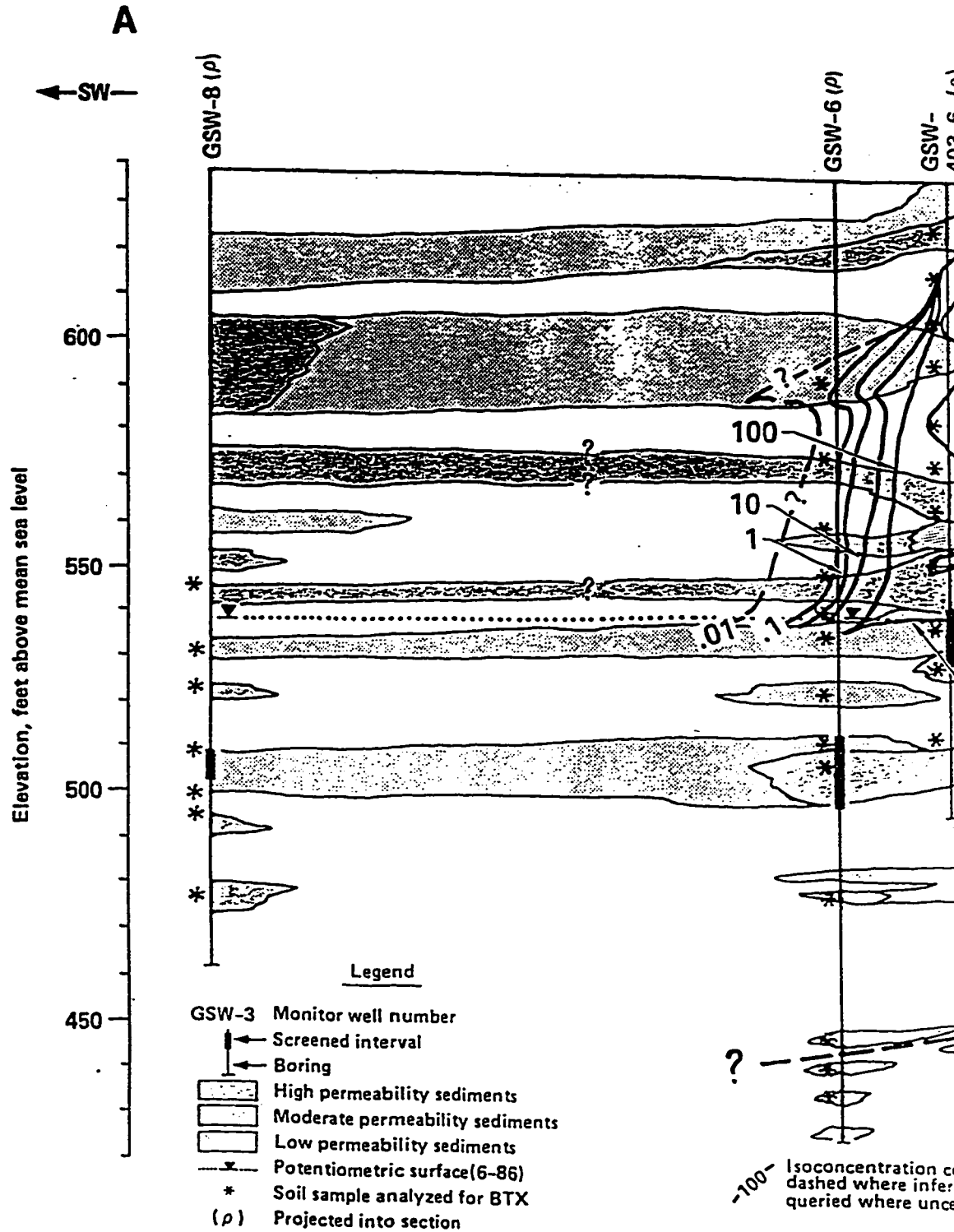
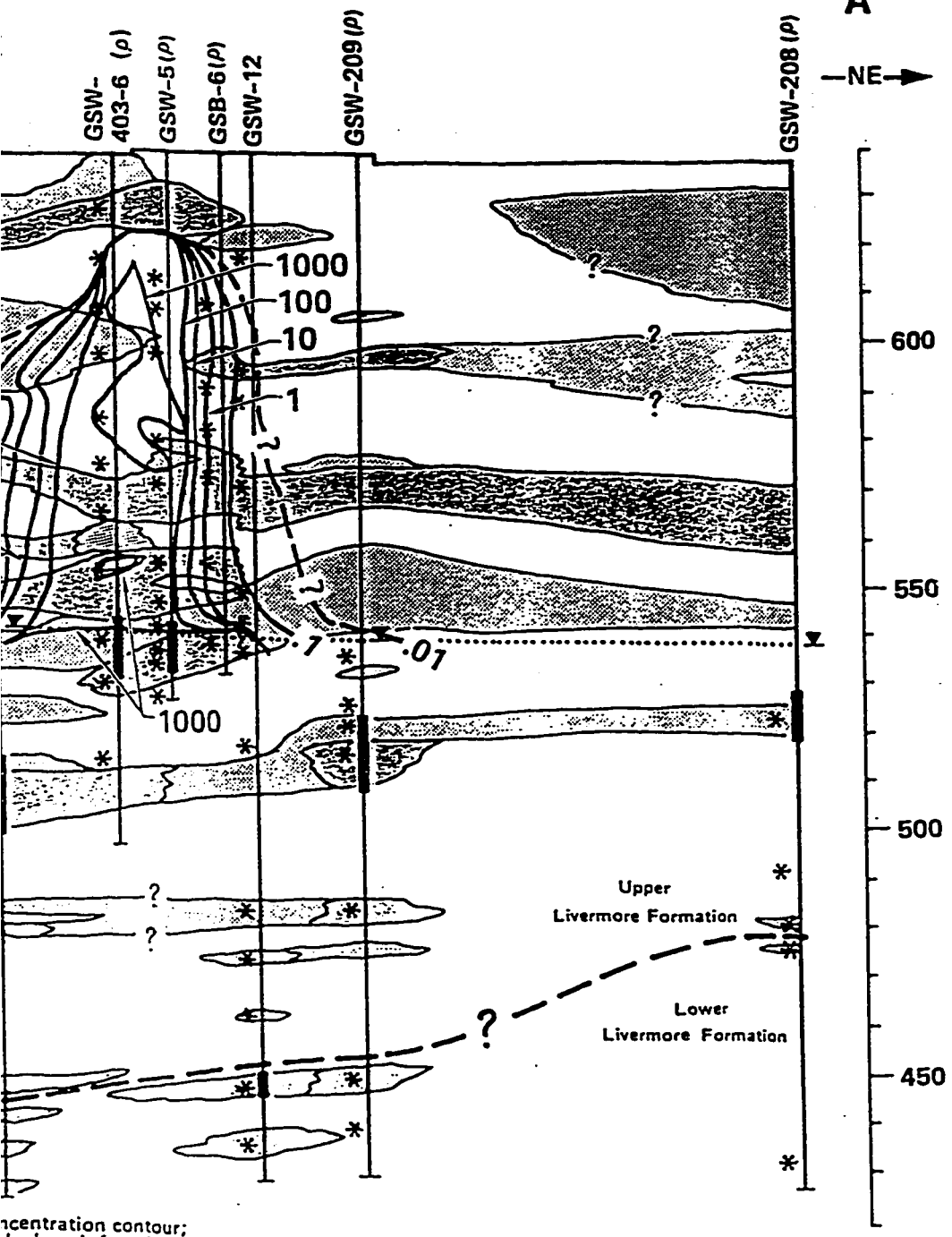


Figure 6. Cross-section A-A' illustrating the subsurface lithology and distribution of benzene, toluene, and xylenes in the vadose zone (Dresen *et al.*, 1986). The horizontal scale is approximately 44 feet per inch.



A'

NE →



Concentration contour;  
dashed where inferred;  
solid where uncertain

and distribution of  
the horizontal scale is



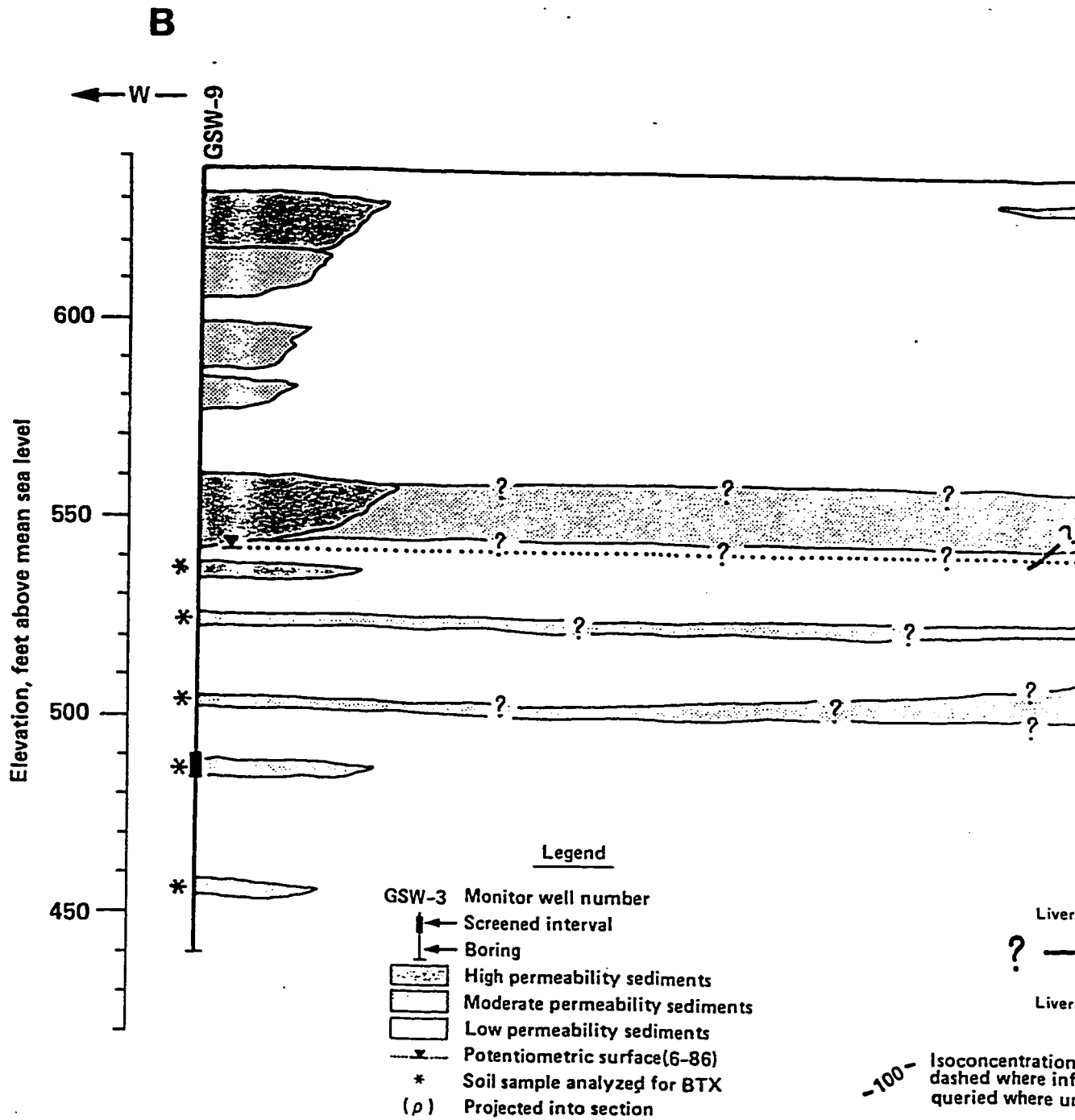
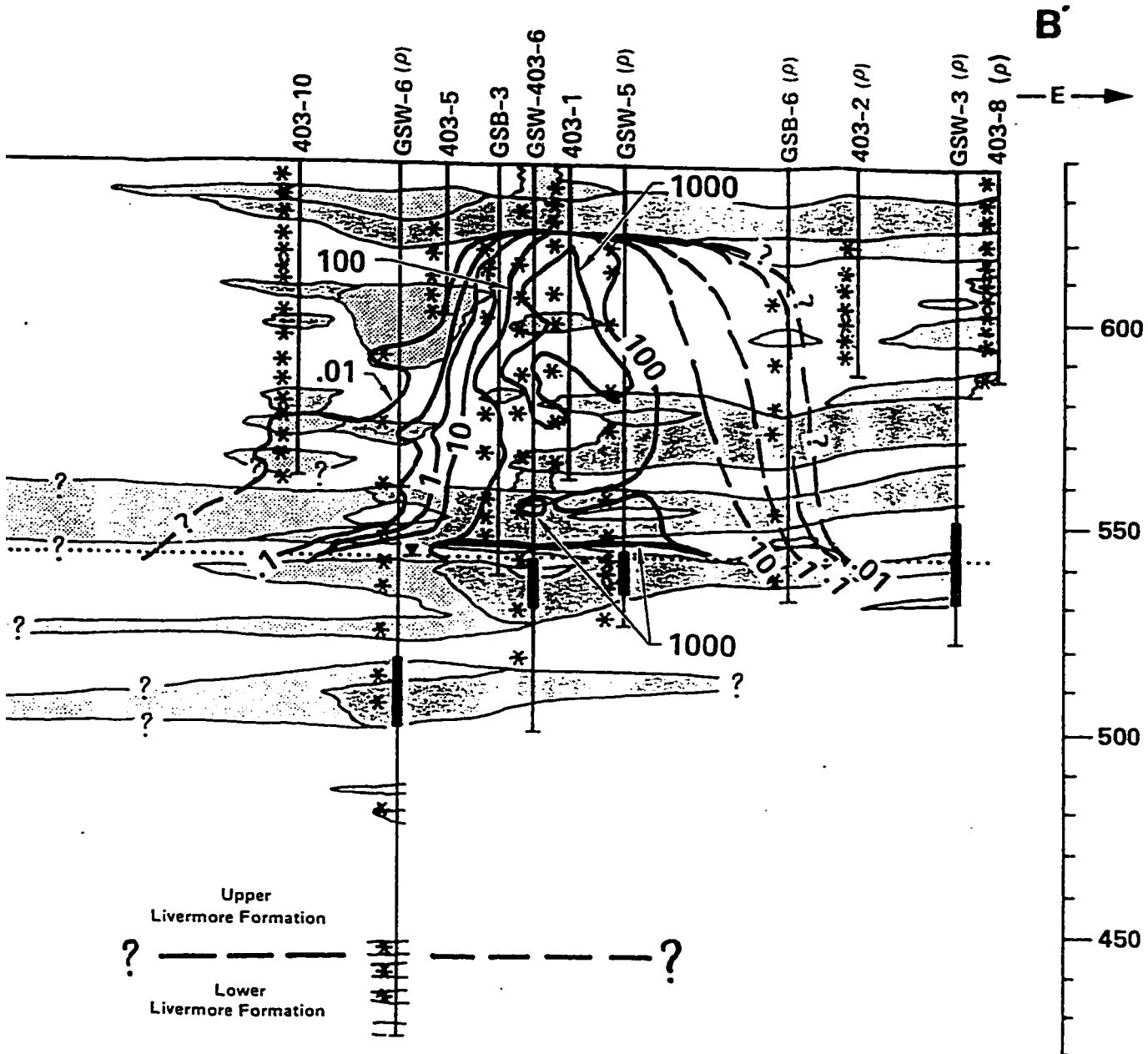


Figure 7. Cross-section B-B' illustrating the subsurface lithology and distribution of benzene, toluene, and xylenes in the vadose zone (Dresen *et al.*, 1986). The horizontal scale is approximately 32 feet per inch







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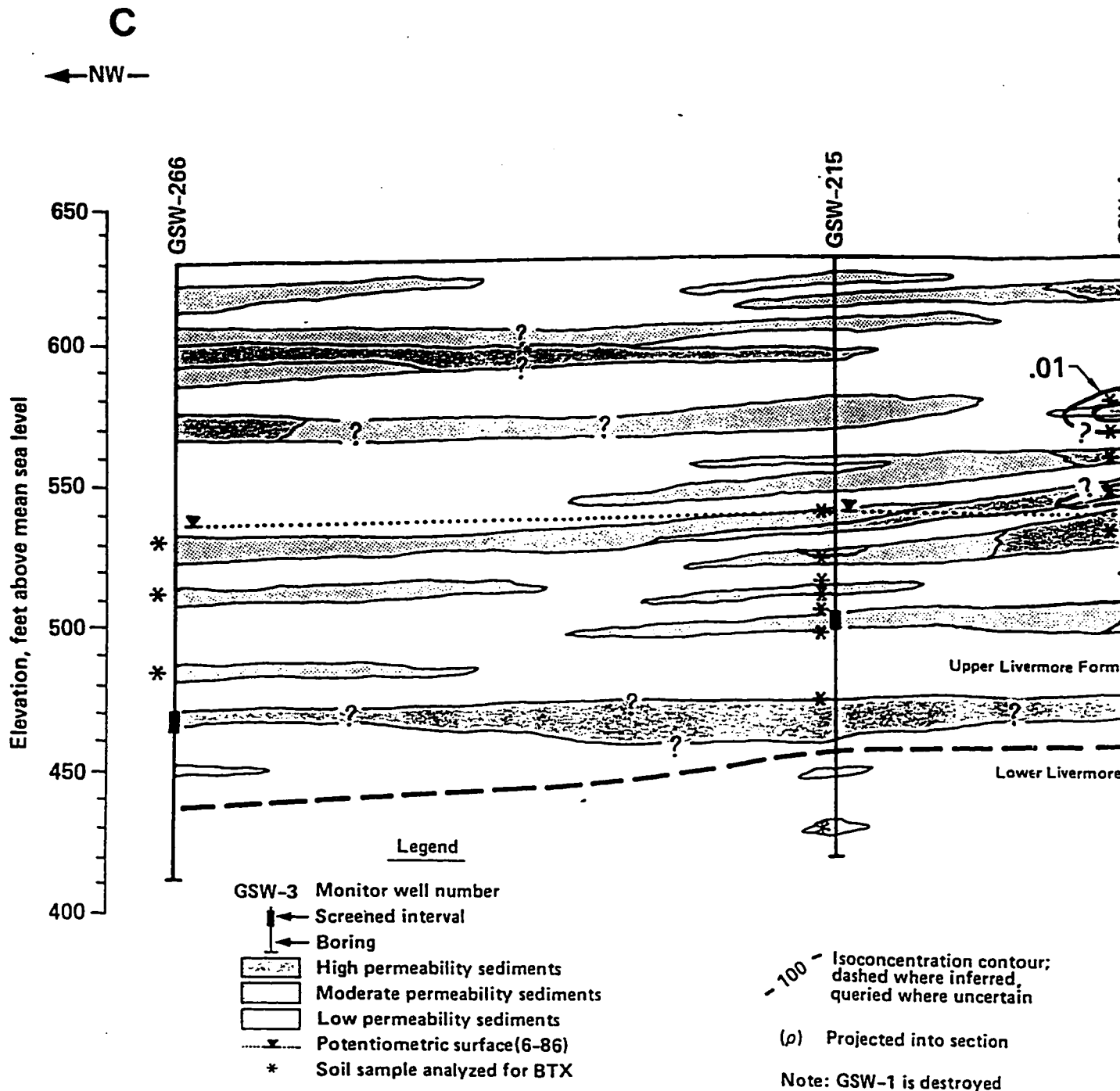
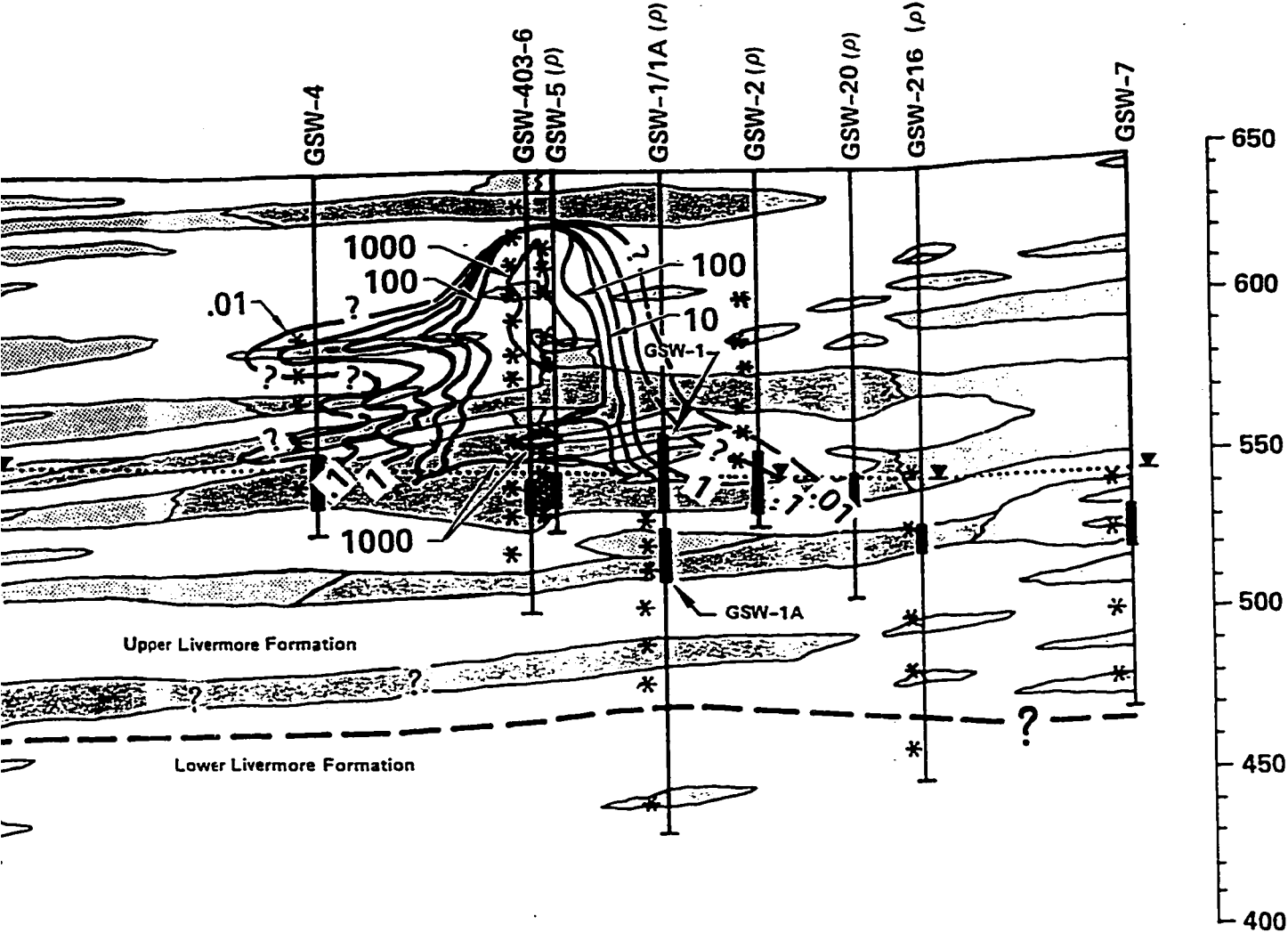


Figure 8. Cross-section C-C' illustrating the subsurface lithology and distribution of benzene, toluene, and xylenes in the vadose zone (Dresen *et al.*, 1986). The horizontal scale is approximately 68 feet per inch.



C  
—SE—>



Concentration contour;  
dashed where inferred,  
solid where uncertain

Projected into section

GSW-1 is destroyed

Location of

Vertical scale is

permeability sediments are interpreted to be more continuous. Dresen *et al.* (1986) inferred that the greater continuity of the lenses is because the section is parallel to the depositional direction. Many lenses have a dip of approximately 1 degree to the northwest.

Figure 9 presents north trending cross-section D-D'. The sediment observed in this cross-section is similar to that in cross-sections A-A' and B-B'. High- and moderate-permeability sediments are present in thin, discontinuous lenses that are roughly parallel to the ground surface.

#### Site Hydrogeology

The hydrogeology of the GSA has been described in several reports. These include reports by Carpenter *et al.* (1984), O. H. Materials (1985), Dresen *et al.* (1986), Nichols *et al.* (1988), and numerous monthly reports prepared by the Environmental Restoration Division of LLNL between June 1986 and the present.

The groundwater in the LLNL vicinity is found at depths ranging from 140 feet bgs in the southeast corner of the site to 30 feet bgs just west of LLNL (Thorpe *et al.*, 1990). Figure 10 presents a contour map of the groundwater elevation in May 1988 for the LLNL site. Depth to groundwater in the GSA area was  $100 \pm 5$  feet (an elevation of  $540 \pm 5$  feet above MSL) in the summer of 1991. The GSA is located on a north-trending groundwater divide. Groundwater flow is split into east-southeast and west-southwest components because of its location on the divide. The hydraulic gradient ranged from

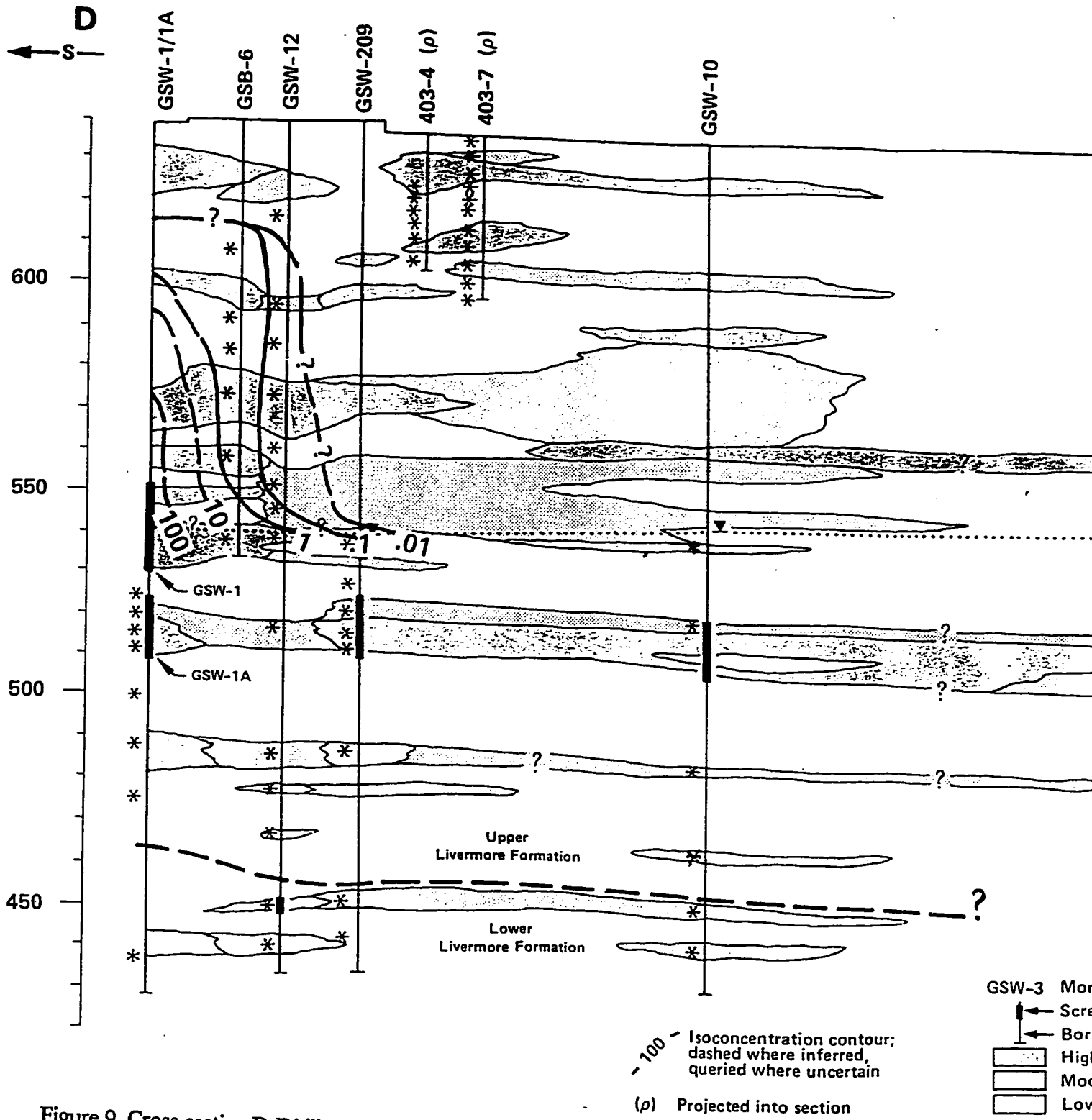
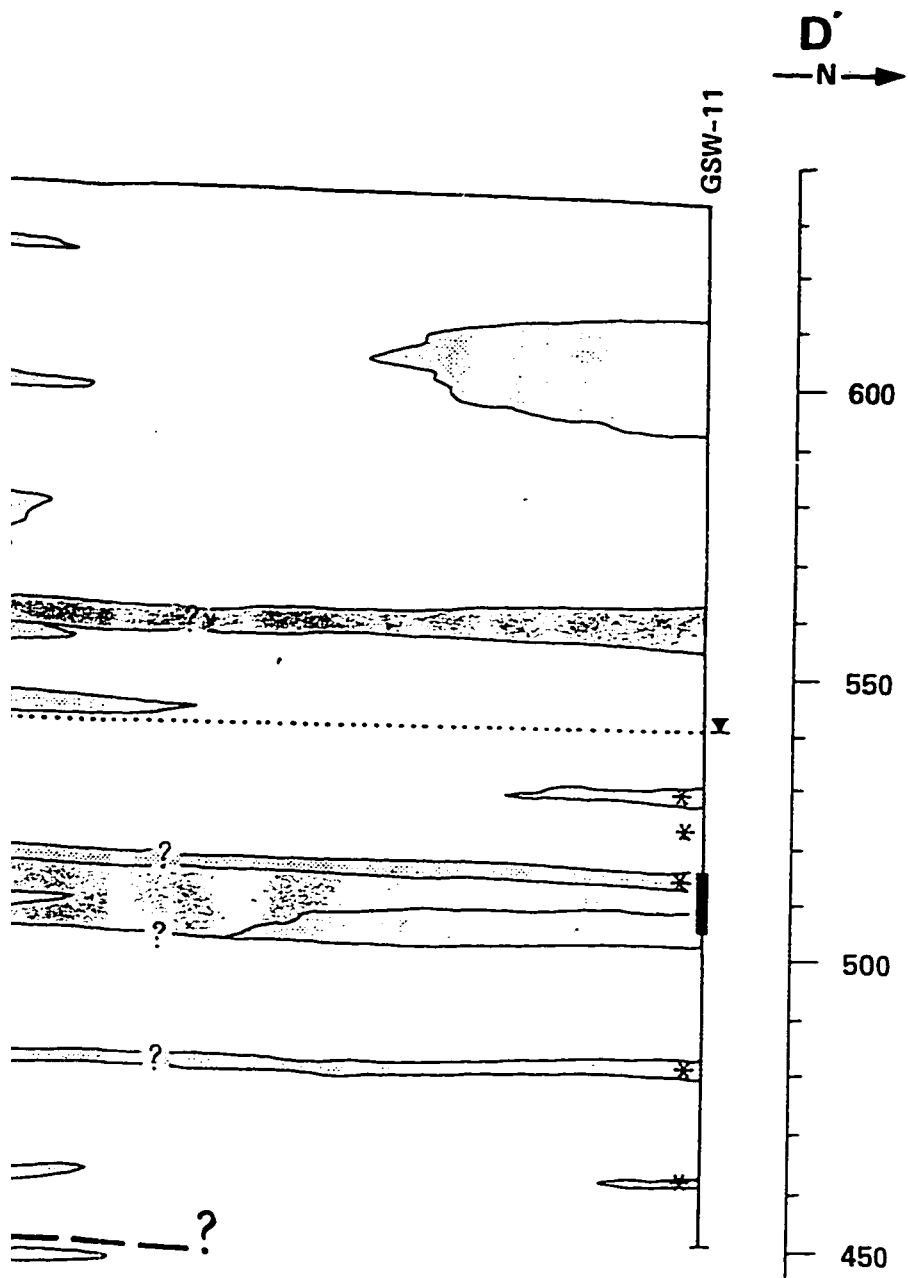


Figure 9. Cross-section D-D' illustrating the subsurface lithology and distribution of benzene, toluene, and xylenes in the vadose zone (Dresen *et al.*, 1986). The horizontal scale is approximately 38 feet per inch.







Legend

- GSW-3 Monitor well number
- ← Screened interval
- ← Boring
- [Stippled Box] High permeability sediments
- [Horizontal Lines Box] Moderate permeability sediments
- [White Box] Low permeability sediments
- [Dotted Line with Triangle] Potentiometric surface(6-86)
- \* Soil sample analyzed for BTX

contour;  
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0.002 to 0.01. The low hydraulic gradient has helped slow contaminant migration in the saturated zone.

### Petroleum Hydrocarbon Distribution

The initial characterization of the site is based on the soil borings and monitoring wells installed between 1984 and 1986. Figures 6 through 9 show the initial distribution of the aromatic constituents, benzene, toluene, and total xylenes (BTX), in the vadose zone. The locations of these cross-sections are shown on Figure 5. The hydrocarbon plume is narrow in the vadose zone, with concentrations of 1 part per million (ppm) restricted to a 35- to 50-foot radius from GSW-403-6 except in the northwest direction, which had a radius of approximately 100 feet (Dresen *et al.*, 1986). The greater lateral migration to the northwest was thought to be the result of the northwest-dipping sediment lenses.

Hydrocarbon contamination was found as shallow as 20 feet bgs near the suspected leak point. This probably resulted from the location of the base of the underground storage tanks at a depth of 18 feet bgs (O. H. Materials, 1985). GSW-403-6 had the highest concentration of BTX at 4,800 ppm at a depth of 31 feet bgs. Near the water table, concentrations of BTX at 1 ppm were found as far away as GSW-6, approximately 75 feet to the southwest (Nichols *et al.*, 1988). The highest concentrations of BTX were observed in clay samples; this was caused by the greater sorption onto the fine sediment (Dresen *et al.*, 1986).

The saturated zone also was affected by the downward migration of gasoline. The water table was 15 to 20 feet below its present level (approximately 100 feet bgs) in 1984 (Carpenter *et al.*, 1984). The high concentrations found in water-saturated soil samples indicate that gasoline may have existed as a separate phase beneath the water table (Hunt *et al.*, 1988). This separate phase may have been trapped beneath fine-grained layers as the water table rose. The dissolved portion of the gasoline plume remains within 250 feet laterally of the suspected leak point.

#### Soil Vapor Extraction at the Gasoline Spill Area

Vadose zone remediation using SVE was initiated in August 1988. The soil vapor was extracted using a single extraction well, GSW-16, near the center of the plume (Fig. 3). GSW-16 is screened in seven individual zones, five within the vadose zone and two in the saturated zone (Fig. 11). SVE can be performed on individual zones or any combination of adjacent zones using pneumatic packers. Screen placement was based on contaminant distribution within the soil column. Thus, the screens are located primarily in fine-grained zones. Thermal oxidation, using propane as a secondary fuel, was utilized to treat the vapor effluent.

The screens in GSW-16 are designated Zones 1 through 7, with Zone 1 being the shallowest. The two deepest screens within the vadose zone, Zones 4 and 5, have become partially blocked. One hypothesis is that grout was pushed into the screens during well installation. In August 1989, the screens were scraped using a wire brush to mechanically remove the blockage. A small chunk of a hard, dirty, white substance was recovered.

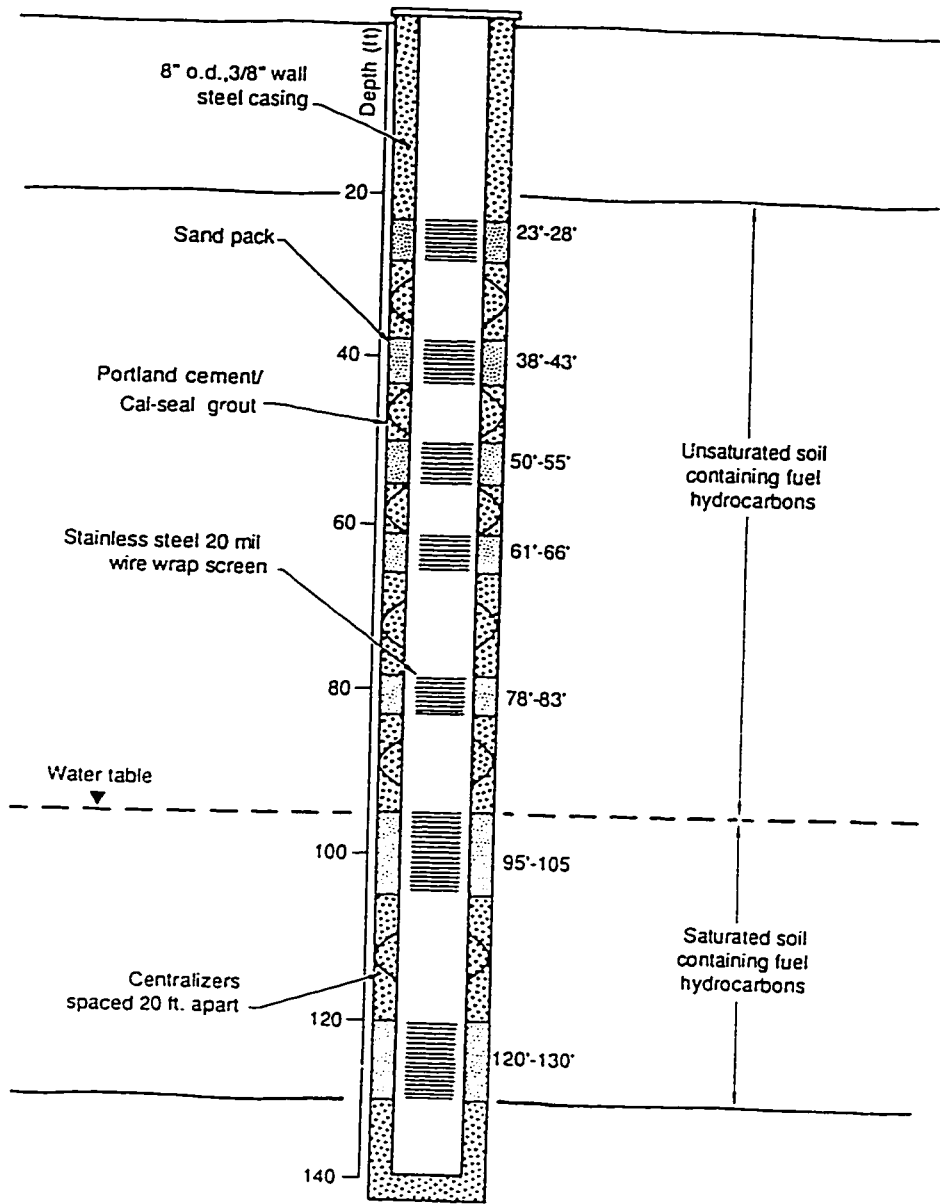


Figure 11. Schematic of extraction well GSW-16 (Nichols *et al.*, 1988).

Analysis by x-ray diffraction indicated the composition to be primarily quartz and feldspar with minor amounts of calcite. This suggests that formational material has been pulled into the screen. The calcite may be a result of chemical precipitation as water evaporates as it enters the borehole. Another hypothesis is that biologic activity has resulted in the screens' blockage. No conclusions have been reached. Attempts to remove the blockage by cyclic pressurizing of the screened zones were unsuccessful.

Prior to this investigation, the SVE system operated for a total of 179 days over a 2.3 year period. Figure 12 illustrates the removal of an estimated 530 gallons of benzene, toluene, ethylbenzene, and xylenes (BTEX) during this time. This provides an average mass extraction rate for BTEX of 3.2 gallons per day (gpd). The assumptions made in determining the amount of gasoline removed are discussed by Cook *et al.* (1991). Approximately 2,200 gallons ( $\pm 25\%$ ) of gasoline were estimated to have been removed from the subsurface. Figure 12 indicates that 50% of the total BTEX removed prior to June 1991 was removed in the first 38 days of operation.

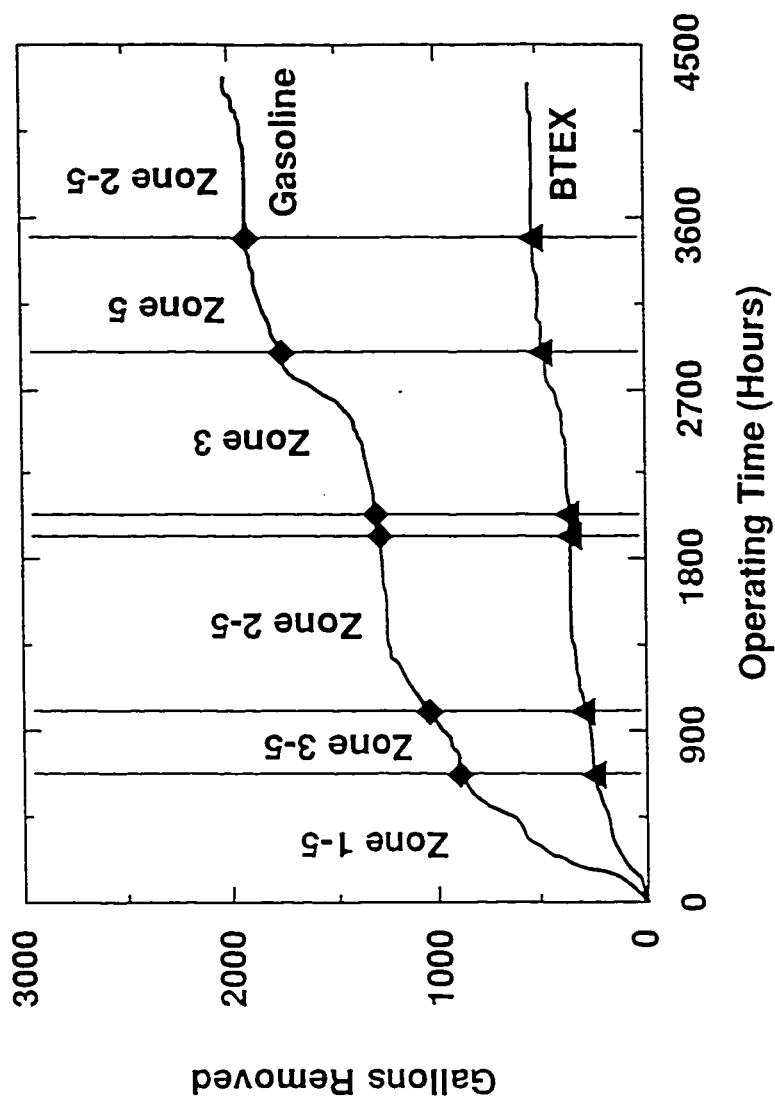


Figure 12. Mass removal of BTEX and gasoline by SVE during the first 179 days of operation (Cook *et al.*, 1991).



## METHODOLOGY

### Vadose-Zone Monitoring Device Placement

Three vadose-zone monitoring devices (SVB-GP-008A, SVB-GP-013, and SVB-GP-014) were installed in order to investigate the effectiveness of SVE (Fig. 3). Several factors were considered in the placement of the vadose-zone monitoring devices. The first was site accessibility. The concrete pad covering the underground storage tanks blocked placement to the east. Other areas of the site were inaccessible because of underground utilities.

The final decision on placement was based on the desire to maintain optimum spatial coverage of the plume and to place the devices at differing distances from GSW-16 to facilitate use of the data for permeability testing. The northwest quadrant of the plume is monitored by SVB-GP-008A, 11.8 feet from GSW-16. Monitoring devices SVB-GP-013 and SVB-GP-014 are located in the southwest quadrant of the plume at radial distances of 6 and 18 feet, respectively.

### Vadose-Zone Monitoring Device Design Test

A test installation of the proposed vadose-zone monitoring device was completed on October 10, 1990. Of particular concern was the recognized difficulty of completing a device with sampling ports at multiple depths in a single borehole. The purpose of the test installation was to determine the feasibility of this design and to evaluate potential problems prior to installation of the vadose-zone monitoring devices.

The materials used for the completion of the test well were Kaiser Permanente Type I-II Portland cement, Cal-Seal gypsum cement, Volclay/Pure Gold 0.25-inch bentonite pellets, Lonestar No. 3 sand, and Lonestar No. 0/30 sand. The Portland cement and the gypsum cement were mixed to form a fast-drying grout. An auger with an 11.5-inch outside diameter and a 6.63-inch inside diameter was used to complete the boring.

The following is the step-by-step procedure for the completion of the test well:

1. The borehole was augured to a depth of 4.92 feet.
2. The vapor monitoring tube was set into the borehole. The tube rested on the base of the borehole and the monitoring port was set at 3.1 feet.
3. The augers were pulled up to 3.38 feet.
4. The grout to be used for backfilling the bottom one foot of the boring was hand-mixed with a ratio of Portland cement to Gypsum cement to water at 3:1:1.
5. The grout was poured through a funnel downhole.
6. The auger was raised 0.67 feet to prevent grout clogging.
7. The grout was allowed to set for approximately 30 minutes.
8. A 1.42-foot layer of Lonestar No. 3 sand was poured downhole. The top of this layer was at a depth of 2.5 feet.
9. A 1-foot layer of Lonestar No. 0/30 sand was placed downhole.
10. A 0.5-foot layer of 0.25-inch bentonite pellets was placed on top of the Lonestar No. 0/30 sand.

11. The grout for the top layer was hand-mixed and funneled downhole. The grout was allowed to set-up for approximately 45 minutes prior to excavation.
12. The soil was excavated to within one foot along one side of the test installation.
13. Observations of the final installation details were recorded.

The only problem encountered was the placement of the first grout layer. The grout was so quick-drying that it started to clog the funnel. This problem was eliminated by mechanical mixing with the drill rig's pump. The top grout layer was expected to come to the ground surface, but it was about 0.42 feet bgs.

A backhoe was used to excavate to within one foot of the test well. The remaining soil was removed by hand. Figure 13 illustrates the completed test installation as it was observed following excavation. The depths of each zone were carefully measured to determine the accuracy of the installation procedures. The first problem encountered was the thickness of the bottom layer of grout. The layer was only about 5 inches thick, instead of the expected 1 foot. This shortfall accounted for the failure of the top layer of grout to reach the ground surface.

The biggest potential problem encountered was a layer of grout smeared on the monitoring tube. It did not block the screen, but had the tremie pipe hit the monitoring point, it probably would have been blocked. The grout was about 0.1-foot thick and reached up to the level of the vapor point. This problem was mitigated by marking the

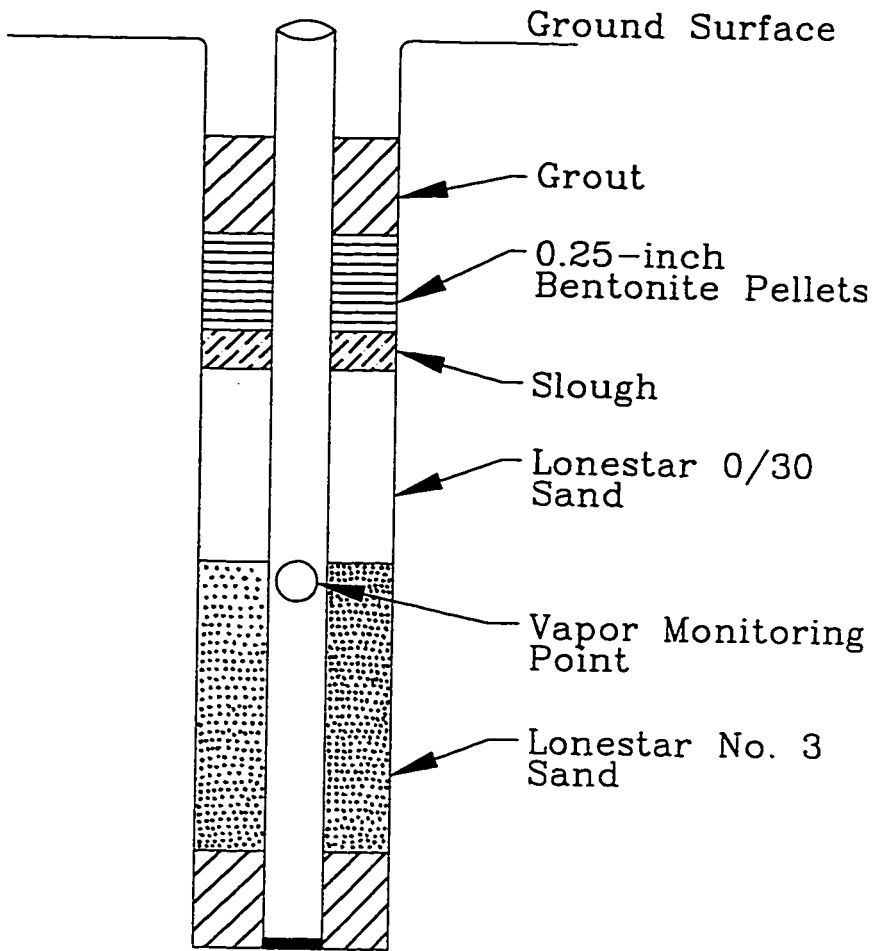


Figure 13. Schematic of completed test installation.

vadose-zone monitoring device so that the side with the openings was known. The tremie pipe was then kept on the opposite side of the device.

The bentonite layer was successful in stopping grout penetration. The top 0.1 foot of the bentonite layer was completely swollen. Grout had seeped through this layer to only a very minor degree. Beneath the top layer of bentonite was a 0.1-foot layer of slough. This stopped the remaining portion of grout. The bottom 0.1-foot of bentonite swelled slightly, but individual pellets were still recognizable. No grout reached the top of the fine sand pack. This design would protect the soil vapor point from becoming clogged because of grout penetration.

The procedure selected for installation of SVB-GP-008A was based on our observations from installation of the test well. There were several factors that needed to be carefully observed to prevent clogging of the screen. The first was to make sure the tremie pipe stayed away from the vapor points. Secondly, it was important to carefully tag the depths of each layer of material added to the monitoring device.

### Drilling and Soil Sampling

A Flailing 150 drill rig equipped with 12-inch augers was used to install the soil borings. A solid core barrel was placed inside to obtain 5.75-inch diameter cores. The boring was advanced in 3-foot intervals to increase the core recovery rate. At the end of each interval, the core barrel was brought to the surface where a hydraulic press would extrude the core. Prior to each boring, the augers were steam cleaned to prevent cross-contamination. Extensive sampling of each extruded core was performed to characterize

the current soil-contaminant distribution and physical properties of the soil (Fig. 14).

Sample aliquots were taken by driving a 1.5-inch or 2.5-inch brass liner into the core. The first samples taken were immediately sent to a California State Certified analytical laboratory for chemical analysis. The samples were analyzed for Benzene, Toluene, Ethylbenzene, and total Xylenes (BTEX) by EPA Method 8020 and Total Petroleum Hydrocarbons as gasoline (TPH-g) by modified EPA Method 8015 (EPA, 1996). Once soil chemistry samples were obtained, additional samples were taken to evaluate soil bacteria, horizontal permeability, soil-water partition coefficient, and metals. Some of these analyses were performed for other studies ongoing at the GSA, and therefore are not further discussed. After sampling, the lithology was described in detail using the Unified Soil Classification System.

#### Vadose-Zone Monitoring Device Screen Placement

It was necessary to decide the monitoring point depths prior to installation of the monitoring device. Numerous factors were considered in selecting the zones to be monitored by the vadose-zone monitoring devices. The first factor was the depth of the screened zones in GSW-16. Monitoring points were placed at depths equivalent to the screened intervals in GSW-16 (Fig. 11). Lithology was also considered due to its effect on permeability and adsorption. The final decision was made following receipt of the overnight results of chemical analyses. Zones that appeared to be showing signs of remediation (those areas with low concentrations) were important to observe as well as

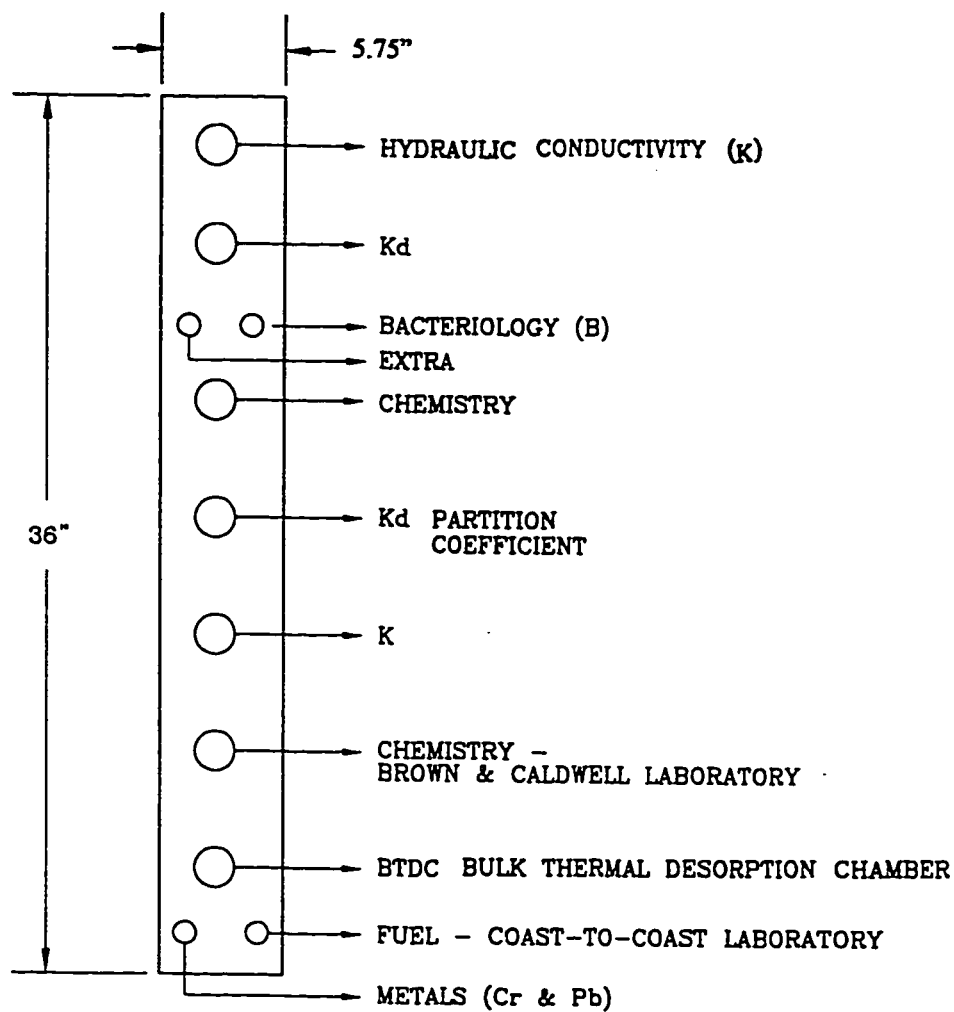


Figure 14. Soil sampling plan for each 3-foot soil core obtained during installation of the vadose zone monitoring devices. Chemistry and bacteriology samples were stored in an ice chest cooled to 4°C. All other samples were stored on dry ice.

those with high levels of residual contamination. The monitoring points were placed along a concentration gradient, where possible, to investigate the effects of diffusion.

Figure 15 shows the monitoring point depths in SVB-GP-008A, SVB-GP-013, and SVB-GP-014. From here on, the monitoring points are referred to in an abbreviated form. The entire monitoring device will be referred to as SV-8A (SVB-GP-008A), SV-13 (SVB-GP-013), and SV-14 (SVB-GP-014). The individual monitoring points are designated as either points Z1 through Z5 (SV-8A) or points Z1 through Z7 (SV-13 and SV-14), with point Z1 being the shallowest. Monitoring point Z5 in SV-13 (not included in Figure 15) was blocked during installation and was not used during these tests. For example, the first monitoring point in SVB-GP-008A will be referred to as SV-8A-Z1.

#### Vadose-Zone Monitoring Device Design

Figure 16 illustrates the design of the vadose-zone monitoring devices. A 2-inch-diameter pipe was used to house the teflon tubing, extending from the ground surface to the monitoring points, and the electrode and thermocouple wires. Each vapor-monitoring point consisted of a tee and a separate, machine-tooled screen housing. The screen housing was connected to the teflon tubing with a crimp fitting and press-fit into the tee. The tee was then attached to the 2-inch diameter pipe.

After the vadose-zone monitoring device assembly was lowered into the borehole, the annular space was backfilled with sand, bentonite, and grout. Approximately 18 inches of sand (12 inches of medium sand and 6 inches of fine sand) were placed around the screen in SV-8A and 30 inches of sand was placed around the screen in SV-13 and



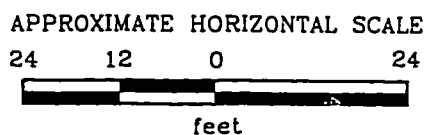
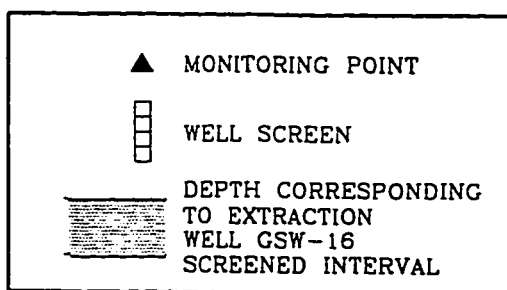
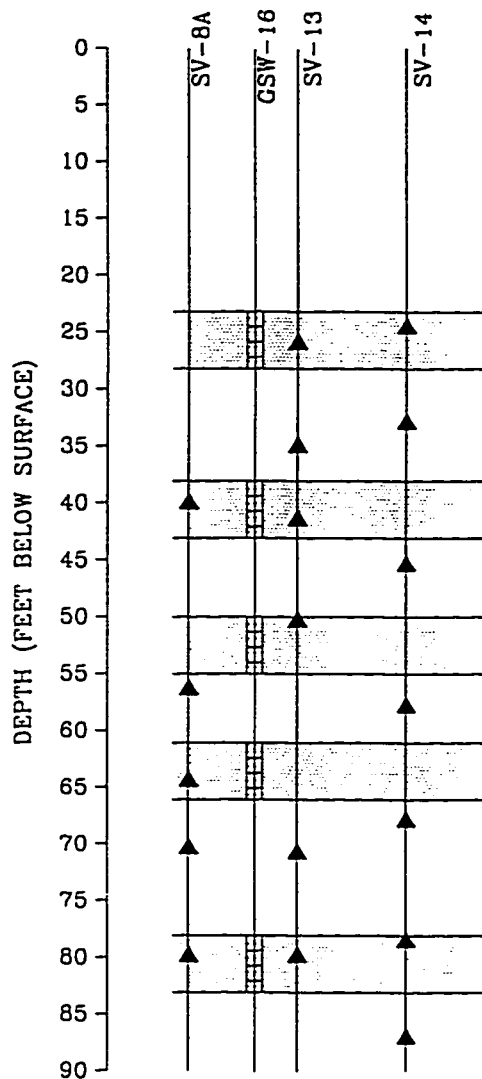


Figure 15. Placement of the screens in the vadose zone monitoring devices in relation to the screened intervals in extraction well GSW-16.

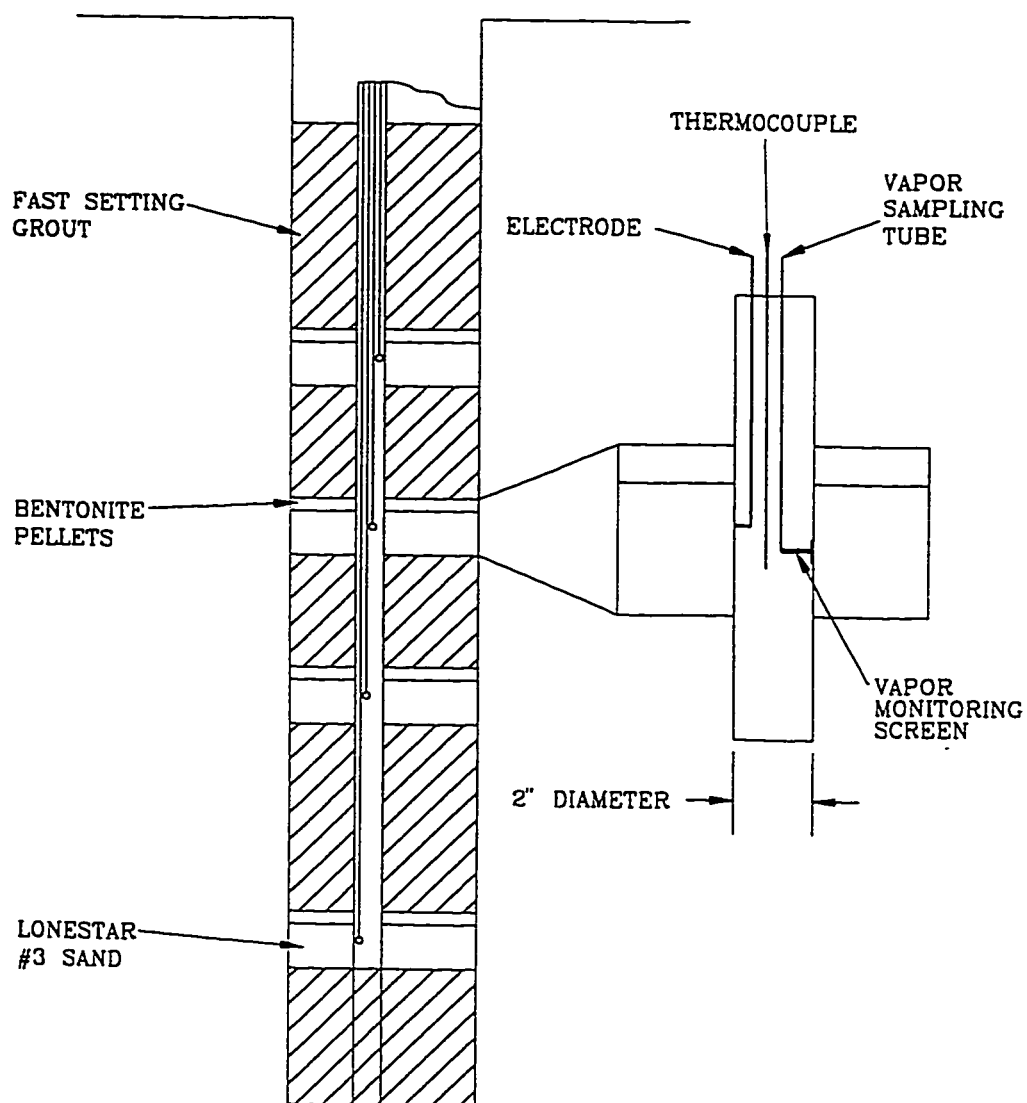


Figure 16. Design of vadose zone monitoring devices. The electrodes and thermocouples were installed in anticipation of a steam injection project which followed this study.

SV-14. A 0.5- to 1.0-foot layer of bentonite was placed above the sand to prevent the overlying grout from entering the sandpack. The grout was then extended to approximately 6-inches below the overlying monitoring point or 1 foot bgs. Fast-drying grout was used to reduce the time required for installation.

#### Installation of Vadose-Zone Monitoring Devices

The initial step in the installation of the vadose-zone monitoring device was to cut the casing sections into the proper lengths so the monitoring points would be at the appropriate depths. The device was assembled at the surface to assure proper depth placement of the monitoring points prior to placing the device downhole. It was then disassembled for placement downhole. Electrodes and thermocouples were also installed inside the vadose-zone monitoring devices for use in monitoring a steam extraction test conducted after completion of the SVE test. There is no further discussion of the electrodes and thermocouples as they are beyond the scope of this investigation. The device was placed downhole one section at a time through the center of the augers.

The screen was installed by first attaching the tee to the top of the assembled casing. The teflon tubing was then fed from the top through the side port of the tee. The teflon tubing was then pressed into the screen insert that was then pressed into the side port of the tee (Fig. 16). The tubing was then fed through the center of the subsequent sections of casing until the surface was reached.

### Installation of SVB-GP-008A

The casing for SV-8A was 2-inch Schedule 40 polyvinyl chloride (PVC). The final construction details for SV-8A are shown in Figure 17. All cement, sand, and bentonite pellets used in the monitoring device completion were placed downhole with a tremie pipe through the center of the augers. During placement of these materials the depth was frequently measured to ensure that the materials were being placed in the correct depth intervals.

The boring was backfilled to a depth of 80.67 feet bgs with fast drying cement. After the cement had dried for approximately half an hour, a one-foot layer of Lonestar No. 3 sand was placed around the monitoring point. A 0.5-foot layer of Lonestar No. 0/30 sand was placed above the coarser sand. In order to protect the sandpack from grout infiltration, a 0.5-foot-thick layer of 0.25-inch bentonite pellets was placed over the finer sand. An approximately 1.0-foot layer of fast drying grout was tremied over the bentonite and allowed to dry. Fast drying grout was then tremied to a depth approximately 0.5 feet below the next monitoring point. This process was then repeated until the uppermost monitoring point was reached. After the 1.0-foot layer of fast drying cement was placed over the uppermost layer of bentonite and allowed to dry, the borehole was backfilled with grout to a depth of approximately 1.5 feet bgs.

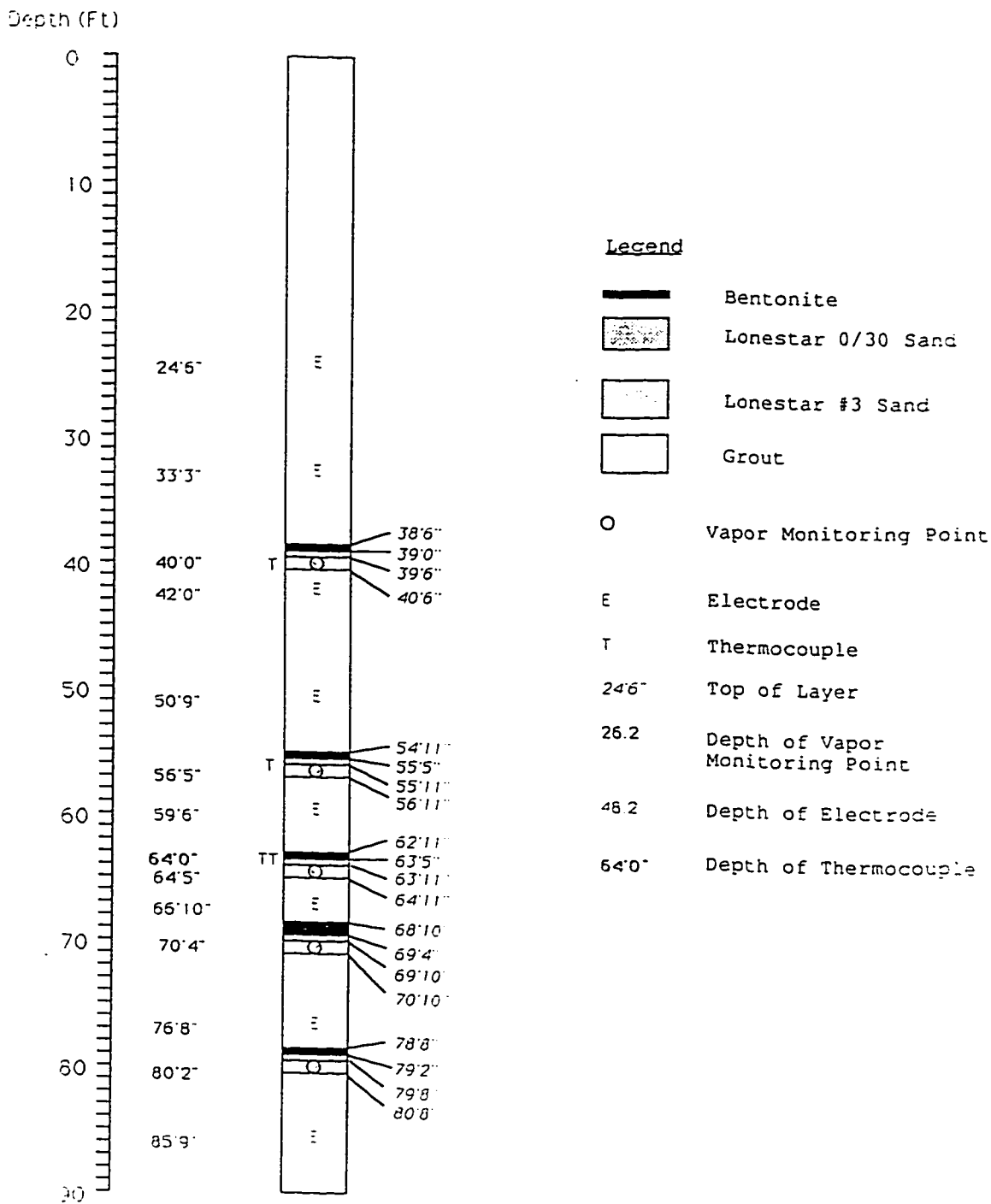


Figure 17. Schematic of vadose-zone monitoring device SV-8A.

### Installation of SVB-GP-013 and SVB-GP-014

The same procedures used during the installation of SV-8A were used in the installation of SV-13 and SV-14 with the following exceptions:

- The casing was 2-inch polyvinyl difluoride (PVDF) to prevent breakdown during the upcoming steam extraction tests.
- The inside of the casing was filled with Lonestar No. 0/30 sand to help minimize potential cross communication between monitoring points.
- Inside the casing below each monitoring point, a 0.1-foot layer of fast drying grout was poured to prevent cross-communication between monitoring points.
- The sandpack was changed to approximately 2 feet of Lonestar No. 0/30 sand and no Lonestar No. 3 sand in order to prevent fine-grained material from entering the screen.

Figures 18 and 19 present the final construction details for SV-13 and SV-14, respectively.

### Soil Vapor Extraction Tests

A series of SVE tests was performed to evaluate the effects of SVE during individual-zone and multiple-zone extraction. Pressure response and vapor concentration response were monitored to observe the locations where air flow was actively remediating the soil.

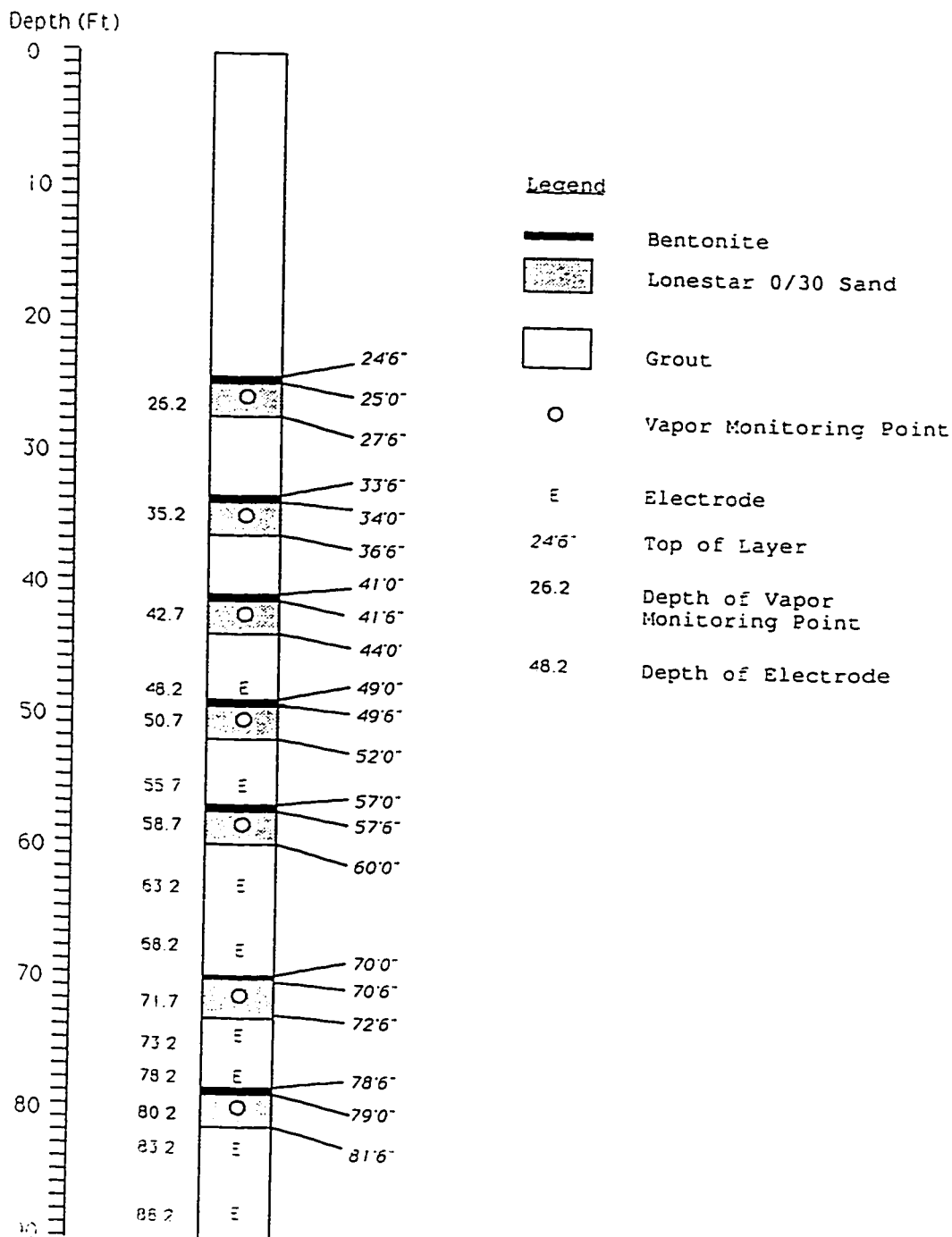


Figure 18. Schematic of vadose-zone monitoring device SV-13.

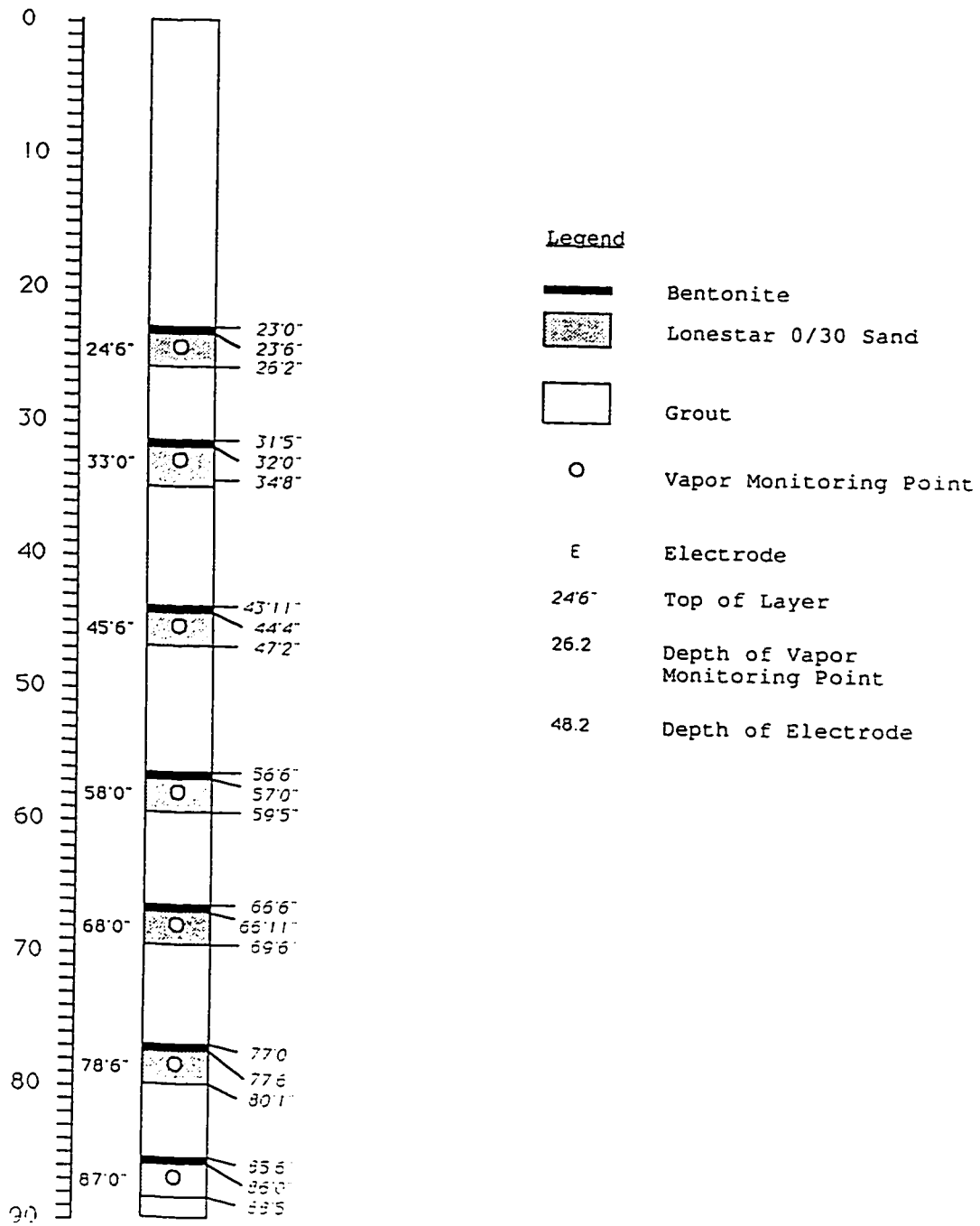


Figure 19. Schematic of vadose zone monitoring device SV-14.



### Individual-Zone Soil Vapor Extraction Tests

The first series of tests involved extracting soil vapor from a single zone in GSW-16. These tests were conducted in Zones 2 through 5 (Fig. 11). The shallowest zone was not tested due to the very low remaining concentrations of contaminants. The purpose of the individual zone tests was to evaluate the vertical and lateral influence of SVE on each zone. Vapor concentrations were monitored to observe the effects of extraction. Ideally, the air-flow rate was maximized during each test. Air flow rates were measured using a Meriam laminar flow element with a Magnehelic differential pressure gauge. Each test was conducted over a period of approximately 24 hours. Over two weeks were allowed at the conclusion of the individual-zone SVE tests to allow the subsurface to re-equilibrate prior to beginning the dual-zone SVE test.

### Dual-Zone Soil Vapor Extraction Test

This test was conducted for a three week period of extraction using Zones 4 and 5 for extraction. The vapor concentrations and pressure response were observed during this test so that a comparison could be made with the individual-zone tests of Zones 4 and 5. The purpose of the dual-zone SVE test was to observe the interaction between two zones and obtain data on the long term effects of vapor extraction on vapor-contaminant distribution. The vapor-contaminant distribution was monitored for two months following termination of the dual-zone SVE test to observe the re-equilibration of the subsurface vapor concentrations.

### Vacuum Response Monitoring

Monitoring points expected to have large responses were monitored using pressure transducers with a range of 0 to 10 inches of water. Pressure transducers with a range of 0 to 5 inches of water were used for those points with an expected moderate response. A pressure transducer with a range of 0 to 30 inches of mercury was used for extraction well GSW-16. Points that were expected to have a small response used transducers with a range of 0 to 2 inches of water.

### Vapor Sampling

Vapor sampling from the monitoring points was done with a metal bellows pump capable of pulling a vacuum of 30 inches of mercury. A 0.5- $\mu\text{m}$  filter was installed at the pump inlet to protect it from inspiration of fine-grained sediment. The pump was attached to the monitoring tube by a piece of tygon tubing pushed onto a pair of barbed fittings. To purge the line and sandpack, we removed 0.6 ft<sup>3</sup> of vapor prior to sampling. The removal of this volume should not significantly impact the overall distribution of vapor contaminants because the radius of influence only slightly exceeds the radius of the borehole. An air-tight syringe was used to obtain the vapor samples. The sample was drawn, while pumping, by inserting the needle through the tygon tubing. The tygon tubing was changed between samples.

Vapor samples were analyzed on a Photovac Model 10S70 portable gas chromatograph. Calibrations were run at the beginning and end of each day. Additional calibrations were completed as necessary. The standard gas used was a National Bureau

of Standards approved canister containing 50 parts per million by volume (ppmv) each of benzene, toluene, ethylbenzene, P-xylene, M-xylene, and O-xylene for a total of 300 ppmv of BTEX.

A series of calibration analyses was performed prior to the initiation of the SVE tests to compare the results of the Photovac with those of a certified analytical laboratory and an on-site (LLNL) laboratory. Two samples from each monitoring point were drawn for this test. The first was taken into a tedlar gas sampling bag. A syringe sample was immediately taken from the bag for analysis on the Photovac. The tedlar bag was then taken to the on-site laboratory to be analyzed. The LLNL laboratory analyzed the samples within four hours of delivery. The samples were stored at room temperature prior to analysis. The second sample was placed in a stainless steel canister and sent to a certified analytical laboratory.

The first comparison test was completed on SV-8A in February 1991. Comparison of the results from SV-8A-Z3 (Fig. 20) indicates a closer correlation for benzene than for other compounds. The other compounds indicated a difference of approximately one order of magnitude, with the Photovac being consistently higher.

The comparison of vapor samples from SV-8A-Z5 (Fig. 21) indicates a closer correlation for benzene, toluene, and ethylbenzene than for total xylenes and BTEX.. This indicates that the Photovac may be more accurate in areas of higher concentration. The conclusion drawn from this comparison was that the Photovac would be adequate to monitor the vapor concentrations because most monitoring points are located in areas of high expected vapor concentrations. It was also decided to maintain a single operator on

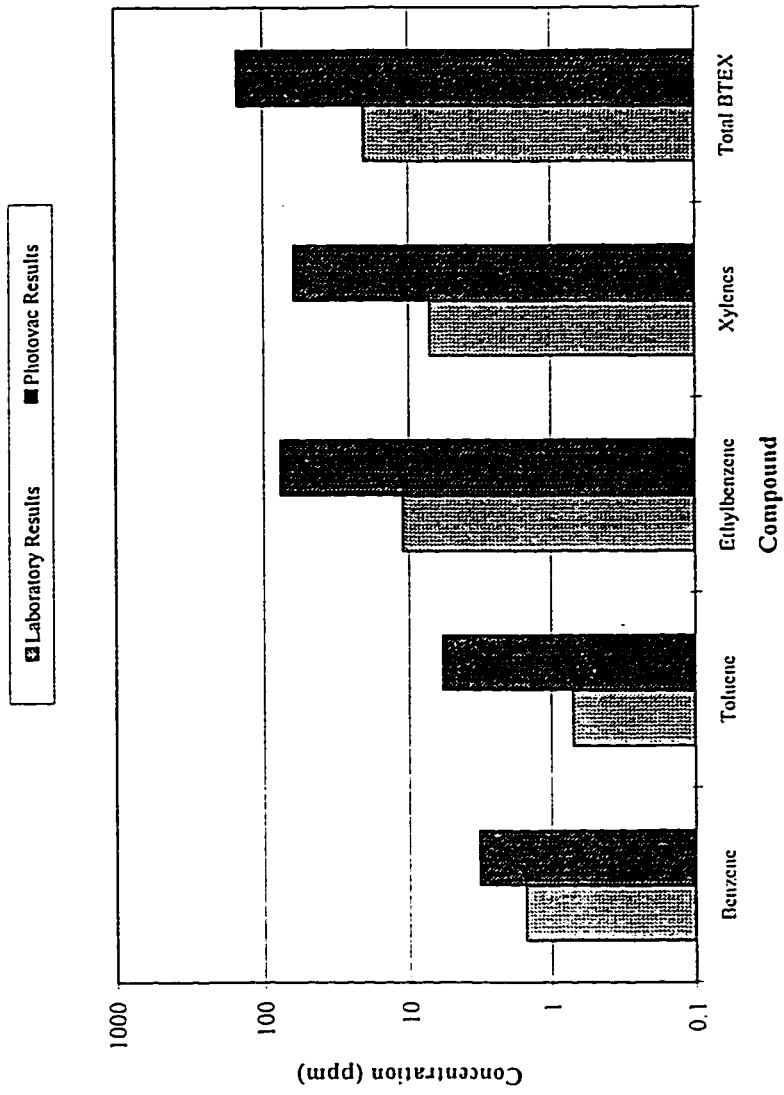


Figure 20. Comparison of analytical laboratory and Photovac analysis results for vapor samples from SV-8A-Z3.

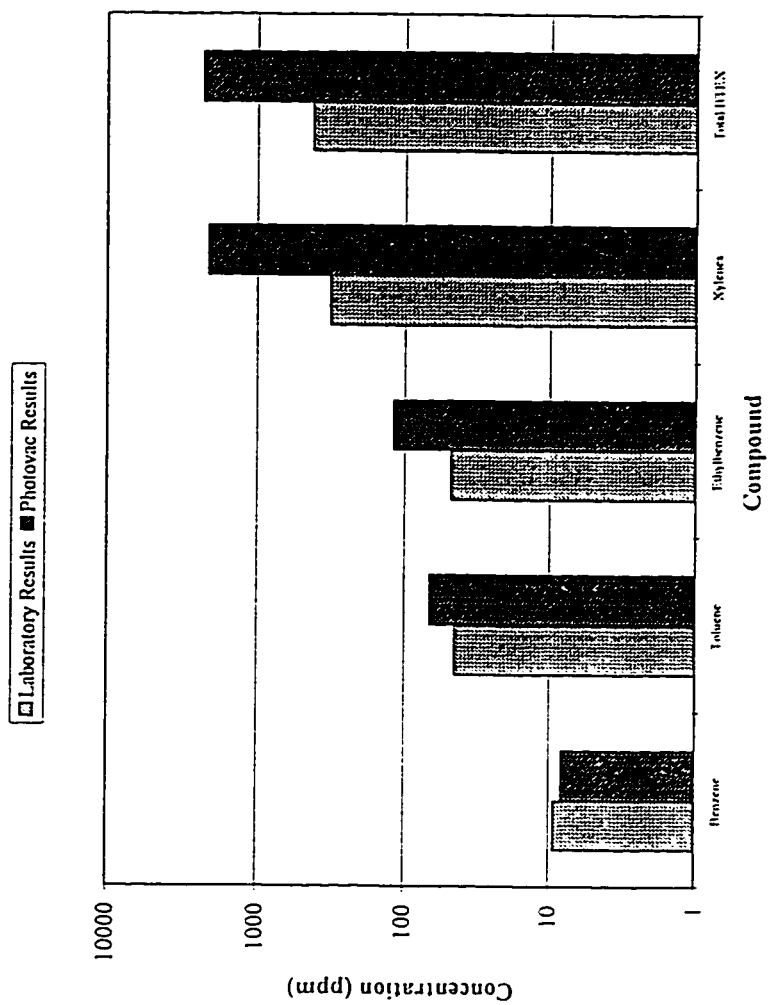


Figure 21. Comparison of analytical laboratory and Photovac analysis results for vapor samples from SV-8A-Z5.

the Photovac as much as possible due to the importance of methodological consistency between analytical runs for precision on the Photovac.

The second round of comparisons was completed in May 1991. Figure 22 shows the results from SV-13-Z1, located in a region of lower vapor concentrations, and from SV-13-Z7 (Fig. 23), in an area of higher vapor concentrations. Results from SV-13-Z1 indicate that the analyses remain within an order of magnitude, except for benzene. Neither the Photovac nor the analytical laboratory provided consistently higher results. Total xylenes and total BTEX are in much closer agreement than in the comparison of results from SV-8A. Analysis of vapor from monitoring point SV-13-Z7 revealed close agreement for all compounds.

The results of the Photovac/laboratory comparison indicate that the Photovac will be adequate to monitor the BTEX concentration in soil vapor. The results were nearly all within an order of magnitude, with the final samples being within a factor of five. The improvement in accuracy over time was most likely due to increased experience in operation of the Photovac.

#### Evaluation of Subsurface Lithology

The high degree of heterogeneity in the subsurface sediment makes the construction of cross sections based strictly on the standard soil classification system meaningless. The sediment was broken into three categories: coarse-, fine-, and mixed-grain size, based on the observations of the field geologist. The coarse unit is composed of sand, gravel, sandy gravel, and gravelly sand. This unit is estimated to have the highest

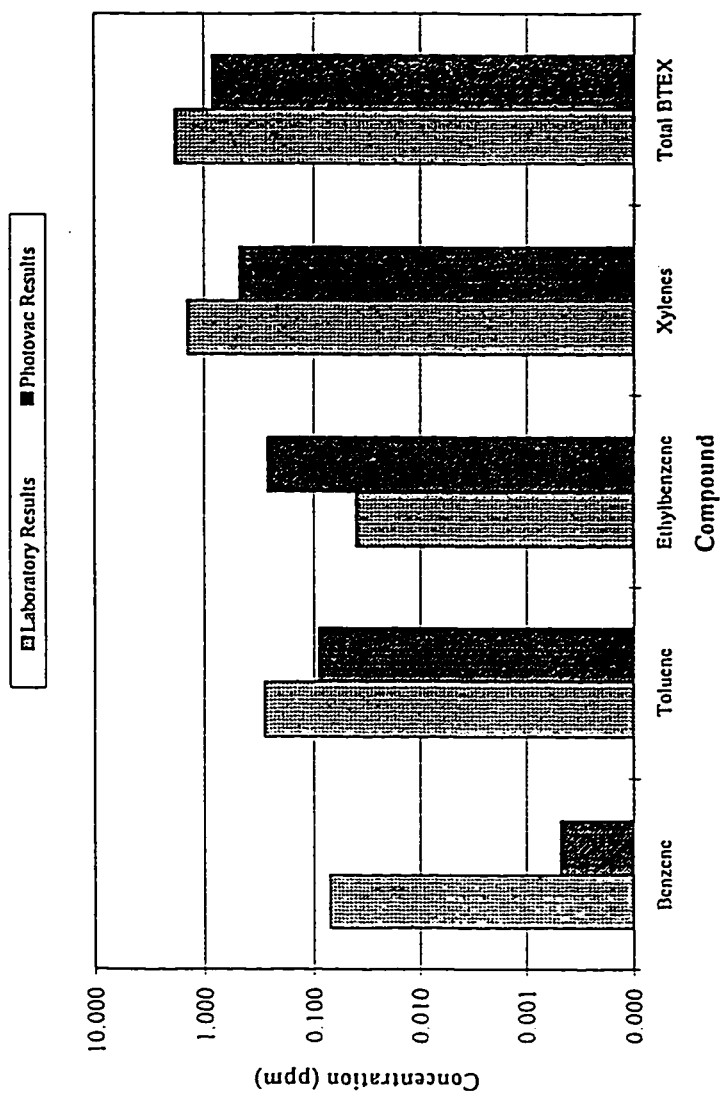


Figure 22. Comparison of analytical laboratory and Photovac analysis results for vapor samples from SV-13-Z1.

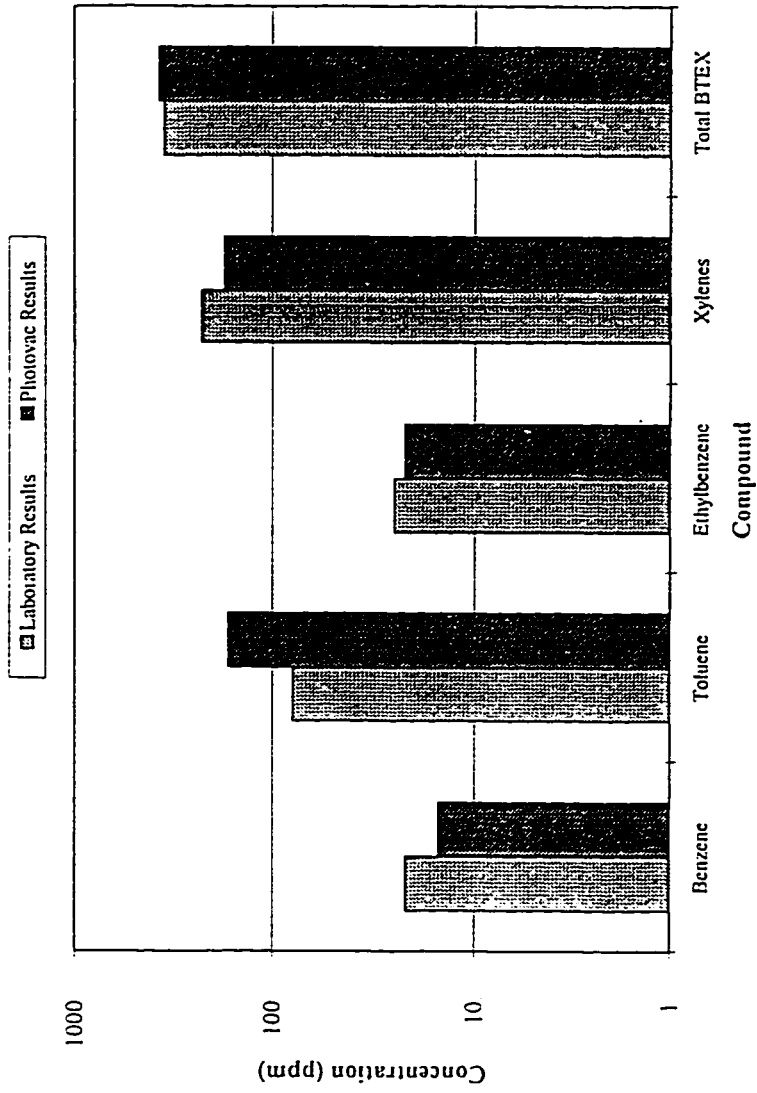


Figure 23. Comparison of analytical laboratory and Photovac analysis results for vapor samples from SV-13-Z7.



permeability. The fine unit, composed of silt, clay, silty clay, and clayey silt, is estimated to have the lowest permeability. The mixed unit is composed of sandy silt, sandy clay, gravely silt, gravely clay, silty sand, silty gravel, clayey sand, and clayey gravel. Because of the wide range in particle sizes, the permeability of this unit is highly variable.

### Evaluation of Soil Physical Characteristics

Soil samples taken from the soil cores obtained during installation of the vadose-zone monitoring devices were sent to a geotechnical soils testing laboratory for analysis for saturated hydraulic conductivity (ASTM D5084-90) and moisture content (ASTM D2216-90). Data reported with the results of these analyses were used to calculate bulk density, porosity, and air-filled porosity. Bulk density is the oven dried mass divided by the field volume of the sample. Porosity is determined by the following formula (Freeze and Cherry, 1979):

$$n = 1 - \rho_b/\rho_p$$

where:

$n$  = porosity (dimensionless)

$\rho_b$  = bulk density ( $\text{g}/\text{cm}^3$ )

$\rho_p$  = particle density ( $\text{g}/\text{cm}^3$ )

Particle density was assumed to be equal to 2.65 grams per cubic centimeter ( $\text{g}/\text{cm}^3$ ) (Freeze and Cherry, 1979). The air-filled porosity is the porosity minus the moisture content.

### Evaluation of Soil Vapor Extraction Test Data

The data obtained during the individual- and dual-zone SVE tests were evaluated to determine the flow rate, mass removal rate, radius of influence, and gas permeability. The data collected in the field for use in determining the air flow rate were the differential pressure across the laminar flow element near the entrance to the blower and the vacuum applied to the extraction well. The following equation was used to determine the air flow rate:

$$Q_a = X_F \times P_d \times [(P_{atm} - P_w)/P_{atm}]$$

where:

- $Q_a$  = air flow rate (standard cubic feet per minute [scfm])
- $X_F$  = manufacturer's conversion factor = 52.2 actual cubic feet per minute (acfm)/inches of H<sub>2</sub>O
- $P_d$  = differential pressure (inches of H<sub>2</sub>O)
- $P_{atm}$  = atmospheric pressure (inches of Hg)
- $P_w$  = wellhead vacuum (inches of Hg)

The mass removal rate was calculated using the air-flow rate and BTEX concentrations obtained during the operation of the SVE system. Several assumptions were made in order to determine the amount of gasoline removed from the subsurface by SVE. The first assumption was that the amount of BTEX in the soil vapor was proportional to its content in free product. Sampling of the free product indicated that BTEX comprised 27.5% of the total composition. It was then assumed that all components of gasoline are being extracted in proportion to their content in gasoline. These assumptions will cause some uncertainty in the amount of gasoline removed from the subsurface. If the BTEX compounds actually are being removed at a rate exceeding

their proportion in gasoline, then the estimate of gasoline extraction is going to be higher than the true rate. This is most likely to occur during the initial stages of extraction, when the more volatile BTEX compounds are preferentially extracted. Towards the latter stages of extraction, the estimate may be lower than the true value if the BTEX has been mostly removed. Another factor that may cause a low estimate is biodegradation, which is stimulated by SVE. These calculations account for only the gasoline removed with the vapor stream; additional gasoline is likely to be removed by microbial metabolism. The following equation was used to determine the mass removal rate for BTEX:

$$M_{\text{BTEX}} = Q \times C_{\text{BTEX}} / 10^{-26} \times \rho_{\text{VBTEX}} / \rho_{\text{LBTEX}} \times 1,440$$

where:

$M_{\text{BTEX}}$  = volumetric removal rate of BTEX (gpd)

$Q_a$  = air flow rate (scfm)

$C_{\text{BTEX}}$  = BTEX concentration (ppmv)

$\rho_{\text{VBTEX}}$  = vapor density = 0.29 lbs/ft<sup>3</sup>

$\rho_{\text{LBTEX}}$  = liquid density = 7.243 lbs/gallon

Johnson *et al.* (1990) developed an equation to predict the flow rate per unit thickness of well screen based on a steady state radial flow solution for compressible

gasses. The equation solved to determine intrinsic permeability of the geologic materials (k) is as follows:

$$k = \{Q_a \mu / [60(H)(\pi)(P_w)]\} \times \{\ln(R_w/R_i) / [1 - (P_{atm}/P_w)^2]\}$$

where:

k = intrinsic permeability (ft<sup>2</sup>)

μ = dynamic viscosity (atm · s, for air: 1.78 x 10<sup>-210</sup> atm · s)

H = screen thickness (ft)

P<sub>w</sub> = wellhead vacuum (atm)

R<sub>w</sub> = radius of extraction well (ft)

R<sub>i</sub> = radius of influence (ft)

P<sub>atm</sub> = atmospheric pressure (atm)

The radius of influence was determined by plotting the vacuum response versus the logarithm of the radial distance from the extraction well. The radius of influence was the x-intercept of the least squares regression line for the data. This equation was based on the assumption that the air-flow was cylindrical in nature. The air-flow observed in the SVE tests appeared to be more spherical. This difference from the equation's assumption may cause the calculated permeability to be higher than the actual value because the spherical response will cause the air-flow rate to be slightly higher than would be experienced under cylindrical flow. This is a result of the addition of flow from above and below the extraction zone.

## RESULTS

### Vadose-Zone Characterization

Installation of the three vadose-zone monitoring devices allowed further characterization of the lithology, moisture content, porosity, saturated hydraulic conductivity, and the hydrocarbon distribution following the initial 179 days of SVE. Tables 1, 2, and 3 summarize the results of the analysis of physical properties performed on soil samples from SV-8A, SV-13, and SV-14, respectively. Soil samples for physical property analyses were obtained on an average of every 2.6 feet in SV-8A and approximately every 11 feet in SV-13 and SV-14. These are discussed below.

### Lithology

A lithologic cross-section through the three vadose-zone monitoring devices is presented in Figure 24. The location of the cross-section is presented in Figure 3. The boring logs are presented in the Appendix. Mixed sediment is the most common sediment type encountered in the GSA. This is the dominant sediment type between approximately 15 and 60 feet bgs. Thin, discontinuous lenses, typically less than two feet thick, of both coarse and fine sediment are found in this interval. Thicker coarse layers are found from 10 to 17 feet bgs in SV-13 and SV-14, and from 70 to 75 feet bgs in SV-8A and SV-13.

The potential implications of this sediment distribution on SVE are important to note. Preferential vapor flow is likely to occur in the coarse units. The thick sequence of mixed sediment is likely to be an area of lower vapor flow because of the presence of fine

Table 1. Results of physical analyses of soil samples from SV-8A.

Depth (feet)	Soil Type (USCS)	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Porosity (%)	Air-filled Porosity (%)	Hydraulic Conductivity (ft/d)
27.9	CL	1.87	14.9	29.4	14.5	$7.78 \times 10^{-3}$
30.8	CL	1.67	19.9	37.0	17.1	$4.62 \times 10^{-5}$
31.7	ML	1.59	18.3	40.0	21.7	$1.16 \times 10^{-2}$
33.7	ML	1.59	18.4	40.0	21.6	$3.91 \times 10^{-1}$
34.5	ML	1.61	18.5	39.3	20.8	$2.30 \times 10^{-1}$
35.9	ML	1.71	19.5	35.5	16.0	$2.38 \times 10^{-4}$
37.3	SM	1.79	16.1	32.5	16.4	$1.05 \times 10^{-3}$
40.5	ML	1.54	11.1	41.9	30.8	$9.53 \times 10^{-1}$
42.2	ML	1.72	15.6	35.1	19.5	$1.38 \times 10^{-1}$
45.4	ML	1.65	17.3	37.7	20.4	$2.48 \times 10^{-2}$
46.8	ML	1.60	22.8	36.6	16.8	$1.14 \times 10^{-2}$
48.2	ML	1.61	23.2	39.3	16.1	$8.28 \times 10^{-5}$
51.1	SM	1.79	15.0	32.5	17.5	$1.26 \times 10^{-1}$
52.9	ML	1.86	16.6	29.8	13.2	$1.51 \times 10^{-4}$
56.0	CL	1.80	16.7	32.1	15.4	$4.51 \times 10^{-4}$
60.4	ML	1.58	22.0	40.4	18.4	$1.53 \times 10^{-2}$
63.9	SM	1.59	14.3	40.0	25.7	$6.61 \times 10^{-2}$
65.5	CL	1.69	19.2	36.2	17.0	$1.75 \times 10^{-3}$
66.9	ML	1.65	18.4	37.7	19.3	$2.98 \times 10^{-2}$
68.4	SM	1.64	14.4	38.1	23.7	$5.39 \times 10^{-3}$
74.7	GM	1.66	16.7	37.4	20.7	$3.37 \times 10^{-3}$
78.6	ML	1.62	16.7	38.9	22.2	$4.79 \times 10^{-1}$
80.0	SM	1.61	15.1	39.3	24.2	$1.92 \times 10^{-1}$
86.0	SM	1.65	14.7	37.7	23.0	$5.84 \times 10^{-2}$

sediment filling the pore space between the coarser grains. The effect of having a thick sequence of mixed sediment may also result in a vacuum distribution more reflective of a homogeneous medium.

Table 2. Results of physical analyses of soil samples from SV-13.

Depth (feet)	Soil Type (USCS)	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Porosity (%)	Air-filled Porosity (%)	Hydraulic Conductivity (ft/d)
4.2	CL	1.77	14.0	33.2	19.2	1.17 x 10 <sup>-4</sup>
15.5	SW	1.66	14.2	37.4	23.2	8.82 x 10 <sup>-3</sup>
26.7	SM	1.75	15.5	34.0	18.5	4.20 x 10 <sup>-3</sup>
38.6	CL	1.67	18.2	37.0	18.8	5.07 x 10 <sup>-3</sup>
48.4	CL	1.71	7.0	35.5	28.5	1.03 x 10 <sup>-2</sup>
57.0	ML	1.67	19.7	37.0	17.3	4.05 x 10 <sup>-3</sup>
68.6	CL	1.74	16.0	34.3	18.3	3.26 x 10 <sup>-3</sup>
77.0	ML	1.72	18.0	35.1	17.1	2.33 x 10 <sup>-2</sup>

### Moisture Content

The moisture content in the samples from SV-8A ranged from 11.1 to 23.2 %, averaging 17.3%. It should be noted that the three layers with the highest moisture contents (30 to 36 feet, 47 to 48 feet, and 60 feet bgs) correspond with depths located between extraction well GSW-16's screened intervals. The two layers with the lowest moisture contents are at depths corresponding to the screened intervals GSW-16-Z2 and GSW-16-Z4. There is no apparent correlation between moisture content and grain size.

Table 3. Results of physical analyses of soil samples from SV-14.

Depth (feet)	Soil Type (USCS)	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Porosity (%)	Air-filled Porosity (%)	Hydraulic Conductivity (ft/d)
6.9	SC	1.45	10.6	45.3	34.7	4.48 x 10 <sup>-3</sup>
20.1	CH	1.88	15.7	29.1	13.4	2.02 x 10 <sup>-4</sup>
28.5	CL	1.64	14.0	38.1	24.1	5.16 x 10 <sup>-1</sup>
39.1	CL	1.71	13.2	35.5	22.3	1.39 x 10 <sup>-1</sup>
50.8	ML	1.66	13.3	37.4	24.1	2.52 x 10 <sup>-1</sup>
60.1	SC	1.78	13.0	32.8	19.8	4.39 x 10 <sup>-2</sup>
69.7	CH	1.72	20.2	35.1	14.9	1.22 x 10 <sup>-4</sup>
78.5	SM	1.53	18.7	42.3	23.6	3.94 x 10 <sup>-1</sup>

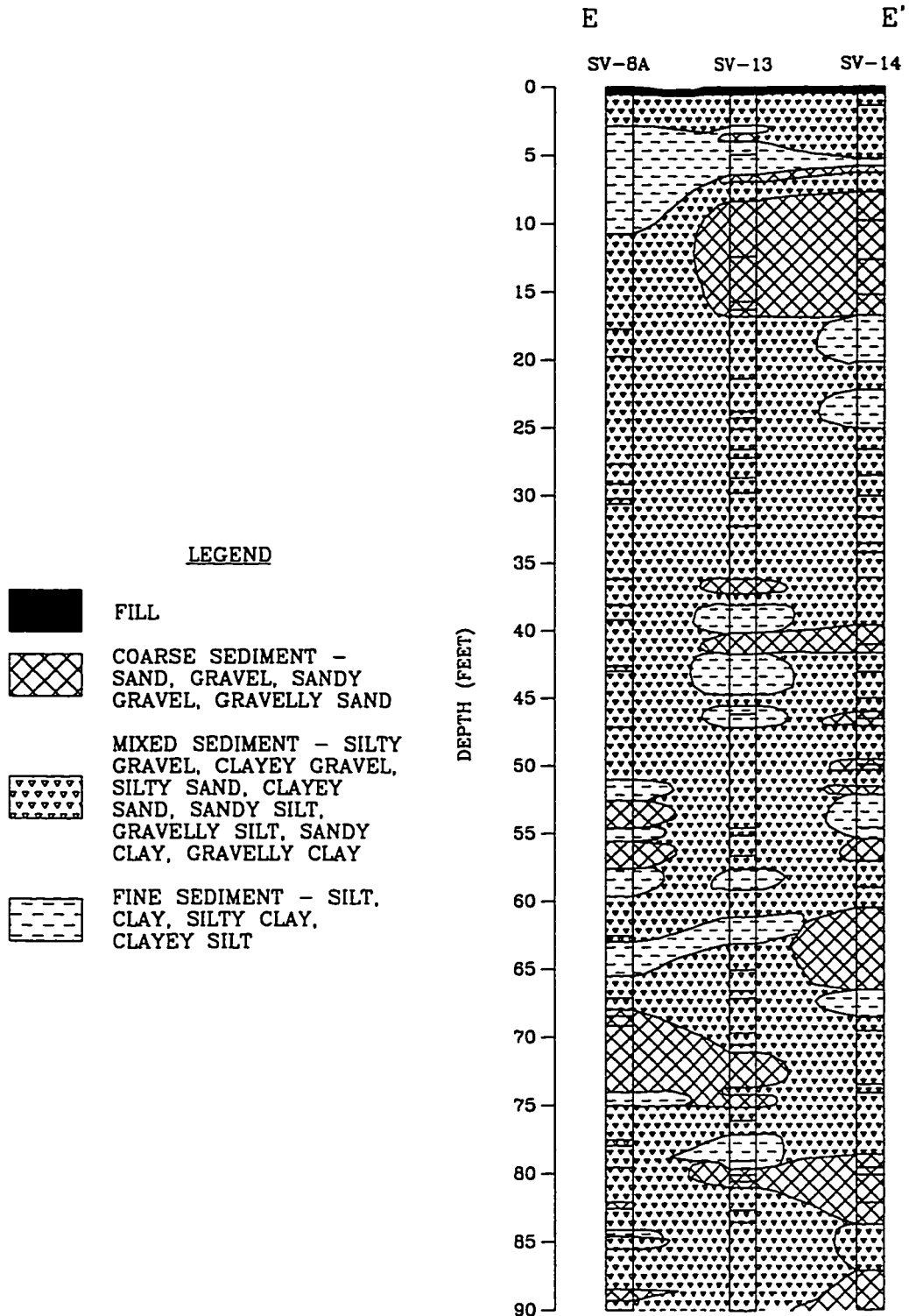


Figure 24. Geologic cross section E-E' (Cook *et al.*, 1991).



The moisture content averaged 15.3%, ranging from 7.0 to 19.7%, in SV-13. The lowest moisture content was obtained from a sandy clay corresponding to a depth immediately above extraction zone GSW-16-Z3. The highest moisture content was obtained from a thin sandy silt just below the depth of GSW-16-Z3. A fine-grained layer underlies the sample location. This may indicate that moisture is being retained in the coarse-grained unit because water is being prevented from downward migration.

Soil samples from the installation of vadose-zone monitoring device SV-14 had an average moisture content of 14.8%. The moisture content ranged from 10.6 to 20.2%. The moisture distribution was much more uniform between 20 and 60 feet bgs at SV-14 than at either of the other two vadose-zone monitoring devices, ranging from 13.0 to 15.7%. The uniformity of the moisture content distribution may indicate that air flow in the vicinity of SV-14 is more uniform through this interval.

### Porosity

The range of total porosity in the samples from SV-8A is 29.4 to 41.9%. The average is 37.0%. Samples from the boring for vadose-zone monitoring device SV-13 had an average total porosity of 35.4%, ranging from 33.2 to 37.4%. The total porosity of samples from SV-14 ranged from 29.1 to 45.3% with an average of 36.9%. SVE works by drawing soil vapor through the soil pores. The portion of the pores that the vapors move through is air-filled. Vadose-zone monitoring devices SV-8A, SV-13, and SV-14 have average air-filled porosities of 19.7% (ranging from 13.2 to 30.8%), 20.1% (ranging from 17.1 to 28.5%), and 22.1% (ranging from 13.4 to 34.7%), respectively.

The air-filled porosity will vary over time because of changes in moisture content related to infiltration from rainfall events, subsequent dry periods, and moisture migration. At the GSA, changes in the moisture content are primarily caused by SVE. The asphalt cover over the GSA most likely minimizes the effects of rainfall infiltration and evaporation. The action of SVE may dry the sediment, thus increasing the air-filled porosity. Johnson *et al.* (1990) stated that changes in air-filled porosity may not be significant when soil moisture is less than 20%. No relation was observed between porosity or air-filled porosity and soil type or screen depth in GSW-16.

#### Saturated Hydraulic Conductivity

The horizontal saturated hydraulic conductivity values ranged from  $4.62 \times 10^{-5}$  ft/d to  $9.53 \times 10^{-1}$  ft/d. No laterally continuous layers of high or low hydraulic conductivity could be correlated between the borings. The apparent uniformity observed in the samples from SV-13 probably was the result of the small number of samples analyzed.

#### Hydrocarbon Distribution

The post-SVE hydrocarbon distribution in soil is presented in Figure 25. A cross section through the three vadose-zone monitoring devices was constructed to illustrate the Spring 1991 hydrocarbon distribution. The location of this cross-section is presented in Figure 3. Both BTEX (Fig. 25-A) and TPH-g (Fig. 25-B) are contoured to show the differing effects of SVE on BTEX and the less volatile compounds found in gasoline.

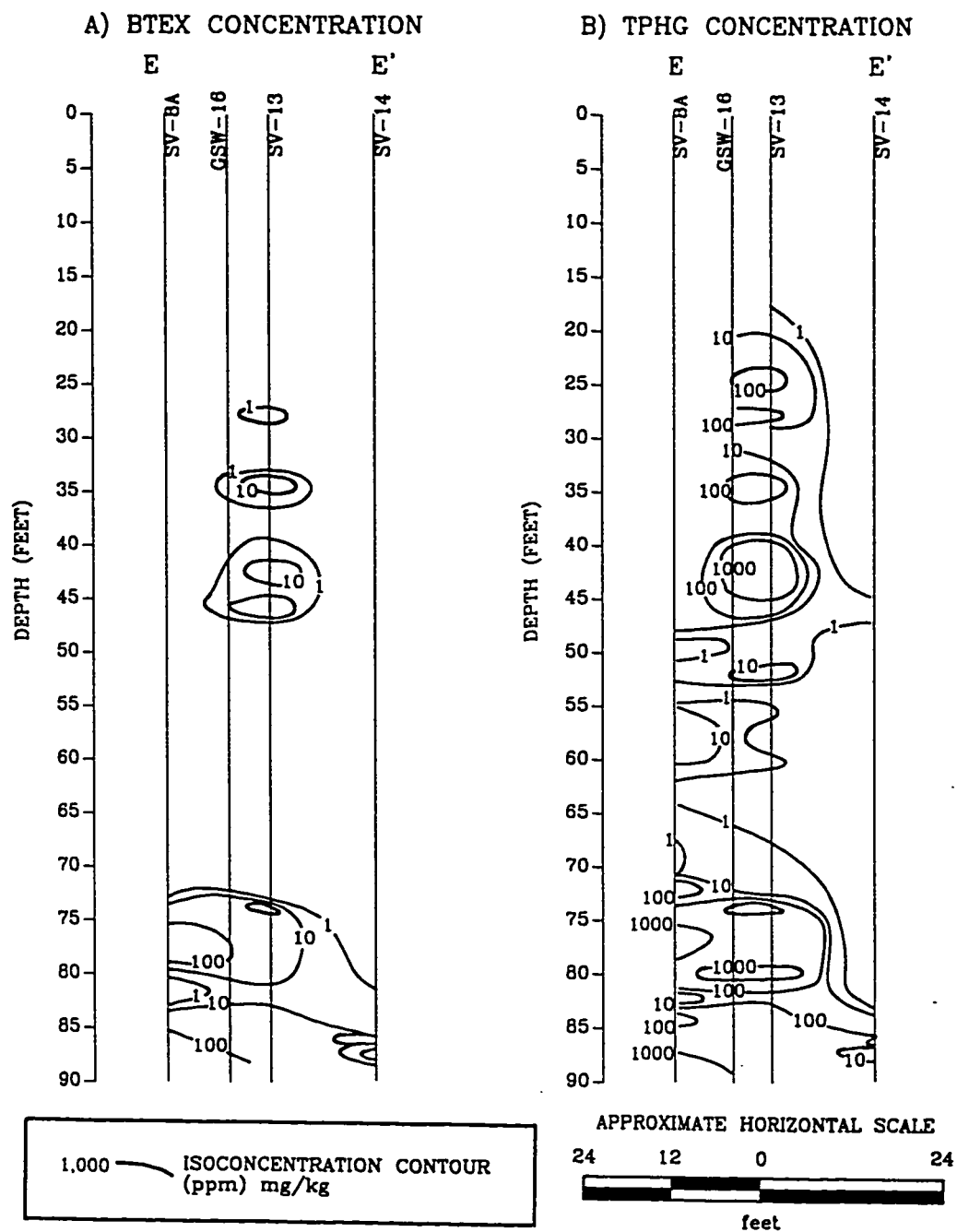


Figure 25. Profiles of BTEX and TPH-g concentrations in soil in cross section E-E' (Cook *et al.*, 1991). GSW-16 is presented for reference only; soil data from GSW-16 were not utilized in preparing the concentration contours.

The remaining BTEX (Fig. 25A) is primarily at depth, near the water table. BTEX concentrations exceeding 10 milligrams per kilogram (mg/kg) remain between 34 feet and 46 feet bgs in the vicinity of SV-13. Between the depths of 46 and 73 feet bgs BTEX concentrations were less than 1 mg/kg.

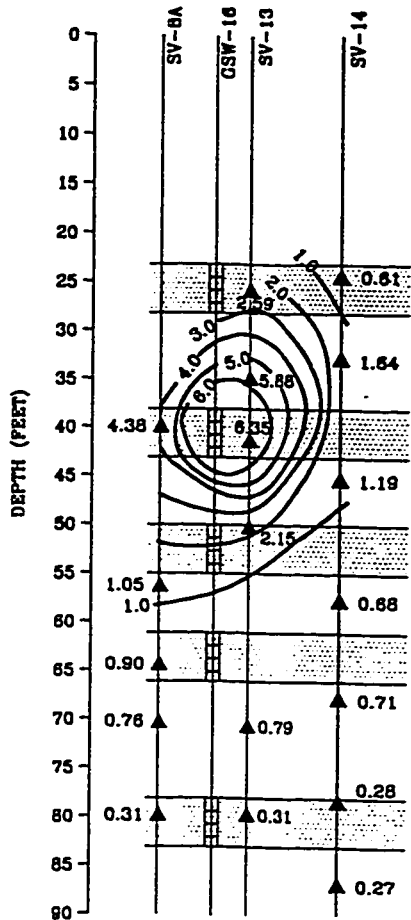
TPH-g (Fig. 25B) remains more widely distributed in the vadose zone below a depth of 18 feet bgs. The TPH-g distribution shows similarities to the BTEX distribution. Between 34 and 46 feet bgs in the vicinity of SV-13, the same interval with BTEX concentrations exceeding 10 mg/kg, TPH-g concentrations exceeded 1,000 mg/kg. TPH-g concentrations exceeding 1,000 mg/kg remain below a depth of 75 feet bgs.

The highest residual BTEX and TPH-g concentrations are associated with fine-grained sediment layers. This is a result of the sorption of fine-grained sediment and indicates that these sediments are bypassed by air flow.

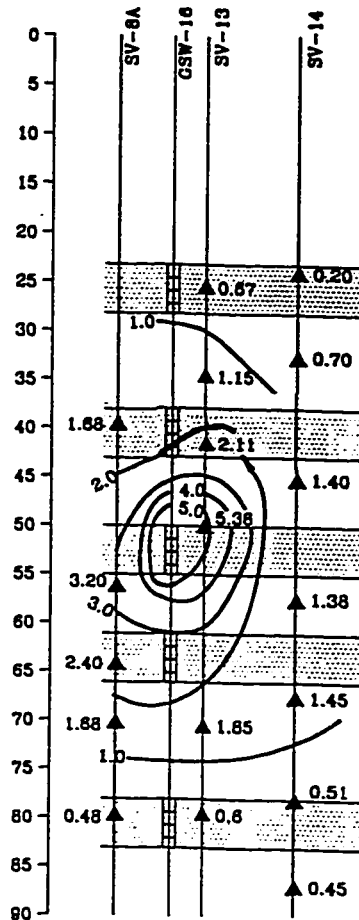
#### Individual Zone Soil Vapor Extraction Tests

The vertical and horizontal vacuum responses for the individual-zone tests are presented in Figure 26. The pressure readings presented represent steady state values. Steady state was reached within one hour during each SVE test. The results are summarized in Table 4.

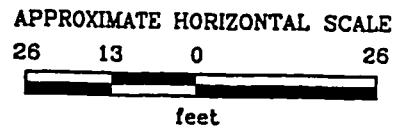
A) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONE 2



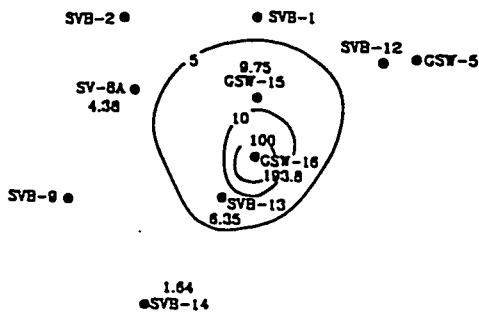
C) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONE 3



- ▲ MONITORING POINT
- WELL SCREEN
- 6.35 VACUUM RESPONSE (INCHES OF WATER)
- 6.0 ISOPRESSURE CONTOUR
- DEPTH CORRESPONDING WITH GSW-16 SCREENED INTERVAL



B) ZONE 2 VAPOR EXTRACTION TEST CONTOURS BASED ON POINTS AT 40' DEPTH (INCHES OF H<sub>2</sub>O)



D) ZONE 3 VAPOR EXTRACTION TEST CONTOURS BASED ON POINTS AT 50' DEPTH (INCHES OF H<sub>2</sub>O)

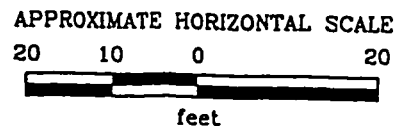
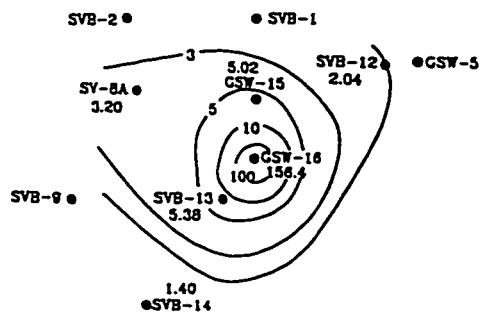
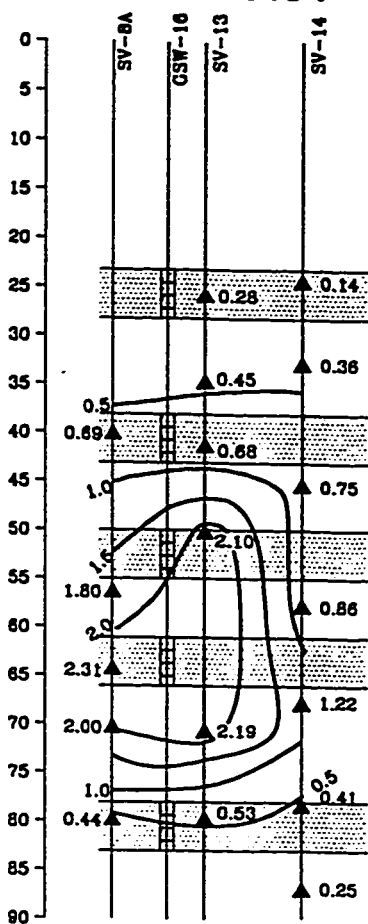


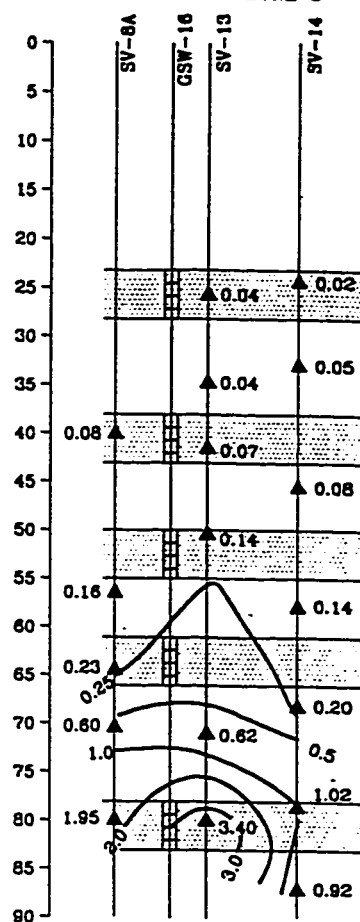
Figure 26. Vertical and horizontal vacuum response profiles for the individual-zone SVE tests. Note the differing contour intervals.



E) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONE 4



G) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONE 5



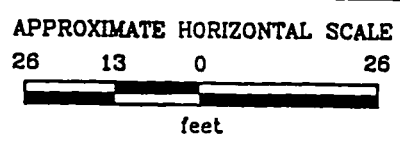
▲ MONITORING POINT

□ WELL SCREEN

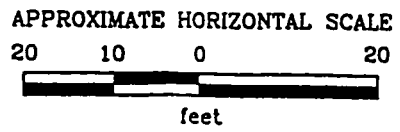
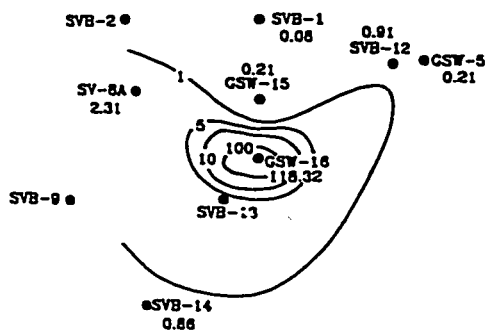
6.35 VACUUM RESPONSE (INCHES OF WATER)

6.0 ISOPRESSURE CONTOUR

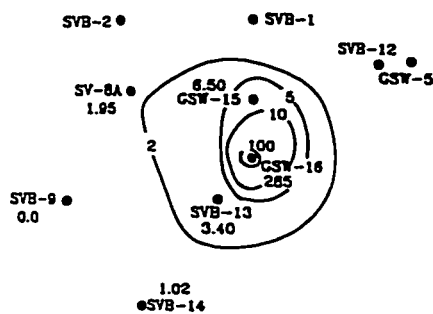
DEPTH CORRESPONDING WITH GSW-16 SCREENED INTERVAL



F) ZONE 4 VAPOR EXTRACTION TEST CONTOURS BASED ON POINTS AT 60' DEPTH (INCHES OF H<sub>2</sub>O)



H) ZONE 5 VAPOR EXTRACTION TEST CONTOURS BASED ON POINTS AT 80' DEPTH (INCHES OF H<sub>2</sub>O)



ual-zone





Table 4. Soil vapor extraction test data from individual-zone SVE tests.

Extraction Zone	Depth (feet)	Vacuum (in H <sub>2</sub> O)	Flow (scfm)	BTEX (ppmv)	BTEX Removed (gallons)	Gasoline Removed (gallons)	Extraction Rate of Gasoline (gpd)
2	38-43	194	21.2	58	0.2	0.8	0.8
3	50-55	156	26.1	156	0.6	2.2	2.2
4	61-66	118	26.8	73	0.2	0.8	0.9
5	78-83	285	16.8	378	0.9	3.3	3.4

### Zone 2

The first individual-zone SVE test extracted soil vapor from zone 2 in extraction well GSW-16. This zone is located between the depths of 38 and 43 feet bgs (Fig. 26-A). A slight vacuum response was observed in monitor well GSW-4, located approximately 100 feet to the northwest. The slight response at the water table (approximately 100 feet bgs) in well GSW-4 is an indication of vertical air flow.

The lateral response was roughly circular in shape (Fig. 26-B). A response of 5 inches of water extended approximately 12 feet to the north of extraction well GSW-16 and 8 feet to the south.

### Zone 3

The vertical vacuum response profile is shown in Figure 26-C. The vertical response is roughly circular in shape. Figure 26-D presents the horizontal vacuum response, which was elongated to the northwest.

#### Zone 4

The third SVE test utilized GSW-16-Z4, located from 61 to 66 feet bgs. The vertical vacuum response (Fig. 26-E) was more vertically elongated than that observed in the other zones. The plan view of the response observed during the zone 4 test was skewed by the low response observed in GSW-15-Z4 (60 to 64 feet bgs; Fig. 26-F). This monitoring point had a response of only 0.21 inches of water, even though it is screened at the same depth as GSW-16-Z4 and is only 5 feet to the north. The lack of response in this zone is interpreted to be caused by the placement of GSW-15-Z4 in a clay layer.

#### Zone 5

The final individual-zone test was conducted on GSW-16-Z5, located at a depth of 78 to 83 feet bgs. Figures 26-G and 26-H present the vertical and horizontal vacuum response profiles, respectively. The shape of the vacuum response in plan view was approximately circular. The vertical response was more restricted than that observed in the previous individual-zone tests. The 1 inch of water contour is located at a depth of approximately 75 feet bgs in each vadose-zone monitoring device. The restricted vertical response results from the fact that the GSW-16-Z5 screen is located in coarse-grained sediment overlain by a zone of fine-grained sediment. The proximity to the water table may also be limiting the response by increasing the moisture content.

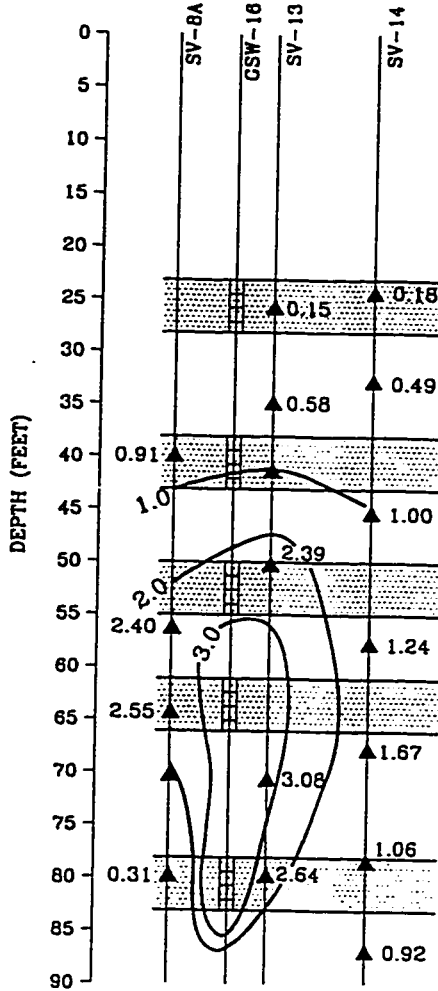
### Dual-Zone Soil Vapor Extraction Test

The dual-zone SVE test utilized two zones, GSW-16-Z4 and GSW-16-Z5, for extraction to test the effects of vapor withdrawal from multiple zones. These two zones were selected due to their differing individual responses to SVE and to the high remaining hydrocarbon concentrations at depth. The total test time was 22 days. The original test methodology called for applying the maximum vacuum possible in order for the operating limits to be imposed by the hydraulic properties of the sediment rather than by the pump. It was not possible to maintain the maximum vacuum and resulting high flow rate because of constraints placed by the thermal oxidizer treatment system. The vapor flow to the thermal oxidizer had to be reduced in order to maintain the flame.

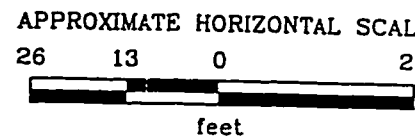
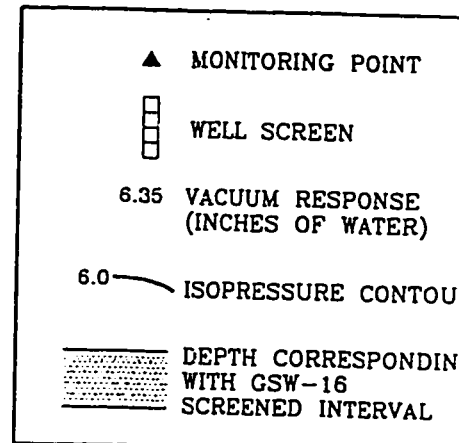
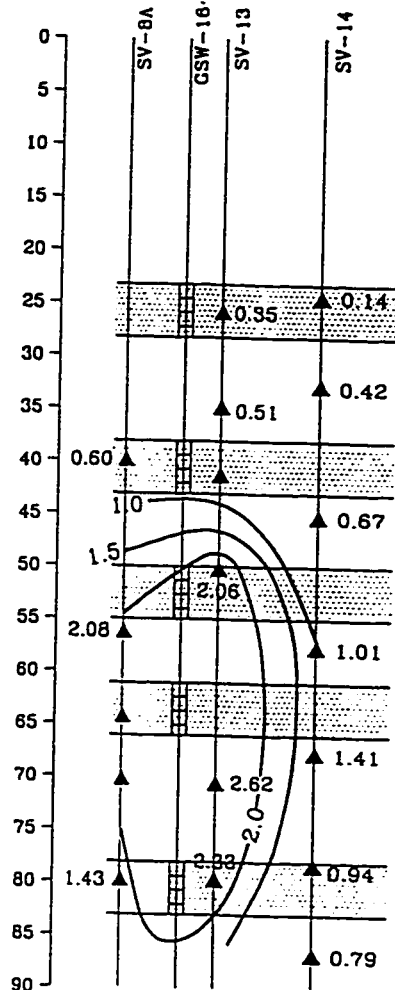
The change in the applied vacuum over the test period resulted in variations in the subsurface equilibrium. Analysis of the wellhead vacuum data indicated that steady state was reached during 12 separate time periods. Each of these periods had differing applied vacuums and flow rates. As a result, the subsurface response also varied over the 12 time periods. Figures 27 through 29 present vertical cross sections through SV-8A, SV-13, and SV-14 illustrating the vertical vacuum response at depths of 55 to 80 feet bgs for each of the time periods. For the plan view, presented below its corresponding cross section, the highest vacuum response from each vadose-zone monitoring device was used for contouring. Table 5 presents a summary of the dual-zone SVE test data.

The response patterns observed were similar to the pattern observed during the individual-zone SVE test for GSW-16-Z4, but a larger response at depth indicated influence from GSW-16-Z5.

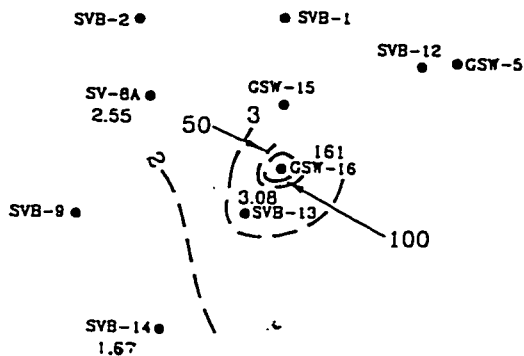
A) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 0 TO 0.27 DAYS



C) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 0.27 TO 1.09 DAYS



B) 0 TO 0.27 DAYS



D) 0.27 TO 1.09 DAYS

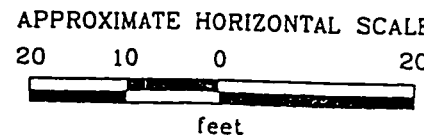
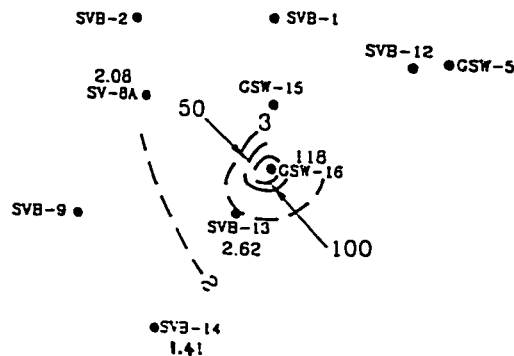
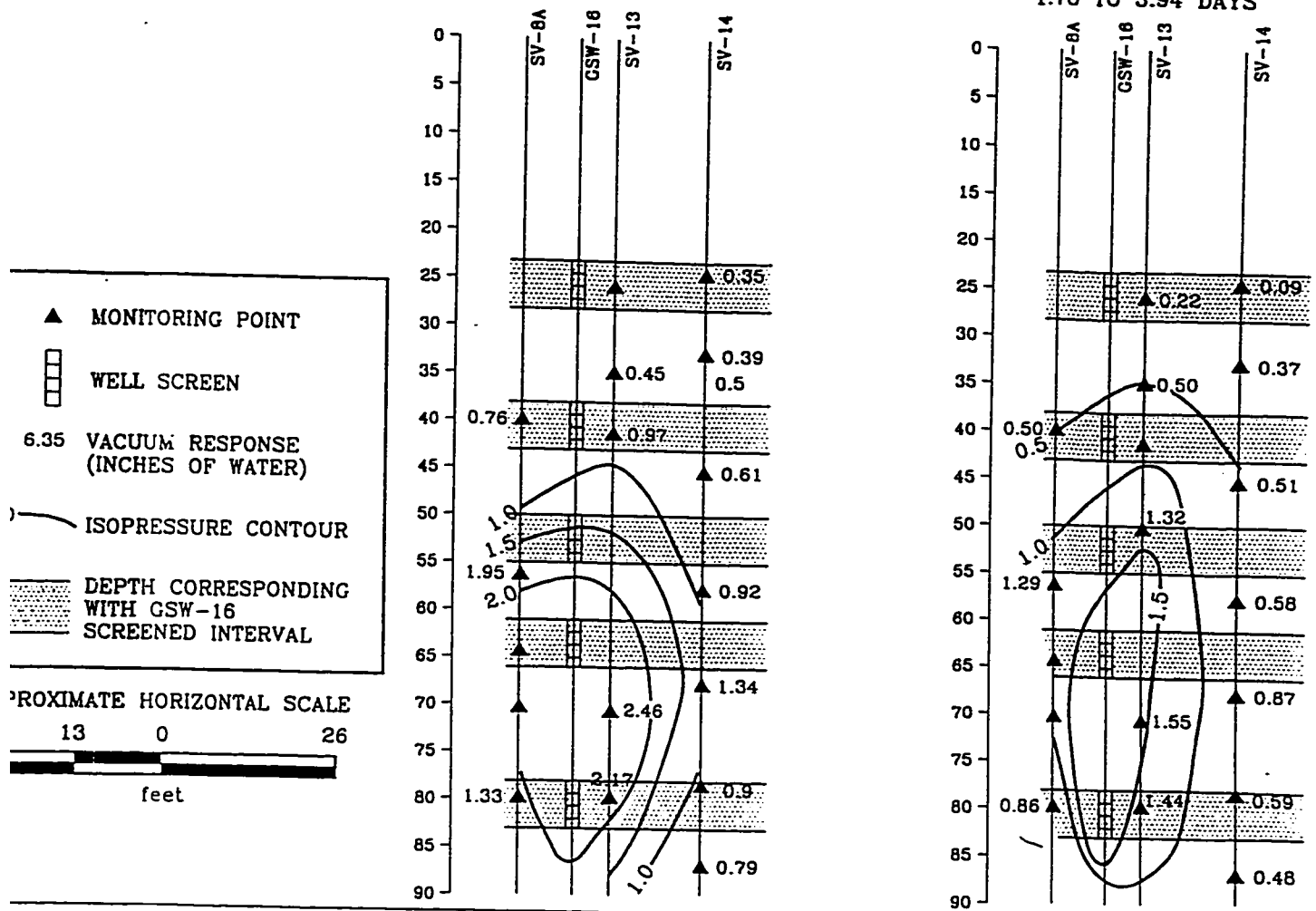


Figure 27. Vertical and horizontal vacuum responses for the dual-zone SVE test, time periods 0 to 3.94 days. Note the differing contour intervals.



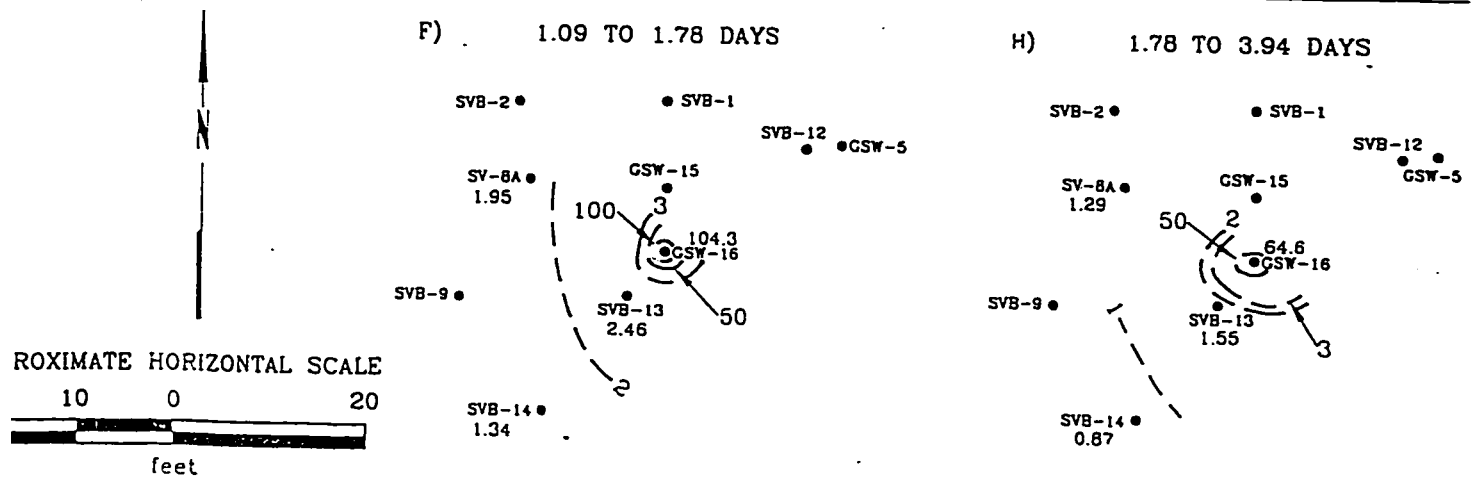
E) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 1.09 TO 1.78 DAYS

G) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 1.78 TO 3.94 DAYS



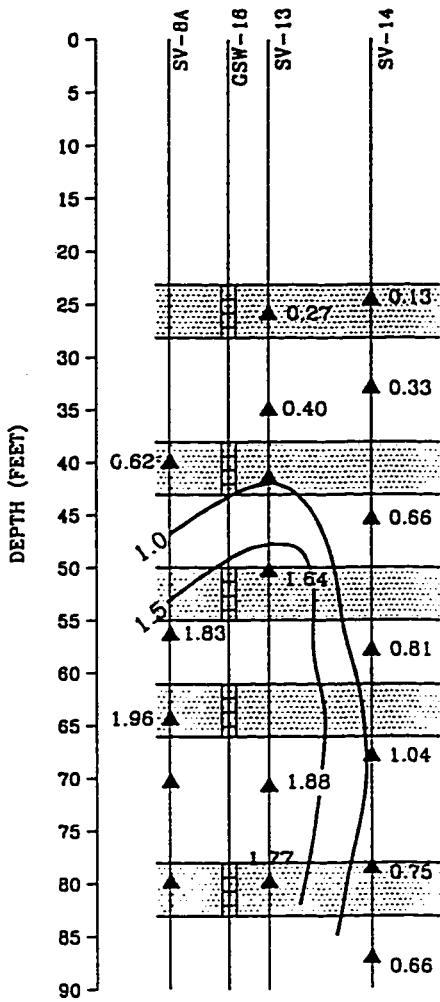
F) 1.09 TO 1.78 DAYS

H) 1.78 TO 3.94 DAYS

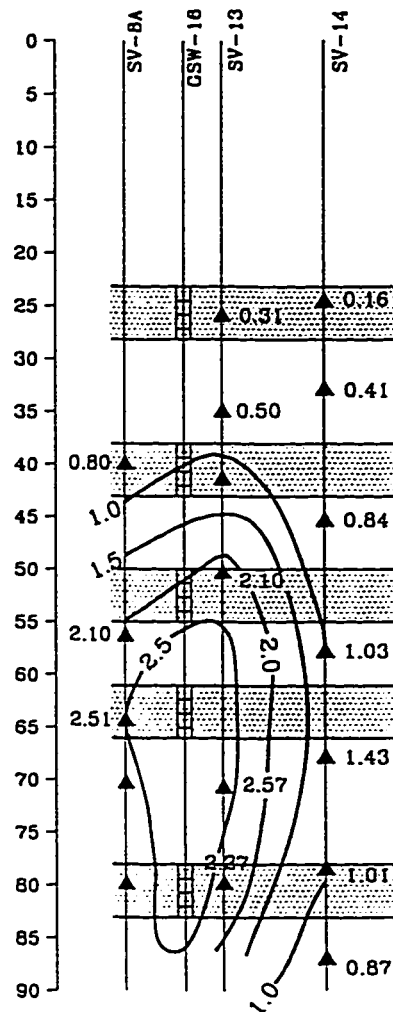




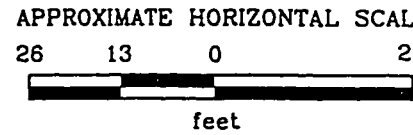
A) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 3.94 TO 9.86 DAYS



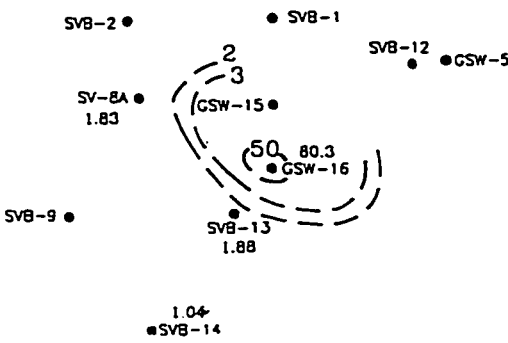
C) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 9.86 TO 10.74 DAYS



▲ MONITORING POINT  
 □ WELL SCREEN  
 2.57 VACUUM RESPONSE (INCHES OF WATER)  
 2.5 ISOPRESSURE CONTOUR  
 [Hatched Box] DEPTH CORRESPONDING WITH GSW-16 SCREENED INTERVAL



B) 3.94 TO 9.86 DAYS



D) 9.86 TO 10.74 DAYS

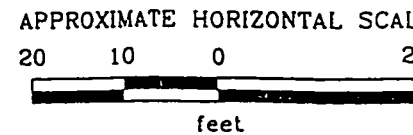
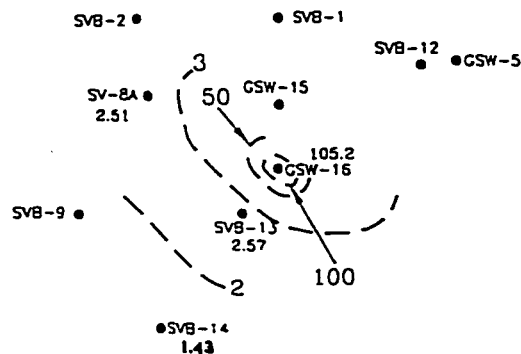


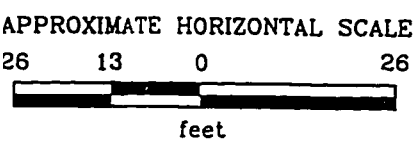
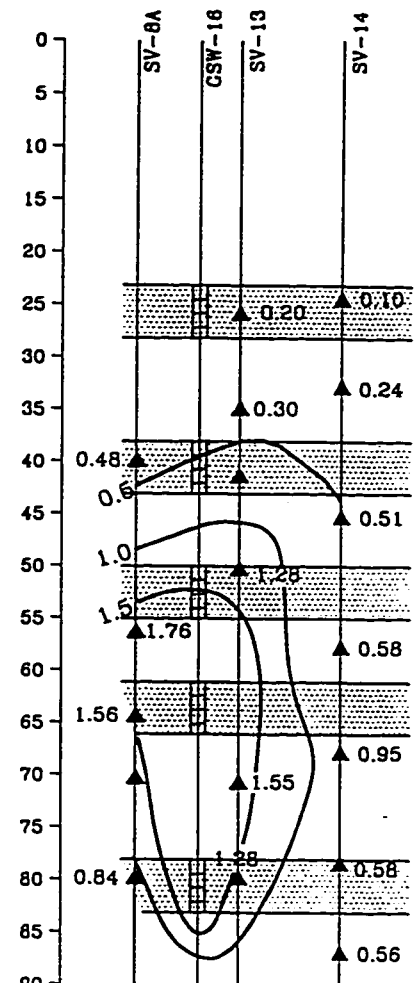
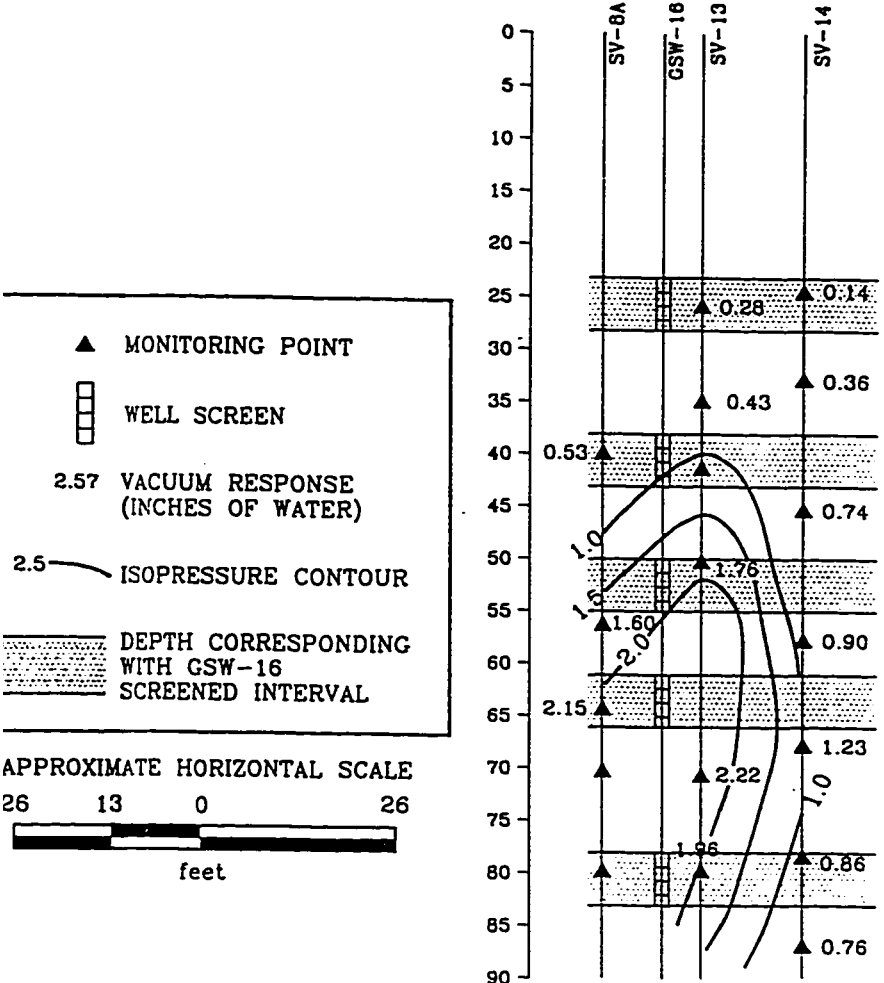
Figure 28. Vertical and horizontal vacuum response for the dual-zone SVE test, time periods 3.94 to 17.83 days. Note the differing contour intervals.





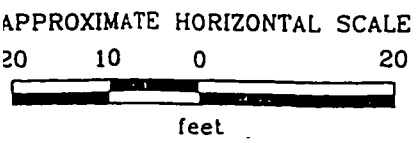
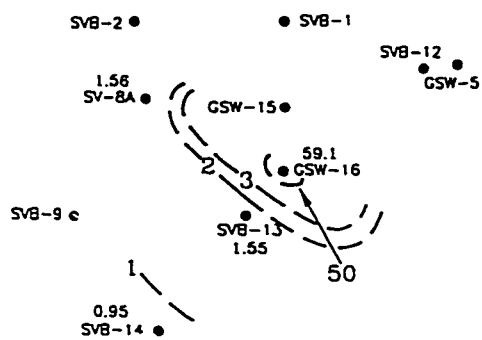
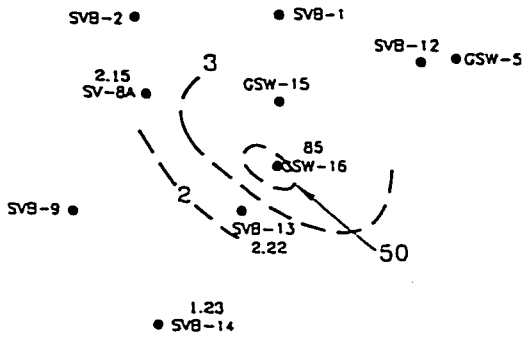
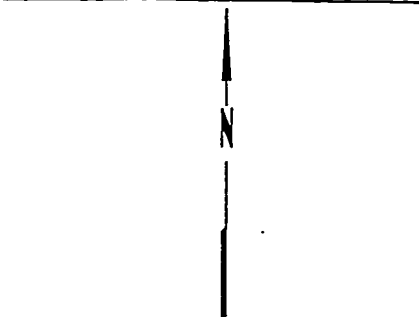
E) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 10.74 TO 11.84 DAYS

G) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 11.84 TO 17.83 DAYS



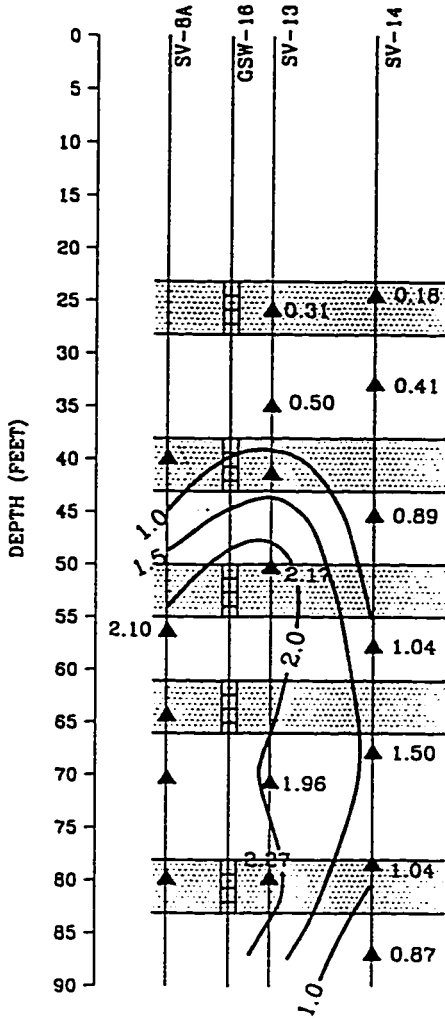
F) 10.74 TO 11.84 DAYS

H) 11.84 TO 17.83 DAYS

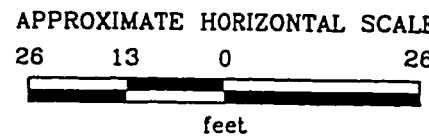
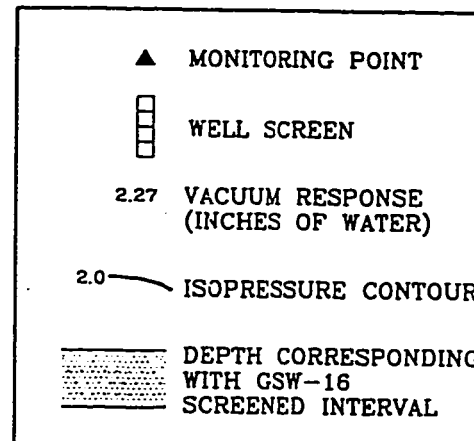
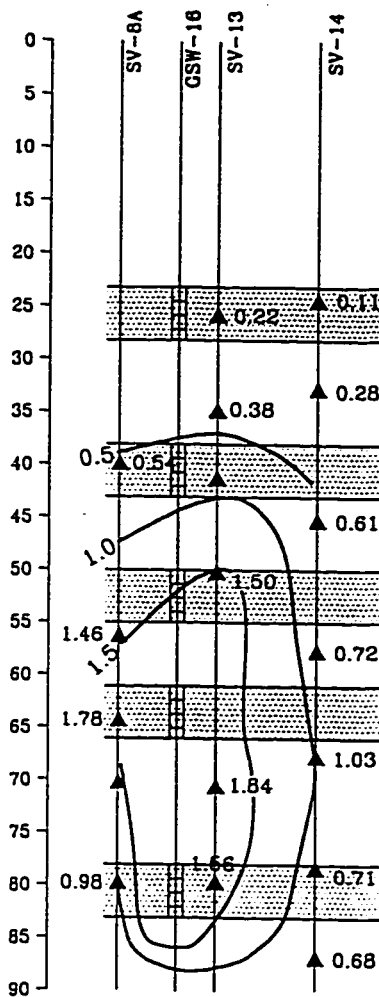




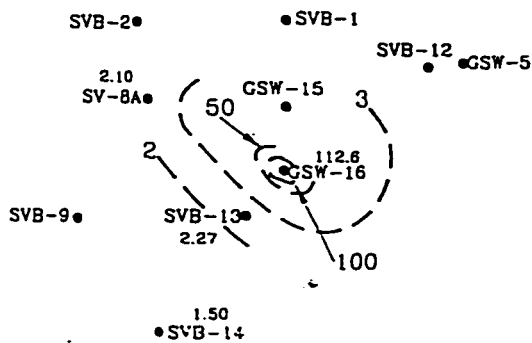
A) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 17.84 TO 18.24 DAYS



C) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 18.24 TO 20.29 DAYS



B) 17.84 TO 18.24 DAYS



D) 18.24 TO 20.29 DAYS

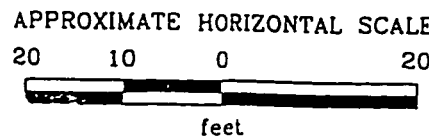
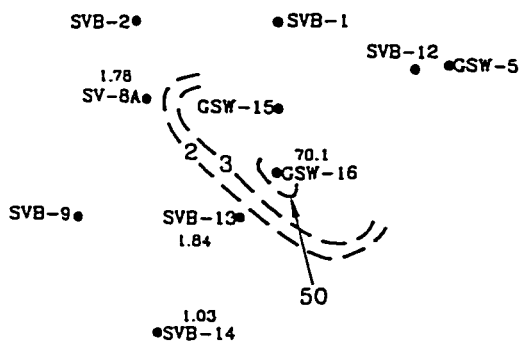
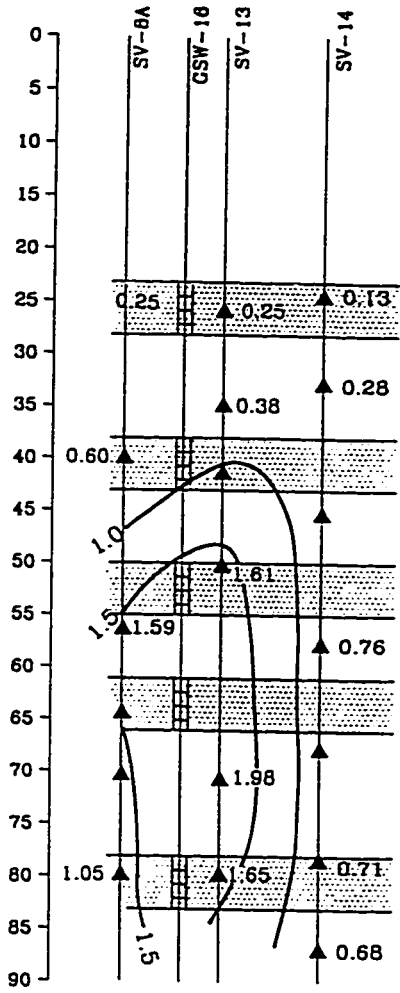
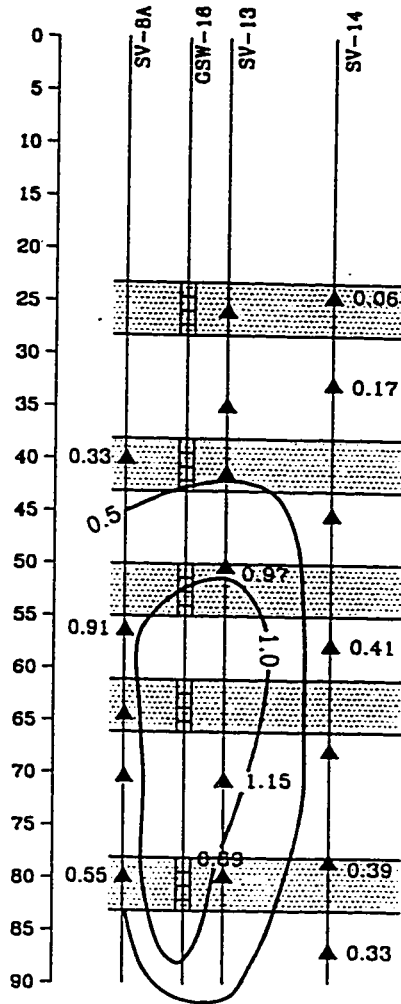
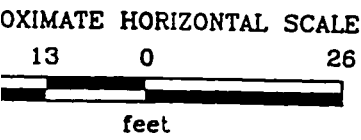
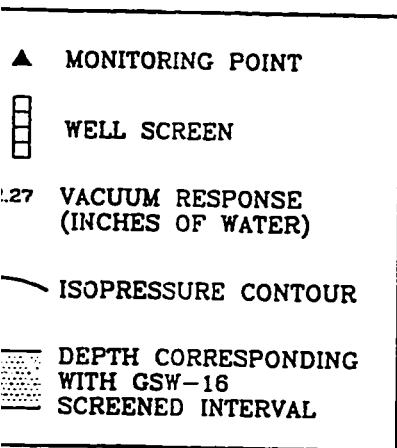


Figure 29. Vertical and horizontal vacuum response for the dual-zone SVE test, time periods 17.83 to 22.01 days. Note the differing contour intervals.



E) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 20.29 TO 20.97 DAYS

G) VERTICAL PROFILE OF RESPONSE TO VAPOR EXTRACTION FROM GSW-16 ZONES 4 AND 5 20.97 TO 22.01 DAYS



F) 20.29 TO 20.97 DAYS

H) 20.97 TO 22.01 DAYS

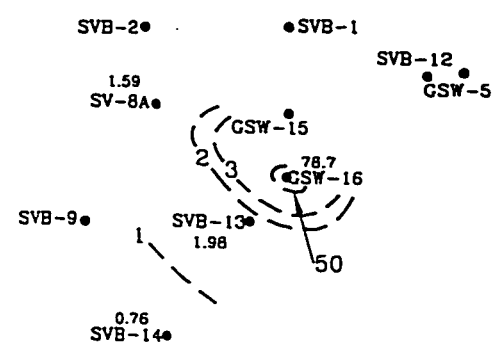
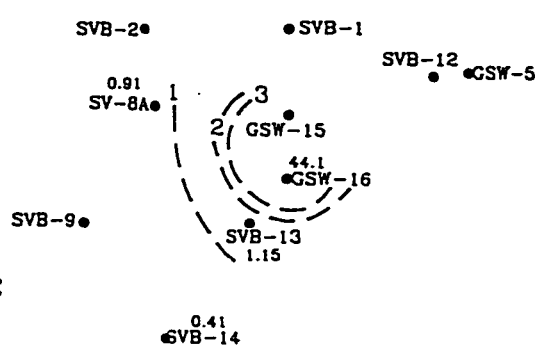
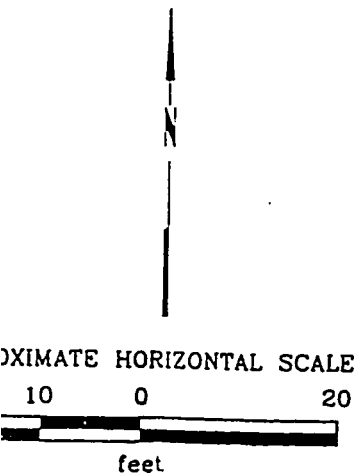




Table 5. Soil vapor extraction test data from the dual-zone SVE test.

Time Period	Time (days)	Vacuum (in H <sub>2</sub> O)	Air Flow (scfm)	BTEX (ppmv)	BTEX Removed (gallons)	Gasoline Removed (gallons)	Extraction Rate of Gasoline (gpd)
1	0-0.27	161	47.8	127	0.10	0.35	1.31
2	0.27-1.09	118	42.1	176	0.36	1.30	1.59
3	1.09-1.78	104	36.4	193	0.31	1.13	1.63
4	1.78-3.94	64.6	24.9	373	0.97	3.52	1.63
5	3.94-9.86	80.3	26.4	301	2.52	9.18	1.55
6	9.86-10.74	105	31.3	341	0.52	1.89	2.15
7	10.74-11.84	85.0	30.4	242	0.45	1.63	1.48
8	11.84-17.83	59.1	22.2	340	2.88	10.49	1.75
9	17.83-18.24	113	35.3	415	0.34	1.24	3.02
10	18.24-20.29	70.1	25.4	502	1.52	5.53	2.70
11	20.29-20.97	44.1	26.3	510	0.46	1.67	2.46
12	20.97-22.01	78.7	21.9	471	0.62	2.25	2.16

The BTEX concentrations were roughly inversely proportional to the vapor flow rate (Fig. 30). This inverse relationship is what would be expected if the removal rate is limited by volatilization or diffusion. The flow rate was directly proportional to the applied vacuum (Fig. 31). Based on these data, the optimal flow rate (the flow rate that results in the highest mass removal rate) for extraction from GSW-16-Z4 and GSW-16-Z5 is approximately 35 scfm, corresponding to an applied vacuum of approximately 110 inches of water. This flow rate is feasible with the liquid ring pump used by the SVE system. However, 35 scfm is near the upper limit for operation of the thermal oxidizer.



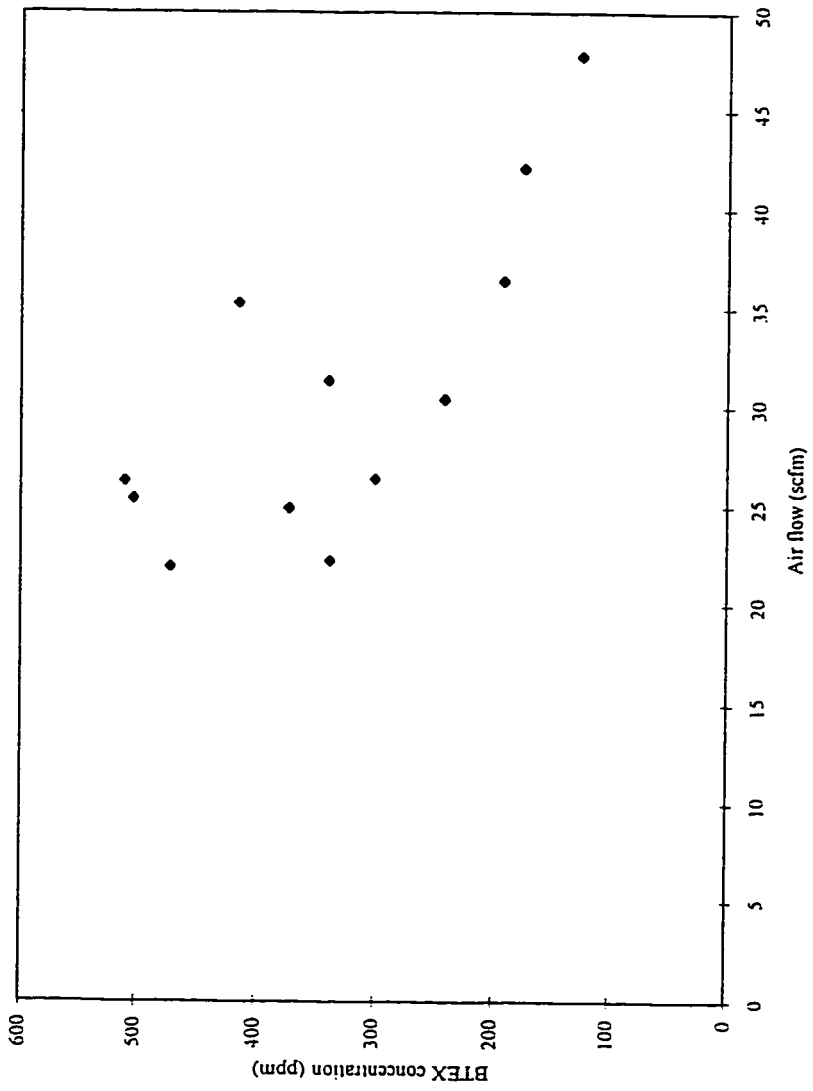


Figure 30. Relationship of BTEX concentrations and vapor flow rate. The data used for this plot are presented in Table 5.

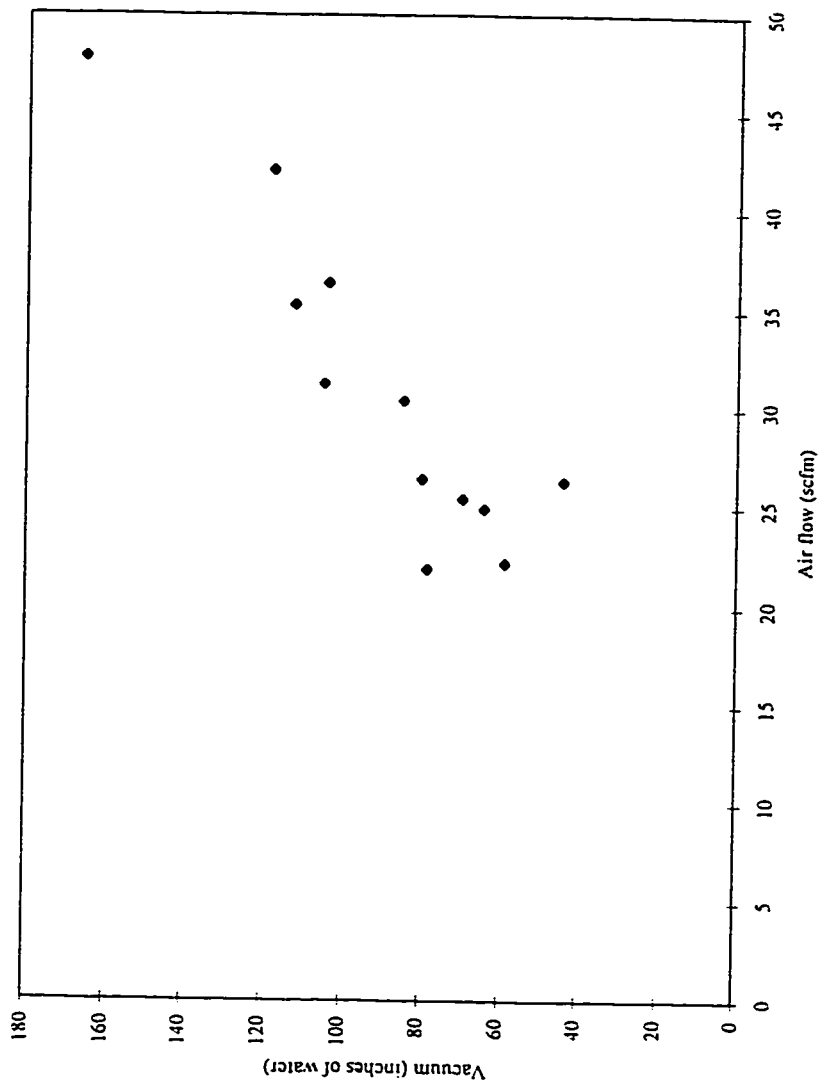


Figure 31. Relationship of vapor flow rate and vacuum. The data used for this plot are presented in Table 5.

### Soil Vapor Extraction Test Calculations

Calculations of radius of influence and gas permeability were performed on data obtained from the individual and dual-zone SVE tests. The radius of influence was calculated by plotting the vacuum response versus the radial distance from the extraction well. Johnson *et al.* (1990) presented the equation used for calculation of the gas permeabilities (see Methodology).

#### Radius of Influence

The radius of influence was calculated for each of the individual-zone SVE tests and for three time periods during the dual-zone SVE test. The radius of influence was determined using a semi-log plot of drawdown (vacuum response) versus distance. The radius of influence is determined as the x-intercept of the best fit regression line and represents the maximum distance of pressure response. The plots for the individual-zone SVE tests are presented in Figures 32 through 35. The calculated values for radius of influence for the zone 2, 3, 4, and 5 tests were 23, 27, 123, and 22 feet, respectively. It would be expected that the radius of influence would increase with depth due to the presence of coarse-grained sediment at depth. This pattern is seen in the upper three zones, but the radius of influence is smaller in the lowermost zone.

The decrease may be attributed to the presence of moisture in the soil pores and blockages in the GSW-16-Z5 screen. This was reflected in the high applied vacuum and the low flow rates achieved during this test.

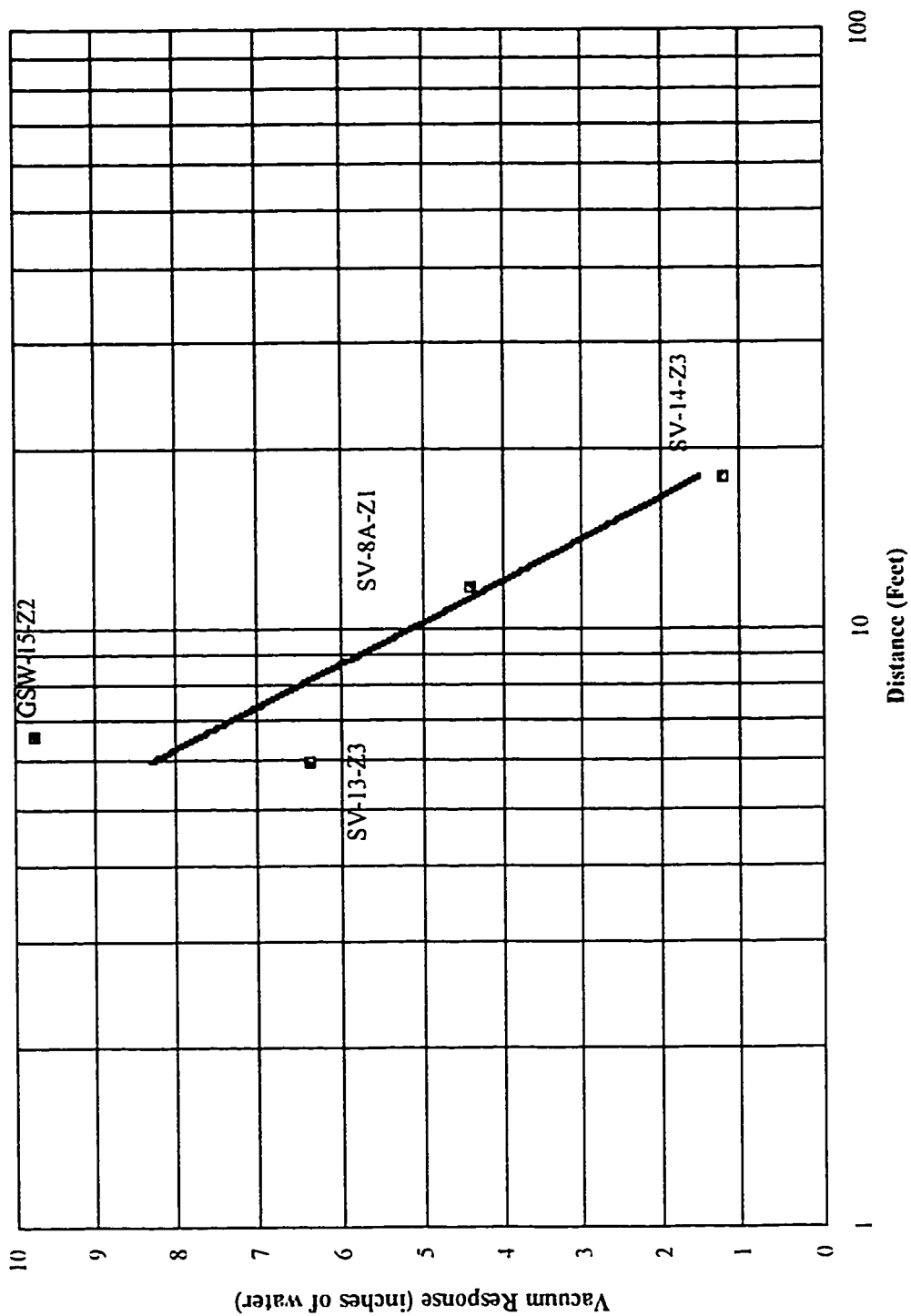


Figure 32. Radius of influence for the zone 2 SVE Test.

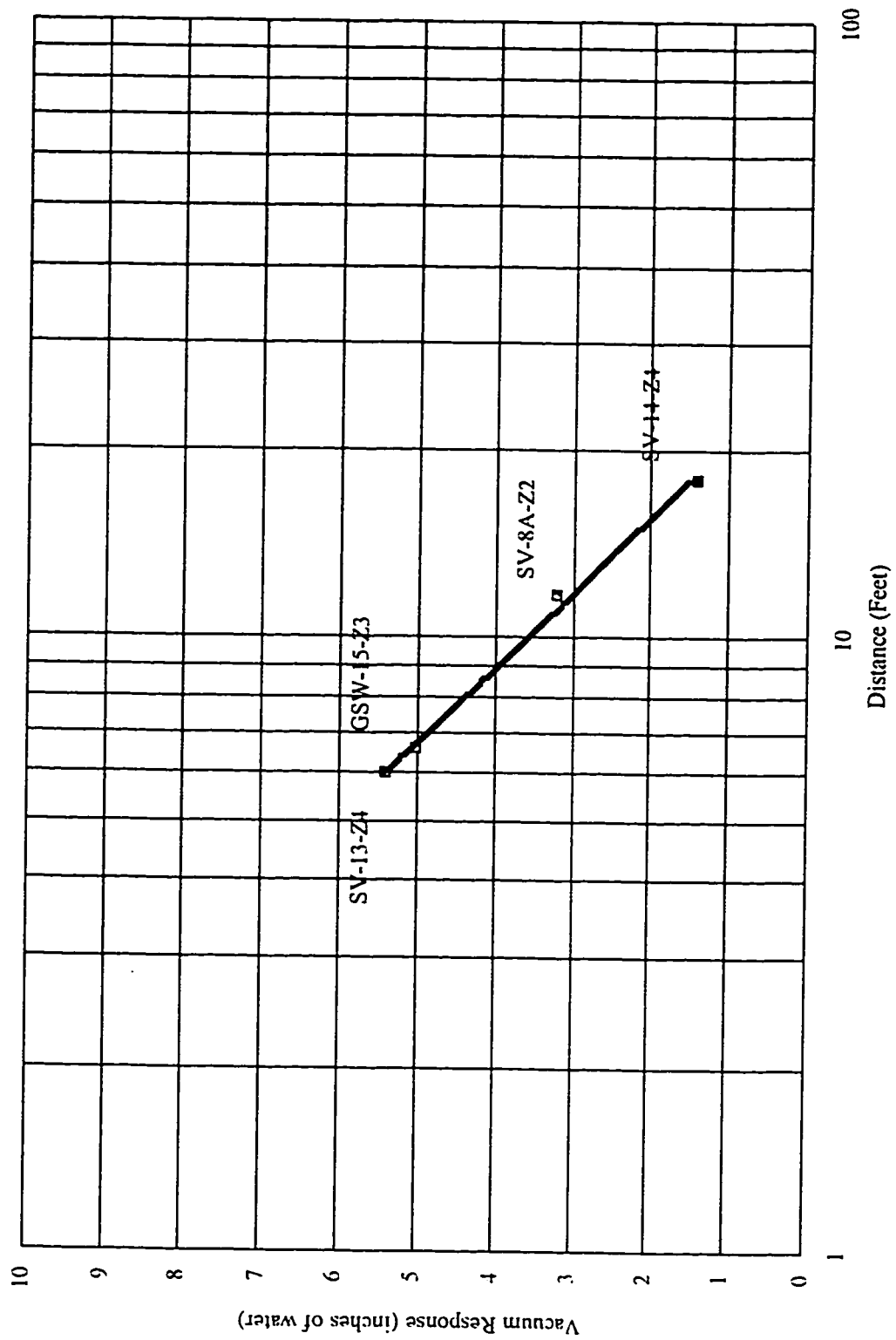


Figure 33. Radius of influence for the zone 3 SVE test.

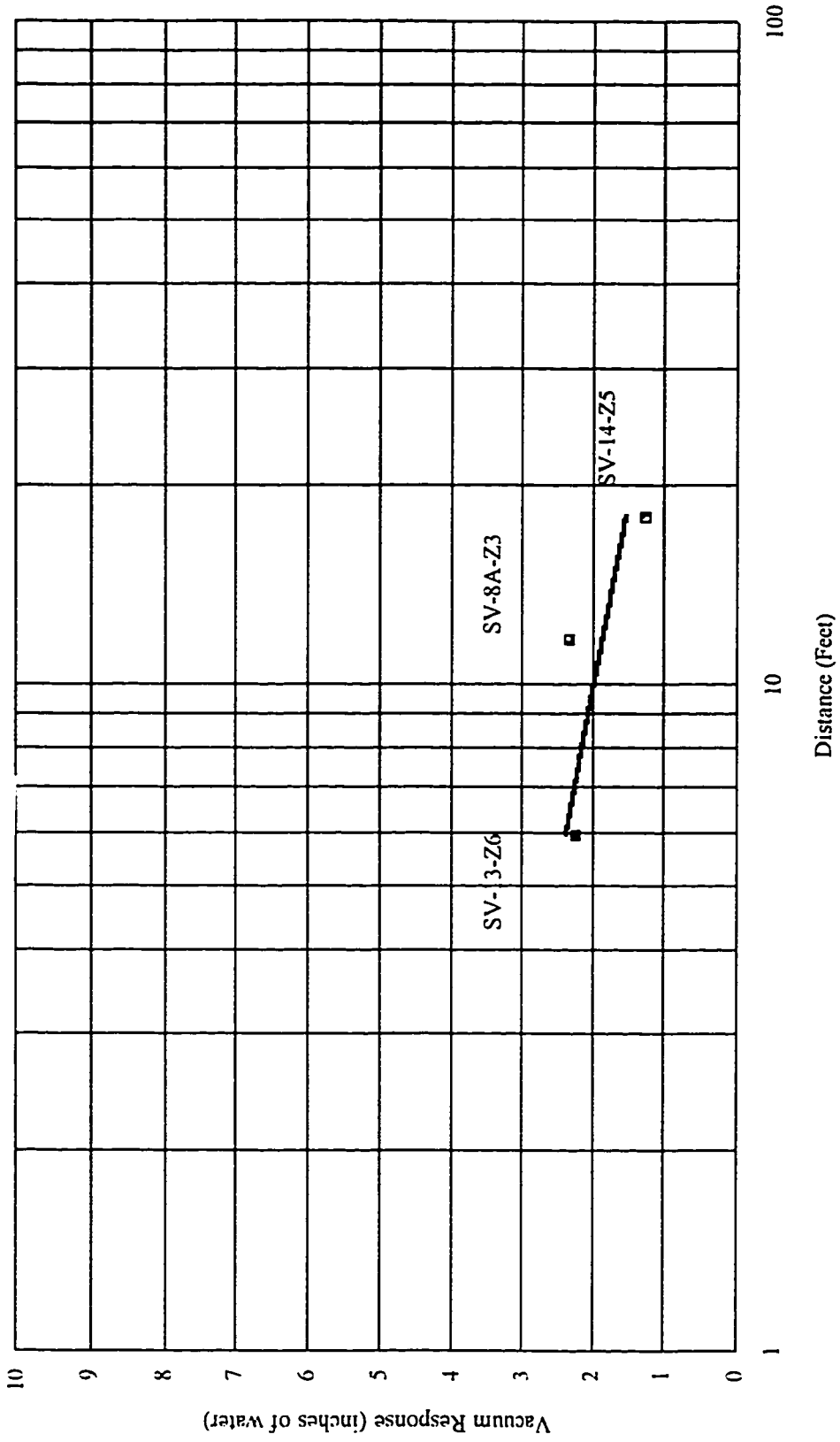


Figure 34. Radius of influence for the zone 4 SVE test.

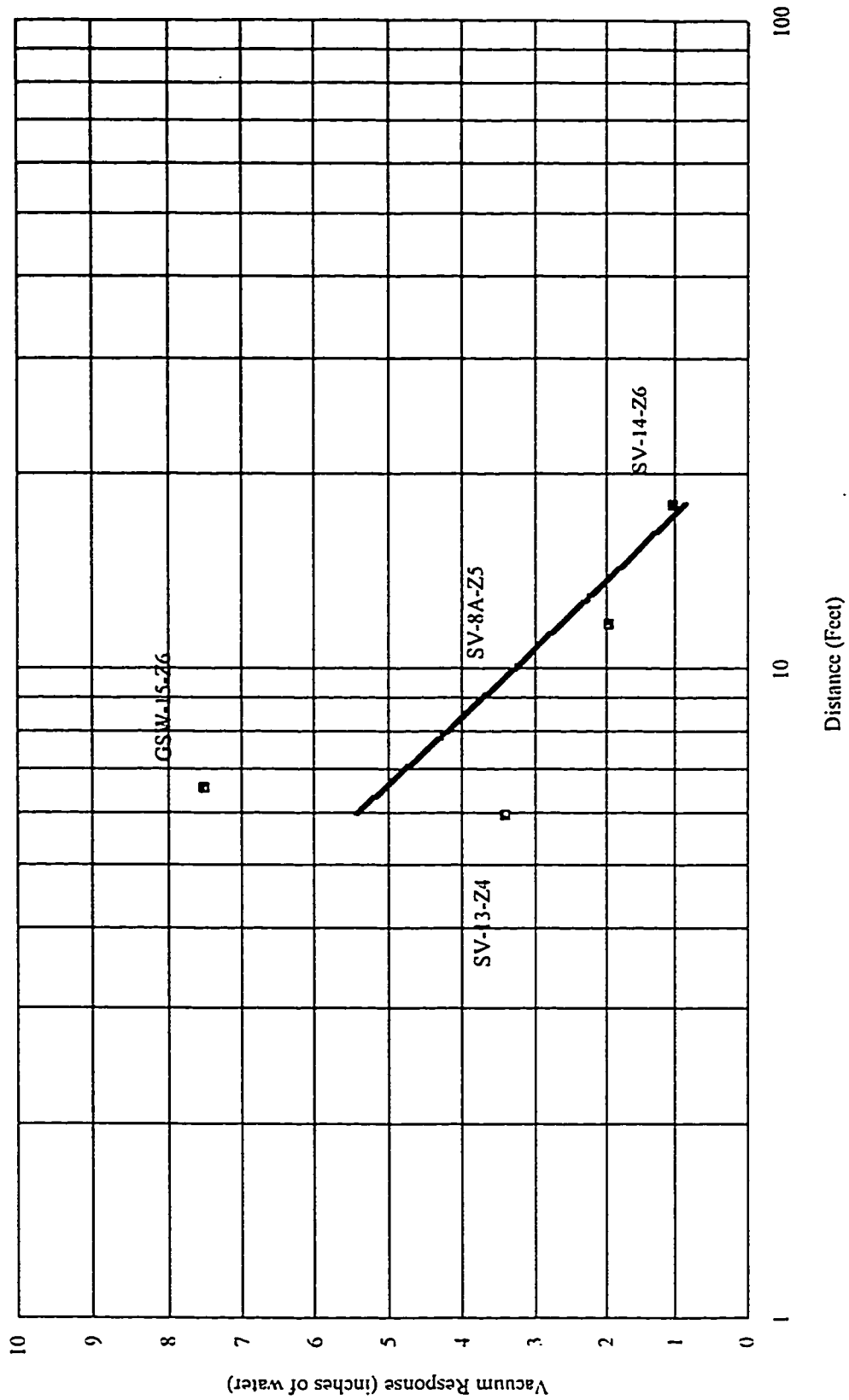


Figure 35. Radius of influence for the zone 5 SVE test.

Figures 36 through 38 are plots for time periods 1, 9 and 12 of the dual-zone SVE test, respectively. During these time periods, the radius of influence ranged from 42 feet (time period 12, 20.97 to 22.01 days) to 211 feet (time period 9, 17.83 to 18.24 days), with time period 1 (0 to 0.27 days) having an intermediate value of 92 feet. Time period 9, when zone 5 appeared to be more effectively influencing air flow, had the largest radius of influence. This indicates that the combination of two effective extraction zones may increase the region influenced by extraction.

#### Gas Permeability

The gas permeabilities calculated from the SVE test data are summarized in Table 6. It was expected that the permeability would increase with depth because of the increased amounts of coarser sediment. This increase was observed in zones 2 through 4, but the permeability decreased in zone 5. The lower permeability observed in zone 5 was probably caused by increasing moisture content as the water table was approached. The material blocking the screen and a portion of the sandpack also may be acting to mask the

Table 6. Gas permeability as determined during SVE tests.

Zone	Depth (feet)	Gas Permeability Results (ft <sup>2</sup> [cm <sup>2</sup> ])
2	38 to 43	1.30 x 10 <sup>-11</sup> [1.20 x 10 <sup>-8</sup> ]
3	50 to 55	2.29 x 10 <sup>-11</sup> [2.13 x 10 <sup>-8</sup> ]
4	61 to 66	4.48 x 10 <sup>-11</sup> [4.17 x 10 <sup>-8</sup> ]
5	78 to 83	6.26 x 10 <sup>-12</sup> [5.82 x 10 <sup>-9</sup> ]
4 - 5, Time Period 1	61 to 66 and 78 to 83	2.45 x 10 <sup>-11</sup> [2.27 x 10 <sup>-8</sup> ]
4 - 5, Time Period 9	61 to 66 and 78 to 83	3.37 x 10 <sup>-11</sup> [3.13 x 10 <sup>-8</sup> ]
4 - 5, Time Period 12	61 to 66 and 78 to 83	5.49 x 10 <sup>-11</sup> [5.10 x 10 <sup>-8</sup> ]



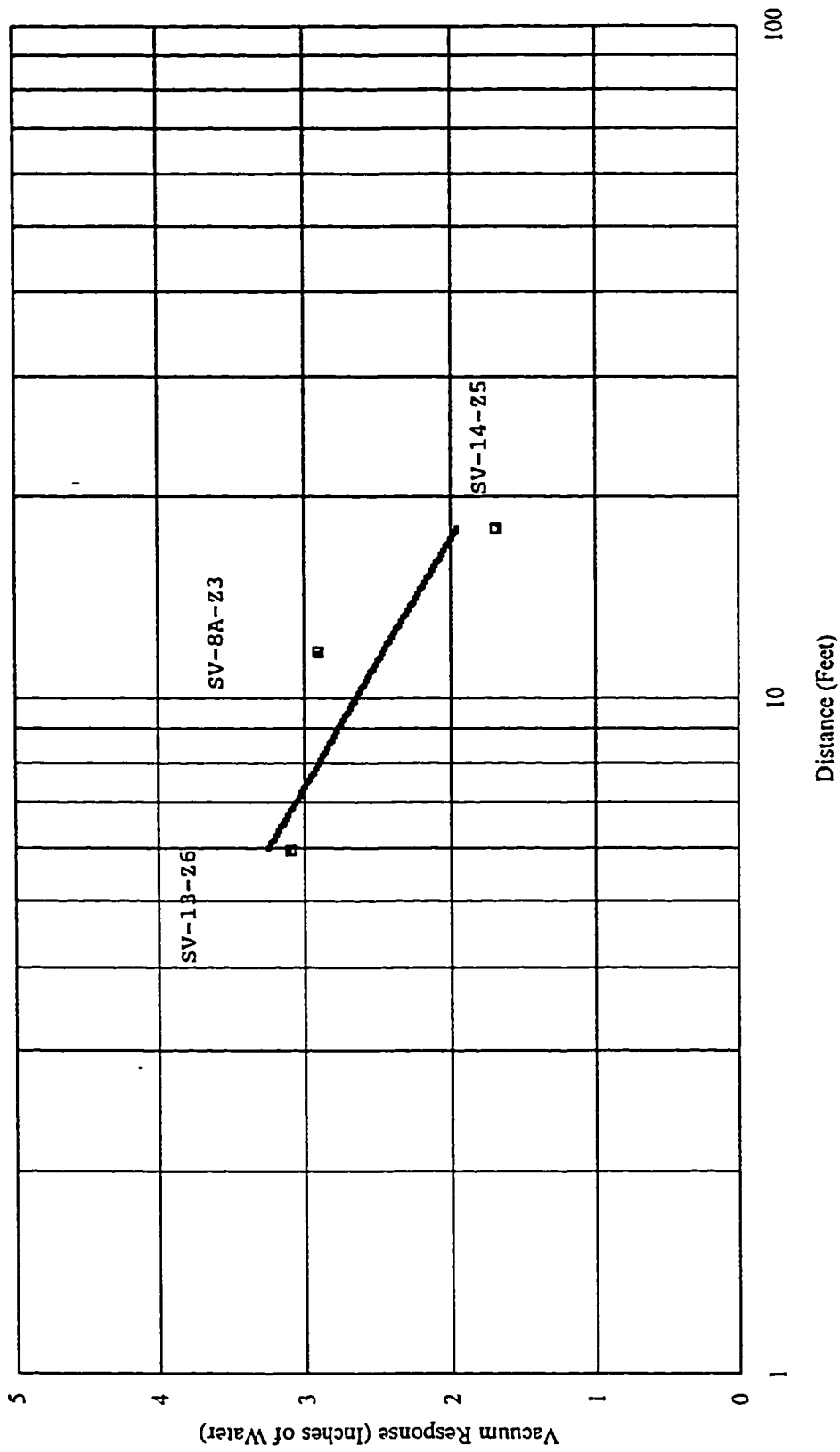


Figure 36. Radius of influence for the dual-zone SVE test time period 1 (0 to 0.27 days).

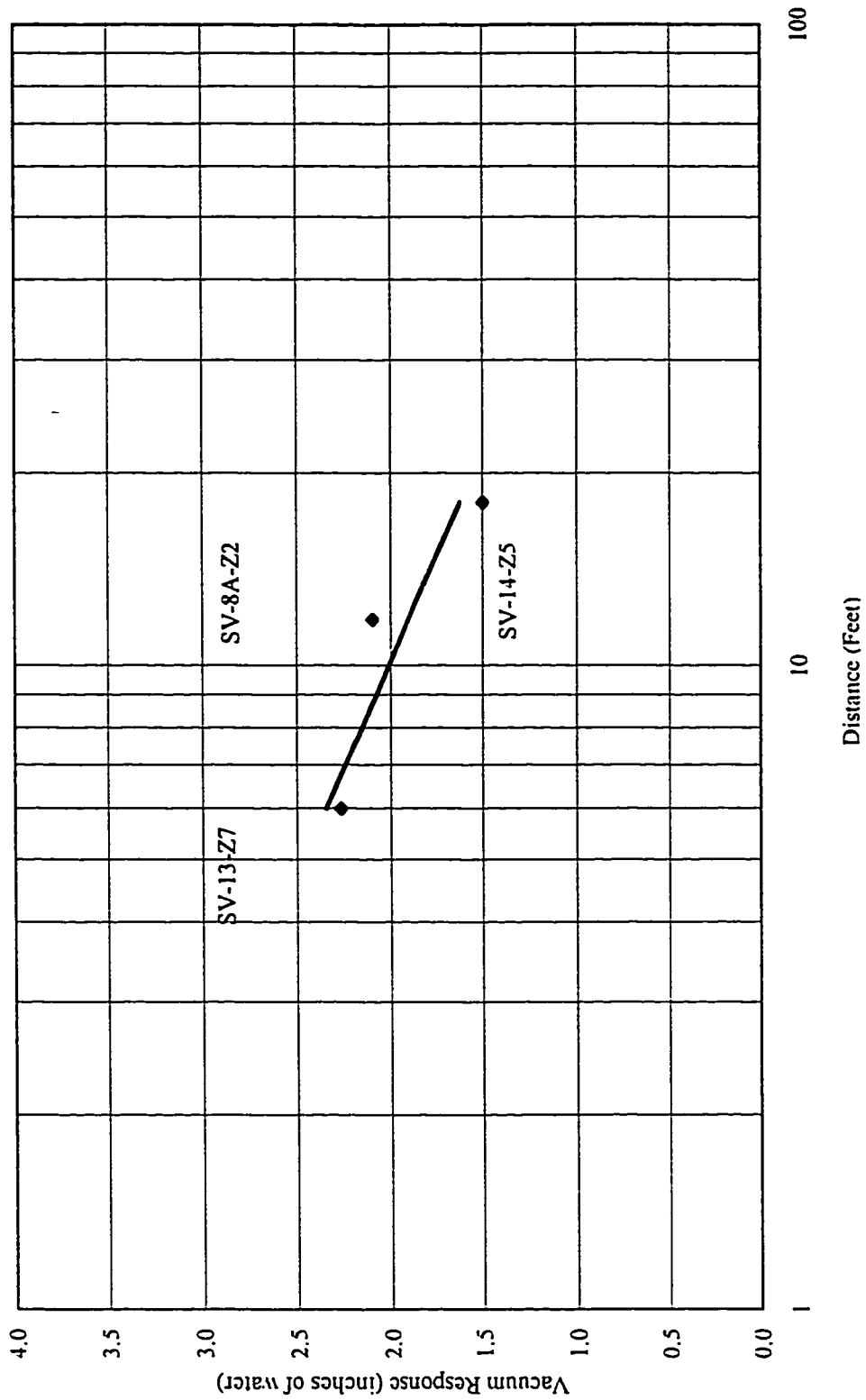


Figure 37. Radius of influence for the dual-zone SVE test time period 9 (17.83 to 18.24 days).

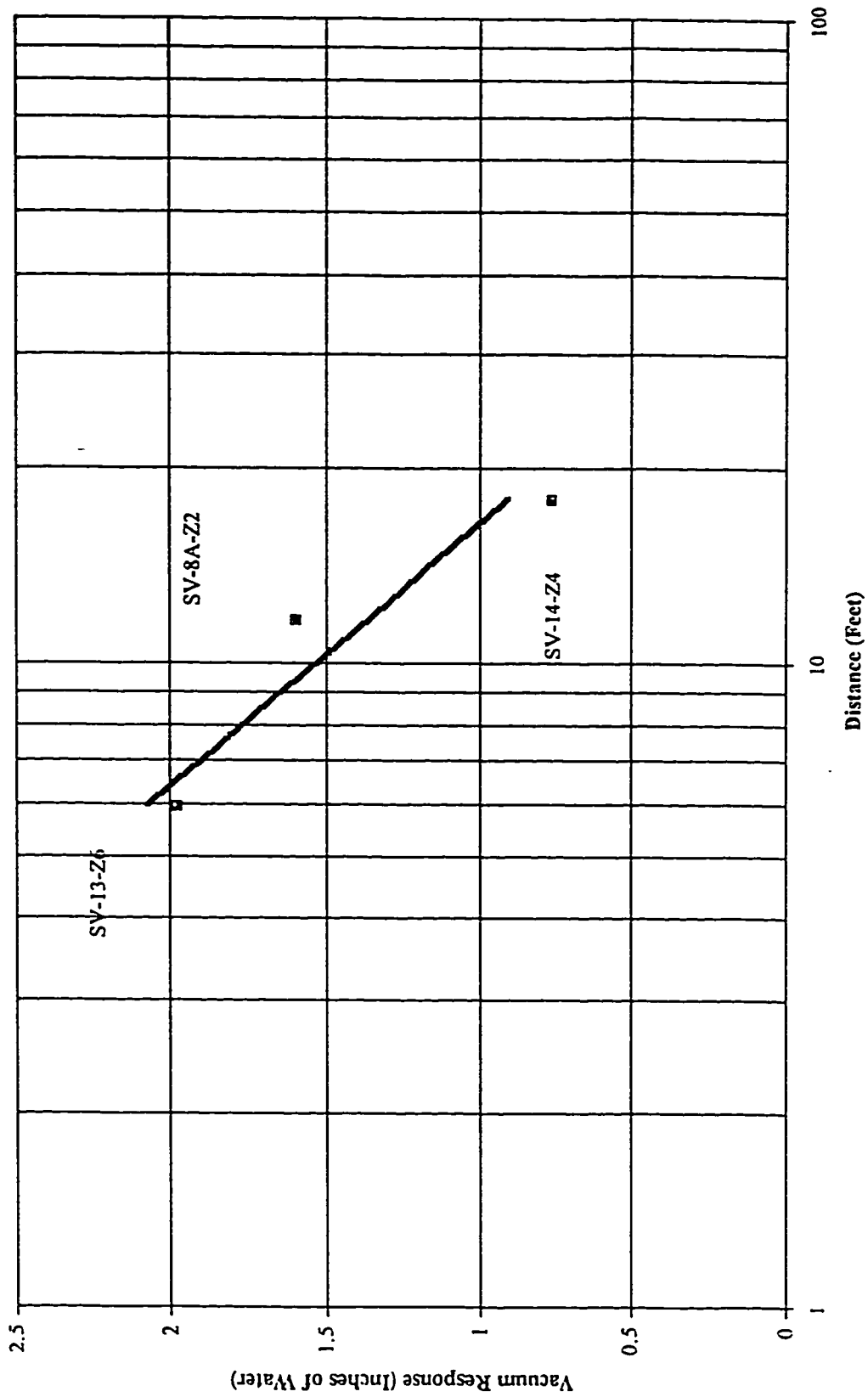


Figure 38. Radius of influence for the dual-zone SVE test time period 12 (20.97 to 22.01 days).

actual permeability of the native sediment. The results of the dual-zone SVE test indicate that the air flow is primarily controlled by the more permeable region in Zone 4.

#### Hydrocarbon Removal by Soil Vapor Extraction

Pre-Soil Vapor Extraction Tests. As discussed previously, the SVE system operated for a total of 179 days over a 2.3-year period (August 1988 to February 1991). Figure 12 shows an estimated 530 gallons of BTEX removed during this time, corresponding to 2,200 gallons of gasoline. This provides an average volumetric extraction rate for BTEX of 3.2 gallons per day (gpd). Figure 12 indicates that 50% of the total BTEX removed to date was removed in the first 38 days of operation.

Individual-Zone Soil Vapor Extraction Tests. In June 1991, a total of 2 gallons of BTEX was removed (Table 4), corresponding to 7 gallons of gasoline. Table 4 shows higher BTEX concentrations in the vapor extracted from zones 2 and 4. Thus the higher hydrocarbon extraction rates in these zones indicate that vapor is passing through more highly contaminated sediment than is encountered by extraction from zones 3 and 5.

By observing the hydrocarbon distribution prior to initiation of SVE (Figs. 6 through 9) and after 179 days of SVE operation (Fig. 25) a possible explanation can be seen. Prior to initiation of SVE, greater soil contamination was found in the zone 3 depth interval than in either zone 2 or 4. The distribution after SVE operation and prior to the individual-zone SVE tests shows that the highest concentrations of TPH-g in the upper vadose zone remain in the area of SV-13 at a depth corresponding to zone 2. The areas

corresponding to zones 3 and 4 have reduced concentrations of TPH-g. Extraction from zone 2 does not appear to be pulling contaminated vapor from the area near SV-13, although good air flow is apparent in the area. This may be caused by vapor flowing preferentially through a single sediment layer that has been remediated, by "short-circuiting" of the vapor flow by inflow of atmospheric air, or by bypassing caused by the low permeability of the fine-grained sediment in this area. If atmospheric air is being pulled into Zone 2 at a point closer than SV-13, the effective air flow through the impacted sediment will be reduced.

Dual-Zone Soil Vapor Extraction Test. In July and August 1991, a total of 11 gallons of BTEX was removed (Table 5) from the subsurface during the 22 day dual-zone SVE test. This corresponds to a total of 39 gallons of gasoline removed (Fig. 39). The gasoline extraction rate ranged from 1.27 to 1.94 gpd, averaging 1.63 gpd, over the first 17.83 days of this test. The gasoline extraction rate ranged from 2.16 to 3.08 gpd, averaging 2.67 gpd, over the final 4.18 days of this test. The mass extraction rate would be expected to decrease over time, but because the extraction zones are located near the free product surface, located approximately 17 feet below Zone 5, the extraction rate has remained elevated. The increase in extraction rate with time may also reflect the extraction of more distant vapor from above the floating product.

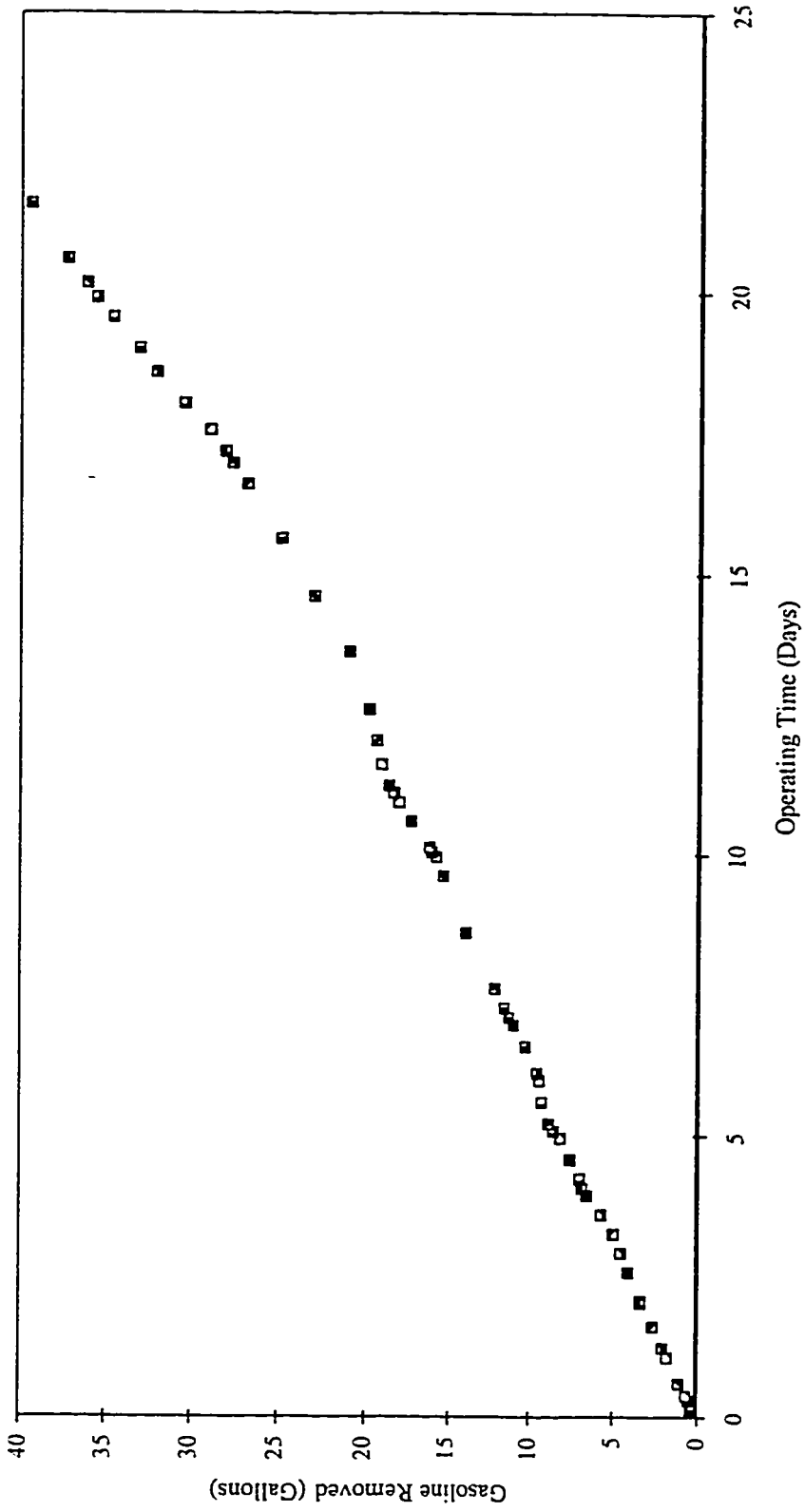


Figure 39. Removal of gasoline during the dual-zone SVE test.

## Vapor Contaminant Distribution

### Pre-Soil Vapor Extraction Tests

Background vapor sampling was conducted on vadose-zone monitoring devices SV-13 and SV-14 on May 1, 1991, approximately 4 months after the SVE system had been shut down. The soil gas was analyzed for BTEX on the Photovac portable gas chromatograph. Figure 40-A shows BTEX distributed in the vapor phase within the soil column between SV-13 and SV-14. The BTEX distribution during this sampling event revealed the effects of residual soil contamination and the effects of diffusion of vapor contaminants.

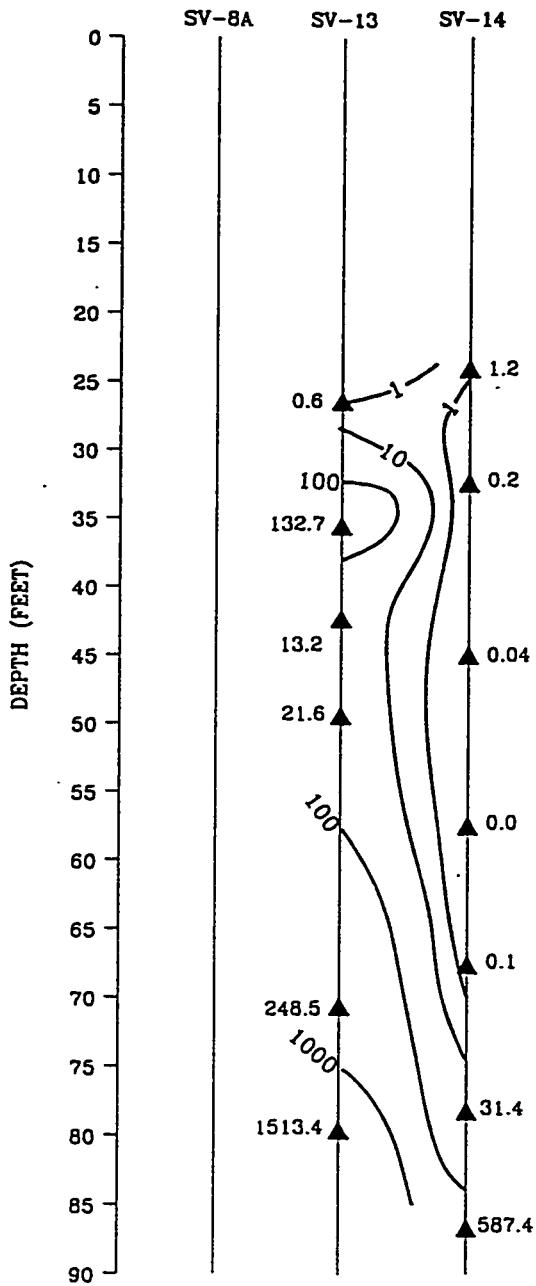
The vapor contaminant distribution was not representative of the residual soil contamination distribution. Vapor samples from regions of high residual soil contamination typically had BTEX concentrations exceeding 100 ppmv. However, vapor samples from regions of low to non-detectable residual soil contamination contained up to 22 ppmv of BTEX. The transport of BTEX vapors from areas of high concentrations to areas of low concentrations most likely resulted from diffusion.

### Post-Individual Zone Soil Vapor Extraction Tests

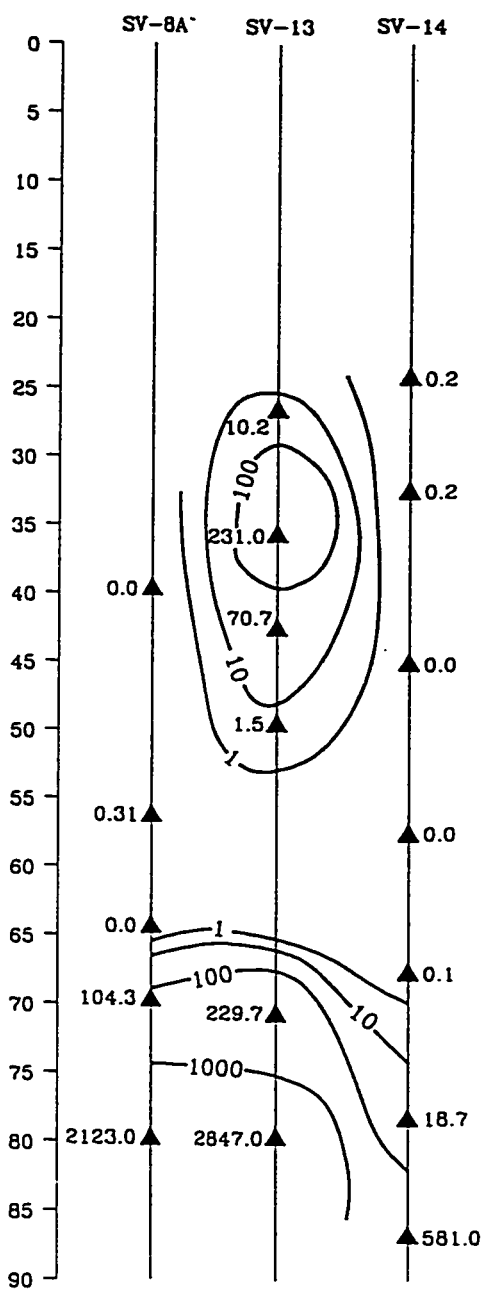
Vapor sampling was conducted on July 11, 15, and 16, 1991, during the week following the completion of the individual-zone SVE tests on July 8, 1991. The vertical profiles are presented in Figures 40-B through 40-D, respectively.

The BTEX profile on July 11, 1991, showed that BTEX concentrations increased near a depth of 35 feet bgs and as the water table was approached (Fig. 40-B). This vapor

A) BTEX CONCENTRATION IN VAPOR  
MAY 1, 1991



B) BTEX CONCENTRATION IN VAPOR  
JULY 11, 1991



C) BTEX C

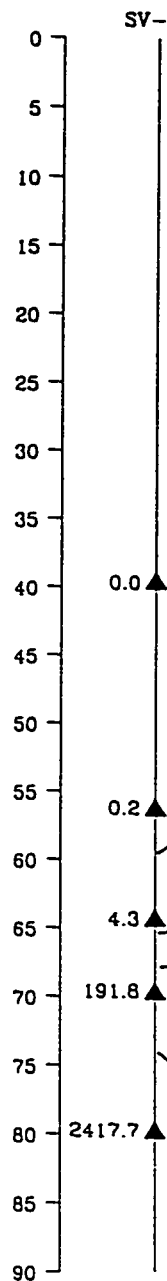
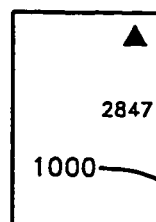


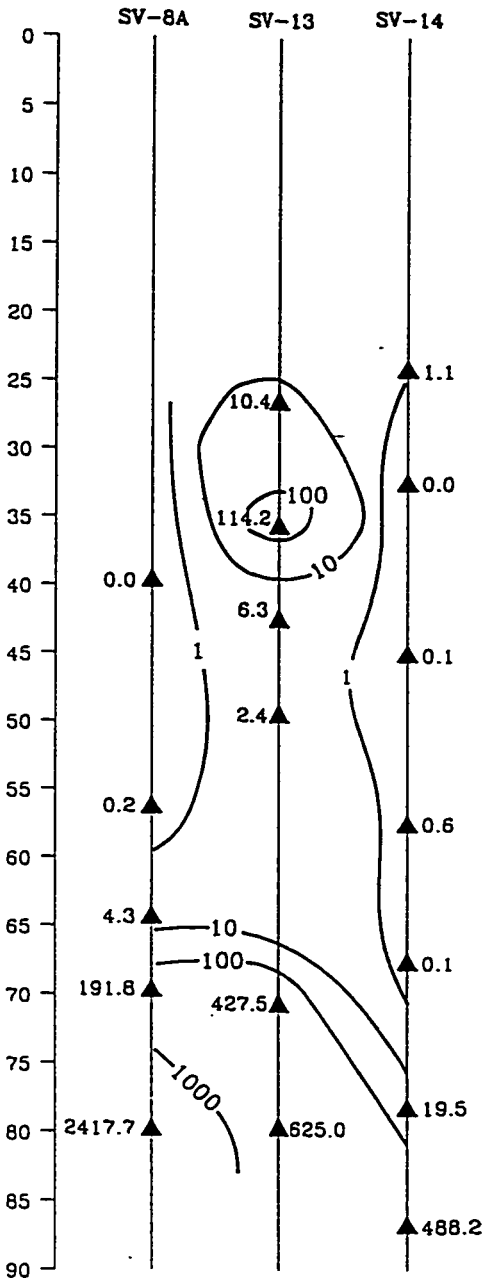
Figure 40. Vertical distribution of BTEX in vapor, May 1 to July 16, 1991.



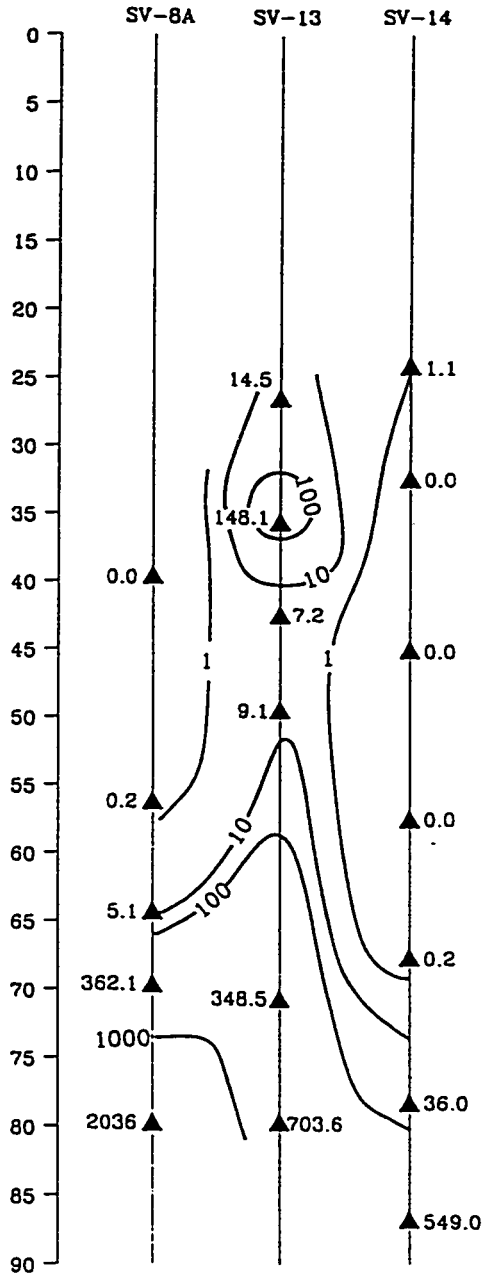




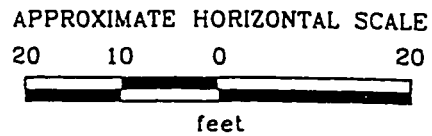
C) BTEX CONCENTRATION IN VAPOR  
JULY 15, 1991



D) BTEX CONCENTRATION IN VAPOR  
JULY 16, 1991



▲ MONITORING POINT  
2847 BTEX CONCENTRATION, PPM  
1000 — BTEX ISOCONCENTRATION CONTOUR, PPM





contaminant distribution resembled that of the residual soil contaminants. The zone between 50 and 65 feet bgs, which had low levels of soil and vapor contaminants, appears to have been preferentially remediated by vapor flow.

The vapor contaminant distribution observed on July 15 (Fig. 40-C) and 16 (Fig. 40-D), 1991, reveals the effects of diffusion. The BTEX vapors were migrating from areas of high concentrations to areas of low concentrations. This series of observations indicates that during and immediately following extraction the vapor profile is a good indicator of the profile of residual soil contamination. Within one week after shutting down the extraction system, the vapor profile had become less indicative of the profile of residual soil contamination.

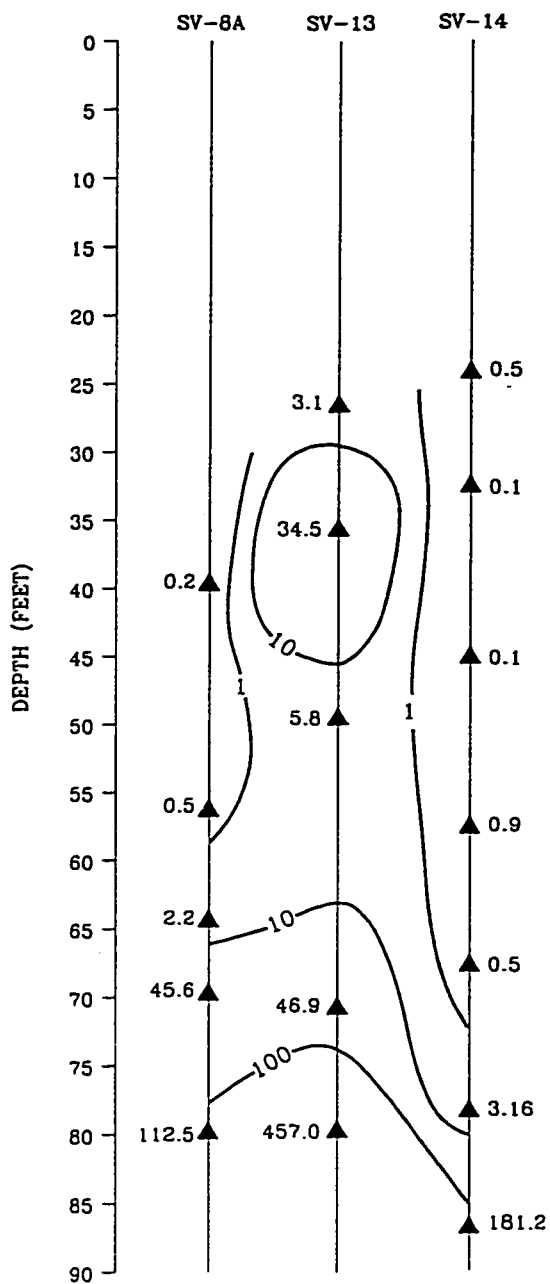
#### Dual-Zone Soil Vapor Extraction Test

The BTEX distribution in the vapor phase was determined on August 7, 1991, the 19th day of the dual-zone SVE test (Fig. 41-A). The concentrations of BTEX were reduced in all monitoring points since the previous analyses on July 16, 1991 (Fig. 40-D), indicating that the SVE system is removing the contaminated vapors and drawing clean air from surrounding uncontaminated areas or the surface.

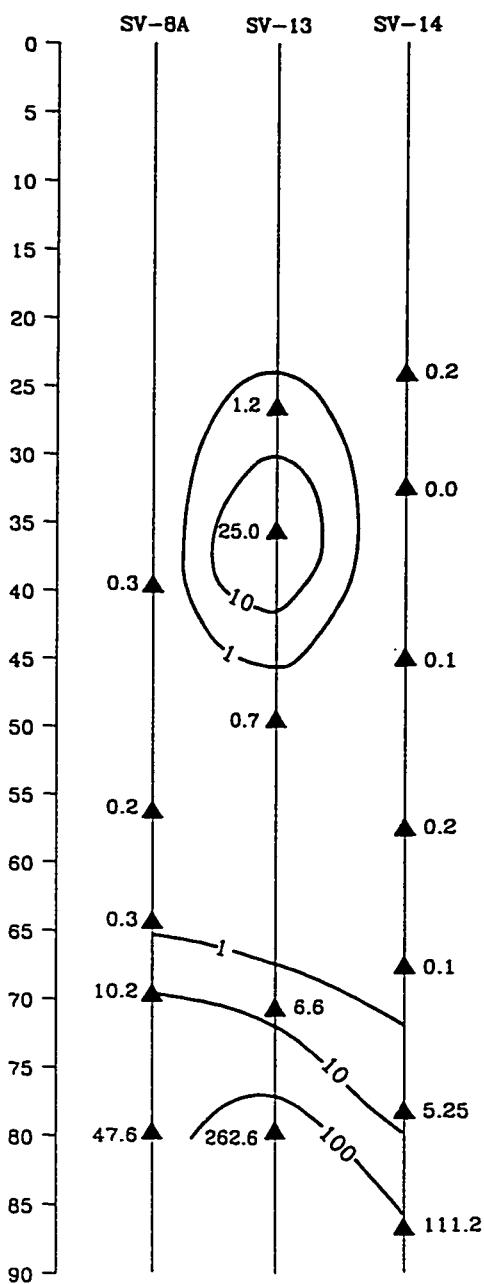
#### Post-Dual Zone Soil Vapor Extraction Test

The vapor BTEX distribution was evaluated weekly from August 14 to September 25, 1991 (Figs. 41 and 42) to monitor the changes in vapor contaminant distribution in the subsurface following a prolonged period of SVE. The vertical profile of BTEX in soil

A) BTEX CONCENTRATION IN VAPOR  
AUGUST 7, 1991



B) BTEX CONCENTRATION IN VAPOR  
AUGUST 14, 1991



C) BTEX CONCENTRATION IN VAPOR

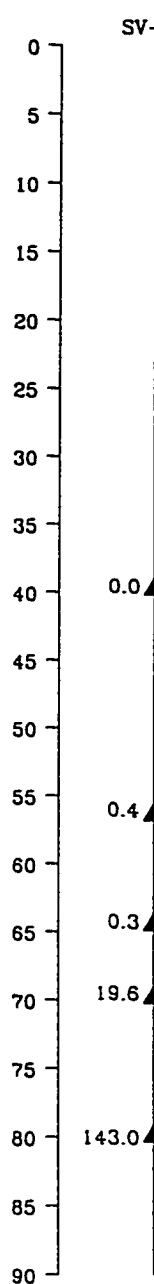
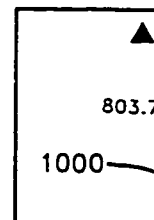


Figure 41. Vertical distribution of BTEX in vapor, August 7 to August 28, 1991.





POR

14

0.2

0.0

0.1

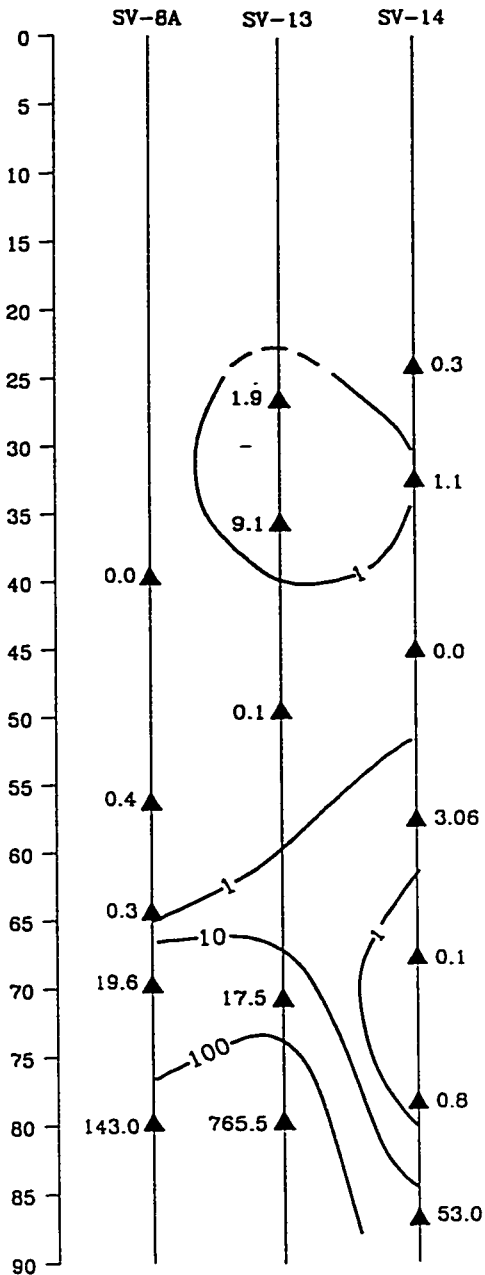
0.2

0.1

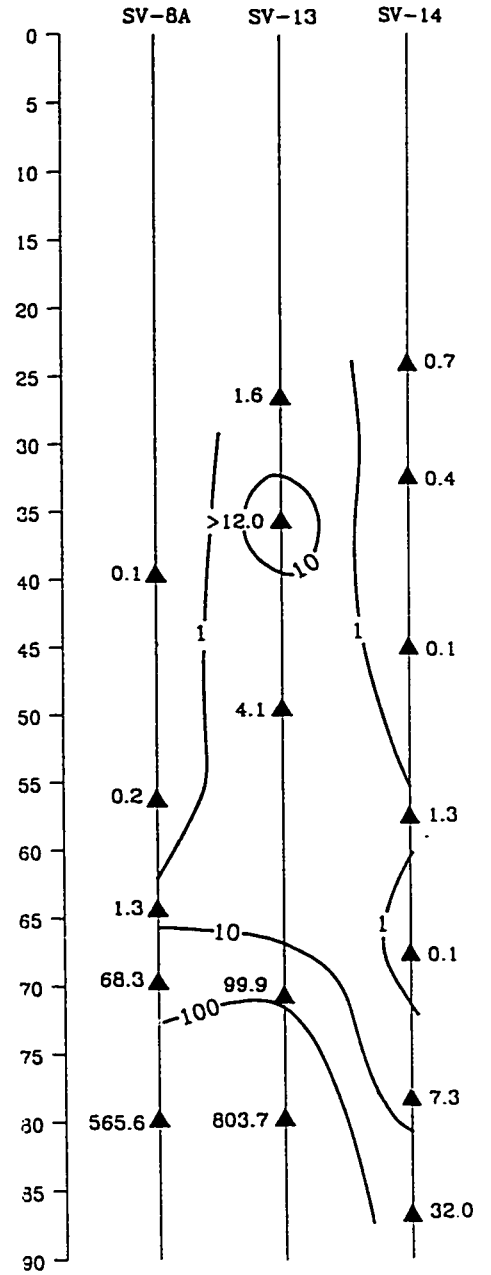
5.25

111.2

C) BTEX CONCENTRATION IN VAPOR  
AUGUST 21, 1991



D) BTEX CONCENTRATION IN VAPOR  
AUGUST 28, 1991

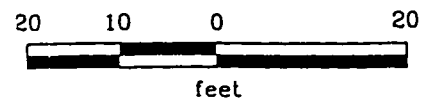


▲ MONITORING POINT

803.7 BTEX CONCENTRATION, PPM

1000 — BTEX ISOCONCENTRATION CONTOUR, PPM

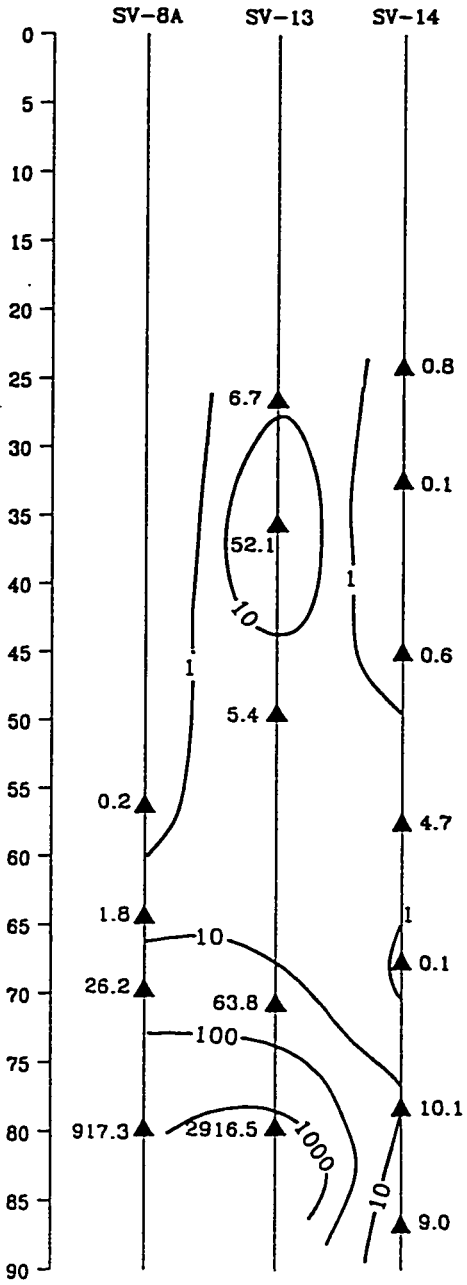
APPROXIMATE HORIZONTAL SCALE



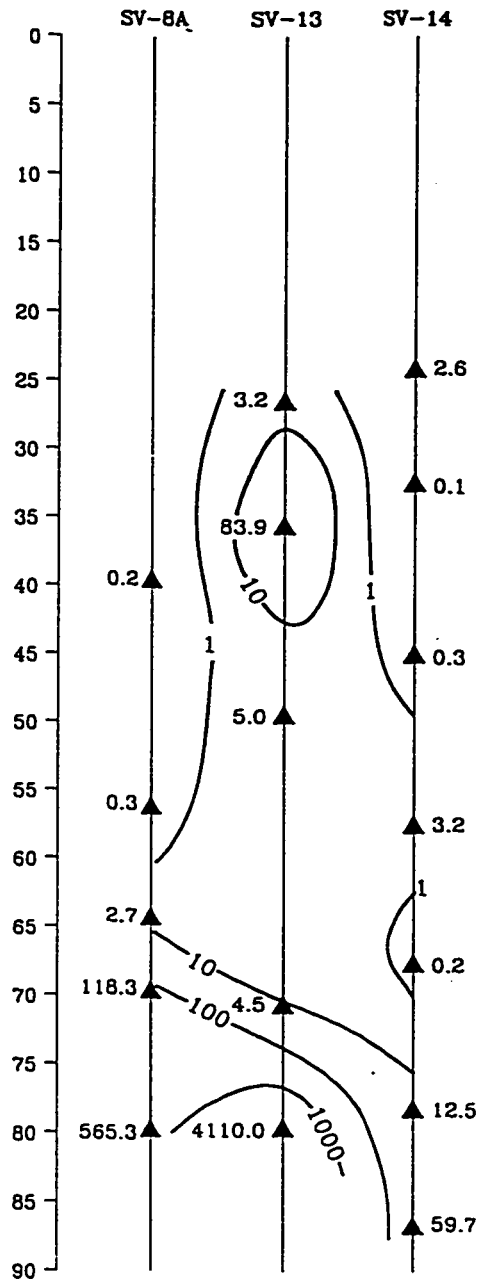




A) BTEX CONCENTRATION IN VAPOR  
SEPTEMBER 4, 1991



B) BTEX CONCENTRATION IN VAPOR  
SEPTEMBER 11, 1991



C) BTEX CONCENTRATION IN VAPOR  
SEPTEMBER 25, 1991

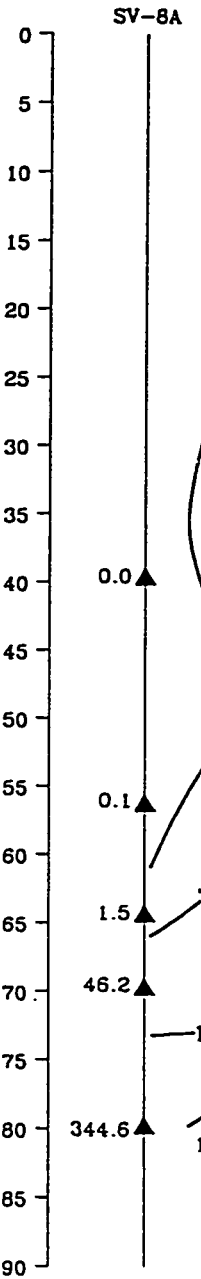
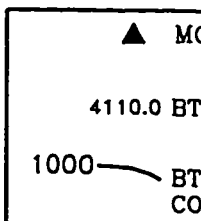
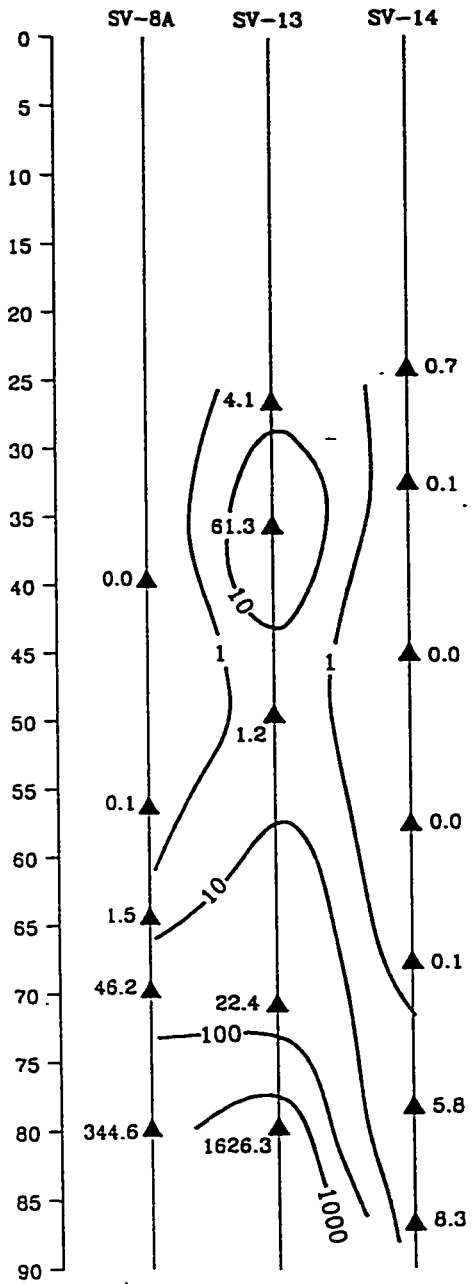


Figure 42. Vertical distribution of BTEX in vapor, September 4 to September 25, 1991.

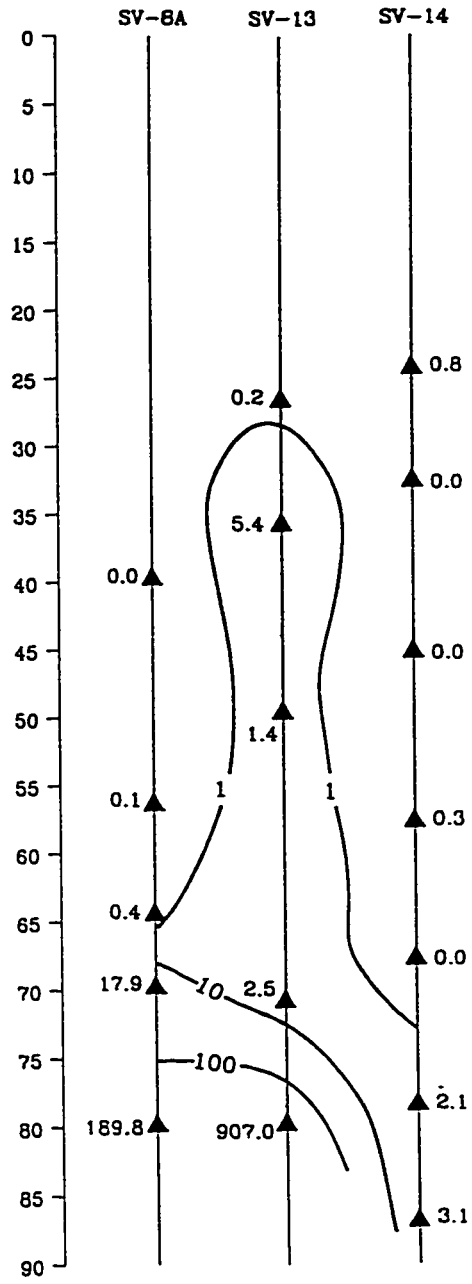




C) BTEX CONCENTRATION IN VAPOR  
SEPTEMBER 18 & 19, 1991



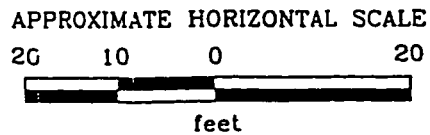
D) BTEX CONCENTRATION IN VAPOR  
SEPTEMBER 25, 1991



▲ MONITORING POINT

4110.0 BTEX CONCENTRATION, PPM

1000 — BTEX ISOCONCENTRATION CONTOUR, PPM





vapor during the two weeks following this test was similar to the residual soil contamination profile (Fig. 25). The time required for the effects of diffusion to be observed following the dual-zone SVE test was longer than that observed following the individual-zone SVE tests. This indicates either that the longer extraction is performed, the longer it will take the residual soil contamination to volatilize and migrate to areas of lower concentrations or that the concentrations in the source area have decreased. Concentrations were showing a decreasing trend in many monitoring points during the last three weeks of monitoring. Potential causes of the decrease in BTEX concentrations are biodegradation of the vapors (Ostendorf and Kambell, 1991) and lateral diffusion of the vapors.

## DISCUSSION

This discussion provides a summary and interpretation the results of the vadose-zone characterization and SVE tests described above.

### Vadose-Zone Characterization

Vadose-zone characterization is critical in determining the applicability of SVE. The characterization performed during this investigation was designed to evaluate heterogeneity in the sediment distribution and to evaluate sediment physical parameters that affect air flow.

### Lithology

Because vadose-zone sediments in the vicinity of LLNL were deposited in an alluvial setting, it was expected that the sediment would be heterogeneous. Zones of coarse sediment, thicker than 5 feet, are present over much of the site between depths of 10 and 15 and over 70 feet bgs. Based on the lithology observed during the installation of the vadose-zone monitoring devices, the most commonly encountered sediment types were those composed of a mixture of fine- and coarse particles (Fig. 24; comparable to the moderate permeability deposits of Dresen *et al.*, 1986 [Figs. 6 through 9]). The interval between 20 and 70 feet bgs in the area surrounding the vadose-zone monitoring devices is primarily composed of this mixed sediment type.

The distribution of fine sediment is important because gasoline compounds sorb more strongly onto fine sediments and because air flow through these sediments is inhibited. Thus, these zones are more difficult to remediate. In the mixed sediments between 20 and 60 feet bgs, there probably are numerous thin lenses of fine sediment. It was expected that these intervals may reduce the effectiveness of SVE in the GSA.

Conversely, coarse sediments are more effectively remediated by SVE because there tends to be more pore space available for air flow and there is less surface area available for sorption of the gasoline compounds. In addition to the coarse sediments below 60 feet bgs, there probably are numerous thin lenses of coarse sediments within the interval between 20 and 60 feet bgs.

#### Moisture Content

Moisture content is important in controlling air flow because air-filled porosity (the pore space available for air flow) decreases with increasing moisture content. The distribution of moisture content was relatively uniform in the vicinity of the vadose-zone monitoring devices. However, small changes over certain zones indicate that preferential air flow may be acting to dry sections of the sediment. The three zones exhibiting the highest moisture contents, 30 to 36 feet, 47 to 48 feet, and 60 feet bgs, are located at depths which correspond to depths between GSW-16-Z1 and GSW-16-Z2, GSW-16-Z2 and GSW-16-Z3, and GSW-16-Z3 and GSW-16-Z4, respectively. This indicates that vertical air flow, although it may be occurring, is not strong enough to dry out these zones.

The lower moisture contents were present at depths corresponding to the depth of the screened zones in extraction well GSW-16, indicating that these areas are being more strongly influenced by SVE. Additionally, the moisture content in SV-14 was relatively uniform, indicating that the volumetric air flow rate at this distance was not sufficient to dry the sediment.

It is important that the sediment is not being completely dried. Sediment that has been dried to the point where no more water can be removed tends to hold VOCs much more persistently. The number of available adsorption sites for VOCs increases with the removal of pore water (EPA, 1991). Thus, optimization of moisture content to the moisture content at which air flow is maximized and available adsorption sites are minimized increases the effectiveness of SVE.

There are insufficient data available to determine the change in moisture content caused by SVE. However, any changes in the moisture content probably were caused by SVE because of the asphalt cover over the site. There was no attempt to regulate the moisture content during this study.

### Porosity

Calculations of porosity indicated a relatively uniform distribution throughout the vadose zone (Tables 1, 2, and 3). It was postulated that this uniformity was caused by compression from the sampling method. However, the spherical response observed during the SVE tests indicates that the vadose zone is responding as a homogeneous unit. Thus, the uniform porosity is thought to represent the actual vadose zone conditions.



The air-filled porosity averaged from 19.7 % in SV-8A to 22.1 % in SV-14 (Table 3). The asphalt cover over the GSA area probably minimizes infiltration of precipitation to the subsurface. The initial 179 days of operation of the SVE system may have acted to dry out the vadose zone, thus maximizing the air-filled porosity. Johnson *et al.* (1990) stated that drying of the sediment by SVE may not be significant in increasing the air-filled porosity when the moisture content is less than 20 percent. Thus, the air-filled porosity has been maximized by the initial 179 days of SVE.

#### Hydrocarbon Distribution

Cross sections drawn before (Figs. 6 through 9) and after (Fig. 25) the initial 179 days of SVE reveal significant remediation of BTEX compounds. Above a depth of 80 feet bgs, the remaining BTEX and TPH-g are associated with fine sediment. The shallow intervals with residual soil contamination, approximately 26 to 28 feet bgs, 33 to 37 feet bgs, and 40 to 45 feet bgs, contain intervals within the mixed sediment that have a larger percentage of fine sediment. The flow characteristics and greater sorption capacity of fine sediment in these intervals are controlling the effectiveness of SVE.

The residual hydrocarbon contamination at depth was caused by several factors. The observed sediment blockages in GSW-16's lower screens restricted air-flow through the deeper sediment, thus the efficiency of SVE was reduced. The similarity in subsurface response between the GSW-16-Z4 and dual-zone SVE tests indicates that preferential air-flow through shallower sediment caused bypassing of the deeper sediments. A third factor was the reduced presence of bacteria between the depths of 80 feet bgs and the water

table (Paula Krauter, LLNL, personal communication, 1991). Reduced BTEX levels in the shallower horizons were facilitated by stimulation of biologic activity by SVE, as well as by volatilization.

The presence of free product on the water table also resulted in increased hydrocarbon concentrations in the deeper sediment. Hydrocarbons volatilizing from the free product and migrating upwards along a concentration gradient probably recontaminate the deeper sediment through sorption. The proximity of the water table may also have resulted in increased soil moisture, thus inhibiting air flow.

#### Individual-Zone Soil Vapor Extraction Tests

The individual extraction zone tests revealed a roughly spherical pressure response in the vadose zone (Fig. 26). A cylindrical response was expected because of the sedimentary layering in the vicinity. The spherical response was caused by the similarity in gas permeabilities of the different layers.

The only zone that showed a restricted amount of vertical communication was zone 5. A much higher vacuum was required to induce vapor flow from zone 5. There are two possible explanations for the restricted vertical influence in zone 5. The first of these is the blockage observed in the screen. This blockage decreased the vapor flow, because of the reduced surface area for air flow, and resulted in a greater vacuum loss across the screen. Another cause of the reduced pressure response was the increased moisture content of the sediment close to the water table. Air-filled porosity decreases

with increasing moisture content, resulting in increased vacuum losses and reduced air flow.

During the zone 4 SVE test, zone 4 in GSW-15, located 6 feet to the north of GSW-16, showed only a very minor vacuum response (Fig. 26). The low response indicates that flow is bypassing this area and flowing through more permeable sediment surrounding this zone. This will result in a pocket of sediment in which the remediation of hydrocarbons will be limited to the rate of diffusion.

#### Dual-Zone Soil Vapor Extraction Tests

The dual-zone SVE test demonstrated the complexity of the interaction of two screened intervals used for SVE. The vacuum response closely resembled the GSW-16-Z4 individual extraction zone test (Figs. 27 through 29). This vacuum response distribution indicates that a large amount of lateral flow, as well as vertical flow both upwards from depth and downwards from the surface, is occurring. This pattern was observed during the dual-zone SVE test with lateral flow more pronounced through zone 5, so that air flow was less spherical with extraction over a greater vertical distance.

The pressure response observed during the dual-zone SVE test results from a combination of the factors that caused the individual responses in the zone 4 and 5 tests. The dual-zone response, however, appears to be dominated by flow from zone 4, as can be seen by the calculated gas permeabilities, which are closer to the zone 4 permeability than the zone 5 permeability. The implication of preferential air flow through the

shallower sediment is that remediation of the deeper sediment will require focusing on extraction from zone 5.

### Gas Permeability

The gas permeability increased with depth over the interval between zones 2 and 4 (Table 6). This increase was expected because the sediment becomes coarser with depth. The calculated permeability of the sediment around zone 5 was lower than the permeability of the overlying sediment. The cause of the decreased permeability is a combination of increased moisture content as the water table is approached and the blockage of the screen. The material blocking the screen is acting to mask the permeability of the native sediment, thus the actual gas permeability of the native sediment may be higher than the calculated value. The similarity in calculated permeability between the zone 4 SVE test and the dual-zone SVE test reveals that air flow is controlled by the more permeable sediment in zone 4.

### Radius of Influence

The radius of influence was similar in zones 2, 3, and 5, at 23, 27, and 22 feet, respectively. Zone 4, the zone of highest calculated gas permeability, had the largest calculated radius of influence at 123 feet. Zone 5 was expected to have a larger radius of influence due to the presence of coarser sediment in this interval. It is thought that the lower calculated radius of influence is due to a combination of the restricted air flow

caused by the blockage of the zone 5 screen and the increasing moisture content as the water table is approached.

The largest radius of influence calculated for the dual-zone SVE test was 211 feet. This occurred when Zone 5 appeared to have its greatest effect during time period 9 (Fig. 29), indicating that two effective extraction zones will increase the radius of influence. The radii of influence observed during the other two time periods of the dual-zone SVE test analyzed resembled the zone 4 radius of influence, indicating the dominance of the zone with the higher gas permeability.

#### Hydrocarbon Removal by Soil Vapor Extraction

It is estimated that 2,200 gallons of gasoline were removed during the first 179 days of operation, an average of 12.3 gallons per day. Approximately 50 percent of the mass removal occurred during the first 38 days of operation. This indicates that the air was flowing through more highly contaminated sediment during the first 38 days. This sediment became less contaminated with time and, thus, the mass extraction rate decreased.

The individual-zone SVE tests revealed that the highest mass removal rates were from Zones 3 and 5. Zones 2 and 4 had lower mass extraction rates. Because soil sample chemical analytical results indicate that hydrocarbon contaminated soil in the shallow vadose zone corresponds in depth with Zone 2, it appears that extraction from GSW-16-Z3 is causing vertical air flow through this sediment while extraction from GSW-16-Z2 is bypassing this zone. Bypassing may be caused by preferential air flow through coarser

sediment or by short circuiting by vertical air flow from the surface. Extraction from GSW-16-Z3 may also be pulling vapor from a section of soil containing higher petroleum hydrocarbon concentrations that is not in line with the cross-section.

During the dual-zone SVE test, the mass removal rate increased over time. This indicates that air flow through sediment retaining higher amounts of hydrocarbons increased over this period of time. This probably was caused by an increase in the amount of sediment available to air flow as the moisture content decreased, particularly in zone 5. An additional source of hydrocarbons at depth is the free product present on the water table. If air is flowing directly above the free product, causing it to vaporize, the overlying soil may not be remediated until the free product is removed.

#### Vapor Contaminant Distribution

The BTEX distribution prior to the SVE tests was measured following a period of approximately 5 months during which there was no extraction at the GSA area. The areas of high residual soil contamination, between 35 and 50 feet bgs in SV-13 and below 70 feet bgs in SV-13 and SV-14, also had high levels of vapor contaminants present. The effects of diffusion were observed in the 50 to 70 foot interval in SV-13 and above 70 feet bgs in SV-14. These areas had low to non-detectable levels of residual soil contamination, but the vapor concentrations in these areas were as high as 22 ppmv. Vapor transport by diffusion was indicated by a vapor profile that differed from the distribution of residual soil contamination.

The vapor contaminant distribution following the individual-zone SVE tests closely resembled the distribution of residual soil contamination. Areas that had low levels of residual soil contamination had low levels of vapor concentrations. Closer to the water table, the levels of vapor contaminants were higher. This probably was caused by higher residual soil contamination and volatilization from floating product.

The effects of diffusion were again observed following the individual extraction zone tests. Vapor contaminants were moving from areas of high concentrations to areas with low concentrations. The rapidity of the contaminant movement between the depths of 50 and 65 feet bgs indicates that this region is more open to vapor diffusion than the surrounding sediment because of the higher gas permeability and greater air-filled porosity. The greater concentration gradient in this interval also stimulates faster migration of vapor contaminants. A more homogeneous medium would provide a more even spreading of vapor contaminants.

The spatial extent of vapor contaminants was reduced during the dual-zone SVE test. This indicates that the vapor extraction was effectively removing the contaminants. The vapor concentration recovery observed following the dual-zone SVE test revealed the effects of the floating product and diffusion.

The changes in vapor contaminant distribution are in accordance with Raoult's Law and Fick's Law. Raoult's Law states that the vapor pressure of a contaminant is directly proportional to the mole fraction of the contaminant and the vapor pressure of the pure contaminant. When the contaminant is a complex mixture such as gasoline, a modified form of Raoult's Law is used. Raoult's Law is applicable to the region that

overlies non-aqueous phase liquids. As hydrocarbon vapor is removed by SVE, the residual soil hydrocarbon will volatilize to establish a new equilibrium (described by Raoult's Law) between the vapor and free product.

Fick's law states that a compound will move from an area of high concentration to an area of lower concentration. This behavior is shown by the vapor contaminant migration after SVE has been shut down for a period of time.

Henry's Law is applicable in sediment overlying aqueous phase liquids. Henry's Law states that the vapor pressure of a compound is directly proportional to its aqueous concentration. The proportionality constant can be expressed as a water-air partition coefficient. Henry's Law was minimally applicable to this study because the monitoring was focused on the region overlying, or in close proximity to, non-aqueous phase liquids.

During the month following the dual-zone SVE test, BTEX concentrations increased below a depth of 75 feet bgs, especially near the center of the free product plume near GSW-16 (Figs. 41 and 42). The region between 40 and 60 feet bgs also showed an increase in BTEX concentrations by an order of magnitude. This revealed the movement of vapor contaminants by diffusion into a zone of low concentration.



## CONCLUSIONS

The main conclusions from the investigation are summarized below.

1. SVE was effective in remediating soil contaminated with gasoline at shallow depths that were not being influenced by the presence of free product. Approximately 37% of the estimated 6,000 gallons of gasoline in the subsurface was removed in the first 179 days of vapor extraction. Much of the remaining soil contamination is at depth near the free product. The sediment overlying the free product cannot be completely remediated until the free product is removed.
2. The vacuum response was approximately spherical in shape. Commonly used models for designing SVE systems assume horizontal flow. The results of this study indicate that a spherical flow model would be more appropriate in cases similar to this study.
3. The use of multiple screens for extraction did not significantly increase the radius of influence. This is because the air flowed preferentially through the more permeable extraction zone.
4. The free product on the water table was a significant source of hydrocarbon vapor for extraction from GSW-16-Z5. The increased mass removal rate during the dual-zone SVE test indicates that this source becomes more important as the air-filled porosity in the vicinity increases. This study suggests that the free product removal is enhanced by SVE. Free product skimming, in conjunction with SVE, would minimize the time required for remediation.

5. The spatial distribution of BTEX in vapor was representative of the residual soil contamination during and immediately after extraction. During periods of no extraction, the distribution no longer accurately reflected the distribution in soil as diffusion of contaminants occurred.

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**APPENDIX:**

**VADOSE-ZONE MONITORING DEVICE  
BOREHOLE LOGS**

### BOREHOLE / WELL CONSTRUCTION LOG

Page 1 of 1

<b>BOREHOLE LOCATION:</b>	Project: <u>LLNL</u>		Job No: <u>10-600-81</u>		Borehole/Well No: <u>SVB-CR-02A</u>	
	Logged By: <u>JCM</u>		Drawn By: <u>A. Bressen</u>		Geophysical Logs: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	
	Drilling Contractor: <u>SP</u>		Driller/Helper: <u>Phil/Ted</u>			
	Drilling Method: <u>Pneuc</u>		Hammer Weight:		Drop:	
	Borehole Diameter (in): <u>Pneuc</u>		Borehole Depth (ft):		Casing Depth (ft):	
	Borehole Started Time:		Borehole Completed Date:		Depth to Water Datum:	
	Well Construction Started Time:		Well Construction Completed Time:		Depth (ft)    Time    Date	
	Well Head Completion:		Well Development Completed Time:		Flow Rate:	
Water Introduced into Borehole/Well Source: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No				Borehole Gel Used: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		

Sample Type/Depth	Screening Method (e.g. Drive / No. Returned)	Name / S.N.	Classification (e.g. CL)	Sample Quality	Sample Identification	Laboratory / DNA / PID	Borehole Depth (ft)	Well Constr.		Depth in Feet	Remarks / Observations Used
								Casing / Screen	Annulus / Plug		

LITHOLOGIC DESCRIPTIONS







BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Sample Type & Depth	Recovery Status	Moisture Content	Shrinkage	Sample ID	Lab/CR/FRD	Coring/Section	Analysis	Depth (ft)	Recovery	Sample Length	Project	Job No.	Borehole/Well No.
								28			LLNL	10-600-91	SVB-GP-008A
								28			Sandy silt ( ) olive, med. stiff, damp, non plast, sand 20-30%, vf to med, est low K, occ caliche, occ coarse sand		
								29			Sandy clay ( ) reddish brown, damp, hard, mod. plast, sand 20-30%, vf to f, occ worm burrow, est low K		
								29			To Clay Gravel		
								30			Gravelly Clay ( ) reddish brown, damp, hard, mod. plast gravel 15-25%, redd, occ caliche or weathered material, est low K, cobble 5-15%		
3								30			<del>Sandy Clay ( ) gray red brown, hard, mod. plast, sand vf to coarse 10-20%, gravel 5-10%, for pebble</del>		
3								31			inc. cobble 10-20%, up to 4.5" w/ manganese stain		
								30-31			GRAVELS TO		
								31			Sandy clay ( ), reddish brown, damp, hard, sand, 30-40%, vf to coarse, & to subgrd, mod plast, low est K, occ. caliche in fractures		
								32			Sandy silt ( ) gray brown, damp, stiff, mod. plast, sand 20-40%, coarse, occ. caliche, est low K, & to coarse sand		



**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type & Depth	Sample ID	Lab/ QVA/ID	Notes	Depth (ft)	Remarks
48 36				36	Sandy Silt ( ) gray brown, damp, stiff, mod. Plast, sand @ 10-20%, v.f. to med, sub K, est low K
				37	grades - 37-38 to
				38	Silty Sand ( ) yellow brown, damp, hard, silt 30-40%, well graded, v.f. to med, occ coarse sand, low Plast, low est K, occ. iron stains, occ Manganese
				39	Silty Sand - ( ) yellow brown, damp, hard; silt 10-30%, well graded, non plast, low/med est K, occ. iron stain, occ gravel 5-10%

BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Sample Type & Depth	Sample Depth	Blow / Char. / Snp Qual	Sample ID	Lab / OVA / PID / Remarks	Coating / Drilling / Lubrication / Notes	Depth (ft)	Remarks / Graphic Log	Project	Job No.	Location / Well No.
38	38					30				
						31				
						32	Sandy silt ( ) yellow brn, damp, v. stiff, low Plast, sand v.t. to coarse 20-30%; low est K, manganese inclusions, clay 10-20%			
						33				
						34				
						35				
						36				
						37				
						38				
						39				
						40				
						41				
						42				
						43	trace gravel 42.7-43.3			
						44				
						45				
						46				
						47				
						48				
						49	Silty sand ( ) yellow brn, damp, dense, non Plast, well graded sand, silt 20-30%, sand v.t. to med.			
						50				
						51				
						52	Sandy silt - as above, sand v.t. to med			

C →

→

BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Sample Type & Depth	Recovery Status	Water/Air Ratio	Chloride (mg/l)	Sample ID	Lab/ OVA/ID Number	Casing / Screen Material	Depth (ft)	Recovery Status	Graphic Log	Project	Job No.	Borehole/Well No.
							44.5					
							44.6					
							44.7					
							44.8					
							44.9					
							45.0					
							45.1					
							45.2					
							45.3					
							45.4					
							45.5					
							45.6					
							45.7					
							45.8					
							45.9					
							46.0					
							46.1					
							46.2					
							46.3					
							46.4					
							46.5					
							46.6					
							46.7					
							46.8					
							46.9					
							47.0					
							47.1					
							47.2					
							47.3					
							47.4					
							47.5					
							47.6					
							47.7					
							47.8					
							47.9					
							48.0					

local inc. clay to 20-30%  
 from 44.6 to 45.4

root structures at 46-46.2'

PO hydrocarbon solvent at 46.5'

45  
 30

BOREHOLE / WELL CONSTRUCTION LOG (cont.) Page   1   of   1  

Sample Type & Depth	Recovery Ratio	Flow/In Completion	Flow Unit	Sample ID	L1/L2 / OVA / PB / Remarks	Casing / Screen / Filter	Depth (ft)	Recovery (%)	Grain Size	Grain Size	Grain Size	Grain Size	Project			
													Job No.	Borehole/Well No.	Notes	
							48									
							40									

EC >

Silty Sand ( ) as above

Silty Sand ( ) as above,  
caliche 15-25% 50.6'-52'

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)** Page      of     

Sample Type & Depth	Recovery Factor	Memo/AS to Client	Sample ID	LAB/ OVA/PIB Results	Geology/ Lithology	Assess/ Notes	Depth (ft)	Recovery Graph	Project	Job No	Borehole/Well No
							15				
							15		Sandy silt: ( ), yellow-brown sand v.f. top		
							16				
							17		Clayey silt: ( ) yellowish brown, moist, hard, med. plast, sand 15-25%, clay 20-30%, sand v.f. to med, occ coarse sand, est low K		
							18				
							19				
							20				
							21				
							22				
							23				
							24				
							25				
							26				
							27				
							28				
							29				
							30				
							31				
							32				
							33				
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							37				
							38				
							39				
							40				
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							42				
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							94				
							95				
							96				
							97				
							98				
							99				
							100				

3/27

54  
36

PO

GRAVELLY  
light Sand ( ), yellowish  
brown, dense, moist, v. well  
graded, pebbles 25-40%, subrd. to rd. li.  
sand v.f. to coarse, silt 5-10%,  
clay 0-1%, est med K

stiff clay (CH), reddish brown,  
hard, moist, high plasticity,  
est med K

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type & Depth	Primary Strata	Notes / Comments	Sample ID	LN / OVA / ID	Depth (ft)	Remarks
					31.5	
					32.0	
					32.5	
					33.0	
					33.5	
					34.0	
					34.5	
					35.0	
					35.5	
					36.0	
					36.5	
					37.0	
					37.5	
					38.0	
					38.5	
					39.0	
					39.5	
					40.0	
					40.5	
					41.0	
					41.5	
					42.0	
					42.5	
					43.0	
					43.5	
					44.0	
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					92.0	
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					93.0	
					93.5	
					94.0	
					94.5	
					95.0	
					95.5	
					96.0	
					96.5	
					97.0	
					97.5	
					98.0	
					98.5	
					99.0	
					99.5	
					100.0	

Pebbly Sand (SM) as above,  
acc cobble

54  
30  
88.5

--- ? --- ? ---

CLAYEY SILT (ML) MED BROWN, MOIST, MED  
STIFF, LOW PLAST., w/c 10% of sand,  
MED slight odor, LOW EST K.



**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type & Depth	Recovery Status	Moisture Content	Grain Count	Sample ID	LAB/OWA/PSD Barcode	Corelog/Screen	Assessor/Title	Depth (ft)	Recovery Status	Project	Job No.	Borehole/Well No.
								50				
								49.5				
								49.0				
								48.5				
								48.0				
								47.5				
								47.0				
								46.5				
								46.0				
								45.5				
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								5.5				
								5.0				
								4.5				
								4.0				
								3.5				
								3.0				
								2.5				
								2.0				
								1.5				
								1.0				
								0.5				
								0.0				

INCLUDE NOTHING 60.3 - 60.6 FT

CLAYY SILT (ML) MED GR BROWN, MOIST  
 MED STIFF, 10-20% FINE SAND, LOW TO  
 LOW PLASTIC, OCC CALCITE AT FRACTS  
 AND NODULES, LOW-MOD EST K

INTY SAND (SM) MED BROWN, MOIST,  
 MED DENSE, VF-MG, N/20-30% MED  
 TO LOW PLAST. FINES, MOD-LOW EST  
 K, MOD HIG OADR

CC 30  
 63 24

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Page \_\_\_ of \_\_\_

Sample Type & Depth	Sample Depth	Interval/ft	Characterization	Notes	Sample ID	Lab/ OVA/ID	Core/ Section	Assess/ PMA	Depth (ft)	Remarks	Project	Job No.	Borehole/Well No.
									1.5	CLAYEY SILT TO SILTY CLAY (MH/CL).			
									2.5	RED BROWN W/ BK MOTTLING (MAO <sub>2</sub> ?)			
									3.5	HARD, STIFF, MED PLASTICITY, LOW			
									4.5	EST K, MILD HYDRO ODOUR, EXTENSIVE			
									5.5	MH VOIDETS.			
									6.5				
									7.5				
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									99.5				
									100.5				

CLAYEY SILT TO SILTY CLAY (MH/CL).  
 RED BROWN W/ BK MOTTLING (MAO<sub>2</sub>?)  
 HARD, STIFF, MED PLASTICITY, LOW  
 EST K, MILD HYDRO ODOUR, EXTENSIVE  
 MH VOIDETS.

CLAYEY TO SANDY SILT (ML) RED BROWN,  
 HARD, MED STIFF, LOW-MED PLASTIC,  
 10-30% VP-SG SAND, LOW EST K,  
 MILD HYD ODOUR
















BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Sample Type & Depth	Recovery (%)	Moisture (%)	Chemical Analysis	Grain Size	Grain Weight	Lab / OVA / PID / Probe	Crating / Nitrogen	Analysis / Other	Depth (ft)	Remarks / Corrigible	Project	Job No.	Borehole / Well No.
									0.5	Gravelly sand (SM) GRAY BROWN, MOIST, DENSE, vfg-mg, w/20-30% n.p.s. FINE, <math>2.5\text{''}</math> SR PEBBLES TO $1/4\text{''}$ . MOD EST K, MOD HIGH ODR			
LC 18	18								1.5	6T-6T-5-6T			
LC 18.5	18.5								2.5				
									3.5				
									4.5				
									5.5				
									6.5				
									7.5				
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									40.5				
									41.5				
									42.5				
									43.5				
									44.5				
									45.5				
									46.5				
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									100.5				

BECOMES COBBLELY 71.2 - 71.9 FT

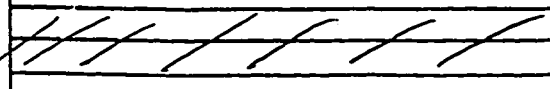
BOREHOLE / WELL CONSTRUCTION LOG (cont.) Page      of     

Sample Type & Depth	Recovery Notes	Moisture Content	Sample ID	LAB/ QVA/PTD Number	Casing/ Screen Material / Size	Depth (ft)	Recovery Graphic Log	Remarks	Job No.	Borehole/Well No.
						72				
						73				
						74				
						75				
						76				
						77				
						78				
						79				
						80				
						81				
						82				
						83				
						84				

cc  
75

becomes sobby / sobby  
74-75

Clayey Silt (M) yellow brn,  
damp, hard, low plasticity,  
clay 10-30%, sand 10-20%,  
rest low k, extensive Mn concretions



**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type (Depth)	Sample Depth	Moisture (%)	Specific Gravity	Sample ID	Lab/ QA/QC Barcode	Coring/ Notes	Analysis Notes	Depth (ft)	Remarks Graphic Log	Project	Job No.	Borehole/Well No.
CC	38	76.2	38					0	↓			
								1				
								2				
								3				
								4				
								5				
								6				
								7				
								8				
								9				
								10				
								11				
								12				
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								50				

SANDY SILT (MC) YELLOW-BRN,  
MOIST, STIFF, NON TO LOW PLAST. w 20-  
40% silt, sand, low-mob ect k.  
STRONG SPOB

SILT (MC) YELLOW BROWN, MOIST, NON STIFF  
NON PLAST, w 5-10% silt, sand strong k  
O.D.

SANDY SAND (ST) YELLOW BROWN, MOIST  
W/ 3-5% silt, w 30-50% non-  
LOW PLAST FINES, MOD ESTIM, some  
rootlets

CC  
79.3  
48

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type & Depth	Barrel	Water / Oil	Chloride	Temp (F)	Sample ID	Log / UVA / PID	Casing / Screen	Annular Filler	Depth (ft)	Remarks / Geologic	Project	Job No.	Borehole / Well No.
									0				
									1				
									2				
									3				
									4				
									5				
									6				
									7				
									8				
									9				
									10				
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									99				
									100				

5' TO GRAVELLY SAND (SM/SP)  
 YELLOW-BROWN, DENSE, 5-1/2% FINE, 10% SAND, 10% SILT, 10% CLAY, 10% ORGANIC, 10% PLAST FINE, 10% MUD-HIGH EST K

BELOW 92-87 FT TO 10% CLAY TO 15 IN.

~~REMARKS TO SAND GRAVEL (GW) GR BROWN, DENSE, 10% FINE, 10% SAND, 10% SILT, 10% CLAY, 10% ORGANIC, 10% PLAST FINE, 10% MUD-HIGH EST K~~

REMARKS TO SAND GRAVEL (GW) GR BROWN, DENSE, 10% FINE, 10% SAND, 10% SILT, 10% CLAY, 10% ORGANIC, 10% PLAST FINE, 10% MUD-HIGH EST K

SAND GRAVEL TO GRAVELLY SAND (GM/SM) YELLOW BROWN, DENSE, 10% FINE, 10% SAND, 10% SILT, 10% CLAY, 10% ORGANIC, 10% PLAST FINE, 10% MUD-HIGH EST K

24  
 87.4  
 36  
 34

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type & Depth	Recovery Status	Flow/Leak	Corrosion	Temp. Qual.	Sample ID	LAB ORG./PID	Remarks	casing / Screen	Annular Fills	Depth (ft)	Recovery Graphs	Project	Job No.	Borehole/Well No.
										87.0				
										87.1				
										87.2				
										87.3				
										87.4				
										87.5				
										87.6				
										87.7				
										87.8				
										87.9				
										88.0				
										88.1				
										88.2				
										88.3				
										88.4				
										88.5				
										88.6				
										88.7				
										88.8				
										88.9				
										89.0				
										89.1				
										89.2				
										89.3				
										89.4				
										89.5				
										89.6				
										89.7				
										89.8				
										89.9				
										90.0				
										90.1				
										90.2				
										90.3				
										90.4				
										90.5				
										90.6				
										90.7				
										90.8				
										90.9				
										91.0				
										91.1				
										91.2				
										91.3				
										91.4				
										91.5				
										91.6				
										91.7				
										91.8				
										91.9				
										92.0				
										92.1				
										92.2				
										92.3				
										92.4				
										92.5				
										92.6				
										92.7				
										92.8				
										92.9				
										93.0				
										93.1				
										93.2				
										93.3				
										93.4				
										93.5				
										93.6				
										93.7				
										93.8				
										93.9				
										94.0				
										94.1				
										94.2				
										94.3				
										94.4				
										94.5				
										94.6				
										94.7				
										94.8				
										94.9				
										95.0				

CLAYEY SILT (ML) MED BROWN, MOIST, MED STIFF, MED PLAST, c10% v% SAND LOW EST K, MOD HCL 0007

FINE SAND (SM) MED BROWN, MOIST, DENSE, IF- LG, w/10-15% - MED - LOW PLAST FINE, MOD EST K, MOD HCL 0002

Sandy Gravel to Gravelly Sand (GM/SM), yellow brown, moist, v. dense, 30-70% subround pebbles to 2", 30-70% v% - VC, well graded, est mod - high K

inc. pebble size to 2.5" Sandy Gravel 97.1 to 97.9

86.3 46 44

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

Sample Type & Depth	Recovery Factor	Flow / L	Chloride	Sulfate	Sample ID	Lot / OVA / TPB Brake	Casing / Screen	Aquifer / Filter	Depth (ft)	Secondary Graphs Log	Program	Job No.	Borehole / Well No.
											inc silt to 20-35%, weathered 98.2-88.5 feet		

Clayey Gravel ( ) reddish  
brown, moist, v. dense, clay 15-35%  
gravel up to 1.5", sub to submd,  
mod platy, est low K

51\*



**BOREHOLE / WELL CONSTRUCTION LOG**

BOREHOLE LOCATION:		Project: <u>LLNL</u>	Job No: <u>10-500-51</u>	Borehole/Well No: <u>SVB-GP-013</u>
Logged By: <u>JCM</u>	Field Log: <u>M. Vresen</u>	Company Log: <u>OTC</u>		
Drilling Contractor: <u>Sierra Pacific</u>	Driller/Manager: <u>Phil Ries / Ted Winters</u>			
Drilling Method: <u>HSA</u>	Flare: <u>None</u>	Drop: <u>None</u>		
Borehole Diameter (in): <u>12</u>	Borehole Depth (ft): <u>90</u>	Casing Depth (ft): <u>90</u>		
Borehole Started Time: <u>10:00</u> Date: <u>3/25/11</u>	Borehole Completed Time: <u>10:00</u> Date: <u>3/25/11</u>	Depth to Water: <u>None</u>		
Well Construction Started Time: <u>10:00</u> Date: <u>3/25/11</u>	Well Construction Completed Time: <u>10:00</u> Date: <u>3/25/11</u>	Depth (ft): <u>None</u>	Start Date: <u>None</u>	End Date: <u>None</u>
Well Head Completion Time: <u>None</u> Date: <u>None</u>	Well Development Completed Time: <u>None</u> Date: <u>None</u>	Flow Rate: <u>None</u>		
Water Returned Into Borehole/Well: <u>None</u>	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	Borehole Gel Used: <u>None</u>	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	

Sample Type/Depth	Recovery Method No. Shells / No. Shards	Shells / No. Shards	Cementation PL CL	Sample Quality	Sample Microfossils	Laboratory / OWA / IWB Borehole Depth	Well Constr.		Depth to Base	Recovery / Sample Log	Notes / Abbreviations Used
							Casing / Screen	Annular Filler			
											LEL → 20% CC = continuously cored
											LITHOLOGIC DESCRIPTIONS
											Asphalt + baserock
											Fill material:
											Sandy silt (ML), red brown, damp. silt, low plastic, sand. 2-30%
											vf - c SR-SA, clay 10-20% (shallow)
											D=20% f-c up to 3" dia SR-acc
											cobbles to 6" dia R, med est K







### BOREHOLE / WELL CONSTRUCTION LOG (cont.)

WEISS ASSOCIATES



Log No.	Project	City & State	Date	Scale	Drill Log	Remarks
	LLNL					
	10-600-51					
22	30					
15-83	35					

*DRAIN*

Gravelly Sand (S.W.) as above

Sandy silt (ML) & yellow brown, damp, stiff, low plast, sand 10-30% v-f-med, clay 10-20%, occ gravel f to 1/2" dia, SF-SA (quartzite, mica stone), low est K

Sandy clay (CL) yellow brown, damp, stiff, low med plast, sand 20-30% v-f, SF, silt 15-25%, occ calcite (?), occ iron stain, low est K

Sandy silt (ML), as above, occ cobble to 3/5" dia R

BOREHOLE / WELL CONSTRUCTION LOG (cont.)

WEISS ASSOCIATES

WA

Sample Type & Depth	Sample ID	Lab/ID	Drains	Notes	Depth (ft)	Program	Job No	Reference Well No
					1	LLNL	10-600-20	SVB-GP-013
					1			
					1			
					1			
CC 30 215-25 30					20			
					1			
					1			
					1			
					1			
					1			
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					1			
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					1			
					1			
					1			
					1			
					1			
					1			
					1			
					1			
					1			
CC 24 215-21 24					22			
					1			
					1			

Sandy silt (ML) yellow brown, damp, stiff, low pl. silt sand 20-30%  
Fc, Sb-K, clay 5-10%, trace iron stain, low est K

Sandy silt (ML), as above, inc. clay to 10-20%

Sandy silt (ML), as above, inc. sand 25-40%, clay 5-10%

? ? ?

Sandy clay (CL), brown, damp v. stiff, low plast, sand 20-30% v. c, SA-A, silt 10-30%, occ. mang. oxide slight "sweat" odor, occ. small burrows, low mod est K









BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Depth (ft)	Soils / Lithology	Remarks	Notes	Moisture (%)	Specific Gravity	Unit Weight (pcf)	Void Ratio (e)	Porosity (%)
0 - 0.25	Sandy Clay (CL)	occ. roots: small						
0.25 - 0.5								
0.5 - 0.75								
0.75 - 1.0								
1.0 - 1.25								
1.25 - 1.5								
1.5 - 1.75								
1.75 - 2.0								
2.0 - 2.25								
2.25 - 2.5								
2.5 - 2.75								
2.75 - 3.0								
3.0 - 3.25								
3.25 - 3.5								
3.5 - 3.75								
3.75 - 4.0								
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6.25 - 6.5								
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6.75 - 7.0								
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8.5 - 8.75								
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29.0 - 29.25								
29.25 - 29.5								
29.5 - 29.75								
29.75 - 30.0								

DRAFT

Sandy Clay (CL) as ...  
 occ. roots: small

Sandy clay (CL) as ...  
 20-30% vf - 2-3

Sand (SW) yellow brown, dense,  
 porous, low plasticity, fine  
 1-2% silt, sand 75-85%,  
 odor, high est K

Sandy Clay (CL) yellow brown,  
 damp, low plasticity, sand 70-80%,  
 vf-med, silt 0-10%, occ. manganese, low  
 est K









BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Sample Type & Depth	Recovery Status	Moisture Content	Classification	Notes	Lab ID / ID Number	Coring Method	Associated Data	Depth (ft)	Recovery Status	Project	Job No.	Borehole/Well No.
								0		LLNL	10-600-51	SVB-GP-013
								1				
								2				
								3				
								4				
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								100				

KC 24  
595525 36

*Handwritten notes in the log grid area.*

Gravelly Clay (CL) w/ burrows  
 damp, stiff, med. Plast. gravel 20-30%  
 f to c, up to 1" dia SR-K, sand 10-20%  
 vf-med, med est K.

Sandy Silt (ML) light yellow  
 brown, damp, stiff, low P<sub>25</sub>  
 sand, 20-40% vf-med, clay 10-20%,  
 occ caliche(?), low/med est K

Sandy Silt (ML), as above,  
 occ burrows (small)

CC  
5755C









BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Depth (ft)	Log Type	Remarks	Notes	Other
		Gravelly Clay (C) red brown damp, med. dense, mod. clay, 23-43% f oc up to 3" dia S&K, w/ 10-20% v-fines, OCC mod. v-fines OCC harden notes, mod. v-fines		
		Disjunctive Contact Clayey Gravel (GC) red brown damp, v. dense, mod. clay, 53-80% silt, mod. 0-15% OCC mod. v-fines, mod. v-fines est K		
		Sub: gravel (GW) red brown damp, v. dense, mod. clay, 20-43% v-fines 10-20% fines 10-20%, red w/ f to c up to 3" dia S&K, v-fines to 4" dia, color, high est K		
		Clayey Gravel (GC) ac. cov. no harden notes, red		

*DRILL*

CC 35/75  
75/72







BOREHOLE/WELL CONSTRUCTION LOG (cont.)

Project		Job No.		Borehole/Well No.		Date		Driller	
LLNL		10-600-51		SVB-GP-013					
Core Type	Core No.	Core Depth	Core Depth	Core Depth	Core Depth	Core Depth	Core Depth	Core Depth	Core Depth
2C 5-71	30 36								

*DEWET*

Gravelly Sand (SM) 5-71  
 25-45% sand, 45-60% silt & clay, 10-25% gravel  
 SR = 2.5, v. calc. + 4% clay, dry  
 high salt K

Gravelly Clay (CL) 5-71  
 hard, fine to med. gravel 25-53%  
 3-5% silt & clay, 10-25% + -  
 SR = 2.5, v. calc. + 4% clay, dry  
 high salt K

TP-710

**BOREHOLE/WELL CONSTRUCTION LOG**

BOREHOLE LOCATION:		Project: <u>LLNL</u>	Job No: <u>10-600-51</u>	Borehole/Well No: <u>SVS-6F-014</u>
Logged By: <u>JCM</u>	Drilled By: <u>M. Vresen</u>	Completed Log By: <u>[Blank]</u>	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	
Drilling Contractor: <u>Sierra Pacific</u>		Driller/Manager: <u>Phil Rice/Ted Whetsel</u>		
Drilling Method: <u>HSA</u>	Blade	Blade Number: <u>1401b</u>	Drop: <u>30"</u>	
Borehole Diameter (in): <u>12</u>	Feet	Borehole Depth (ft): <u>90</u>	Casing Depth (ft): <u>90</u>	
Borehole Started Time: <u>9:00</u>	Date: <u>2/21/11</u>	Borehole Completed Time: <u>3:00</u>	Date: <u>2/21/11</u>	Depth to Water Below: <u>[Blank]</u>
Well Construction Started Time: <u>[Blank]</u>	Date: <u>[Blank]</u>	Well Construction Completed Time: <u>[Blank]</u>	Date: <u>[Blank]</u>	Depth (ft) Time Date
Well Head Completion: <u>[Blank]</u>	Date: <u>[Blank]</u>	Well Development Completed Time: <u>[Blank]</u>	Date: <u>[Blank]</u>	Depth (ft) Time Date
Water Introduced into Borehole/Well Source: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		Borehole Cell Used Product Name: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No		

Sample Type/Depth	Recovery Depth In, Bottom / In, Return	Stratigraphic PL, CL	Length Quality	Remarks	Laboratory / OVA / VIB Results	Casing / Screen	Well Comm.	Depth in Feet	Recovery / Sample Len.	Graphic Log	Notes / Observations Used	
											K = permeability	CC = continuous core
												LITHOLOGIC DESCRIPTIONS
												Asphalt + Base rock
												Sandy silt (ML) brown to olive brown, stiff, damp, non plastic, sand 20-30% med. silt clay 10-20% scc root structures, scc 10-15% to 35% med to k
												Sandy silt (ML) light to green, stiff, damp, non plastic, sand 10-20% to med. root below horizon hole 10-20% high to k





BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Sample Type & Depth	Borehole Number	Meters / Feet	Characteristics	Temp (C/F)	Sample ID	Lab / QA/QC	Casing	Screens	Depth (ft)	Remarks	Project	Job No	Borehole / Well No
											LLNL	10-50051	SYS-GP-014
													Clayey silt / ML ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													Clayey silt ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...
													... (J-2) ...
													... 10-2 ...
													... 2" dia SR ...

in occ. weathered ...

**BOREHOLE / WELL CONSTRUCTION LOG (cont.)**

WEISS ASSOCIATES **WA**  
 Page 4 of 23

Sample Type & Depth	Sample Depth	Notes / Comments	Remarks / Other	Log	Project	Job No.	Borehole / Well No.
				L	LLNL	10-600-51	SVS-SP-014
				L	Sand: gravel / GW. as shown		
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				L			
				X 12			
				L			
				L			
				L			
CC REBT	36 35			L	Gravelly sand, GW. yellow, irony, damp, v. dense, low cohesion, poorly sorted, gravel 20-25% f-c up to 3 dia SR, fine c 5-15%, sand v-f-c SR-A, high est k		
				X 13			
				L			
				L			
				L			
				L			
				X 14			









BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Depth (ft)	Log	Remarks	Notes	Other
0	LLNL	10-600-51	SVS-6P-014	
0-12	CC	42		
12-24	CC	42		
24-36				
36-48				
48-60				
60-72				
72-84				
84-96				
96-108				
108-120				
120-132				
132-144				
144-156				
156-168				
168-180				
180-192				
192-204				
204-216				
216-228				
228-240				
240-252				
252-264				
264-276				
276-288				
288-300				
300-312				
312-324				
324-336				
336-348				
348-360				
360-372				
372-384				
384-396				
396-408				
408-420				
420-432				
432-444				
444-456				
456-468				
468-480				
480-492				
492-504				
504-516				
516-528				
528-540				
540-552				
552-564				
564-576				
576-588				
588-600				

Sandy clay (CL) greenish brown.  
 damp, stiff, med plastic sand 20-30%  
 wt - c SR-A silt 10-20%, occ calcite,  
 occ manganese. low est K

Sandy clay (CL) yellow brown.  
 damp, stiff, med plastic sand 20-30%  
 wt - c SR-A, silt 10-20%, occ calcite,  
 low est K

Gravelly Sand (GW) brown, v  
 dense, damp, firm, med plastic  
 5-10% sand, 10-20% silt, SR-K  
 7-20% sand, 10-20% silt, SR-K  
 low est K





BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Depth (ft)	Remarks	Notes	Other
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
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24			
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26			
27			
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45			
46			
47			
48			
49			
50			

Project: LLN  
 Job No: 10-530-51  
 Borehole/Well No: 45-3P-314

FFS

Sand (GW) with some silt and clay  
 in the upper 10' contains fines 1-10"  
 Sand is CR-A, 5-15%  
 S to 3/4" dia CR-K in 1' of K

FC 42  
 42-44 12

Sand, GW, 15-25% fines  
 in 1' of K

Sand, GW (ML), Fr. in. diam  
 in 1' of K  
 15-25% fines  
 10-20% fines  
 10-20% fines



BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Log No.	Date	Project	Job No.	Borehole/Well No.
CC	75	LLNL	10-600-51	SVS-EP-014
47-50	30			
				Sand (SP) yellow brown, lamp, loose well sorted fines 0-10% no cohesion, sand w/c silt, high est K
				Silty sand (SM) as above
				Sandy clay (CL) non plastic, v. strat. mod. tact. cont. 13-20% silt, occ minor, occ siliceous, low silt
				Sandy silt (ML) non plastic, low silt, non-plastic, sand 20-25%, v-c-cl, clay 0-10%, occ burry, has trace calcite, low silt











BOREHOLE / WELL CONSTRUCTION LOG (cont.)

Project Name	Location	Client	Date	Driller	Well No.	Log No.	Scale	Remarks	Depth (ft)	Soil Description
						LLNL	10-600-51	SVS-6P-014		

CC 42  
5778 42

Clayey Silt (ML) yellow brown, tan;  
stiff, low plast; clay 10-30%, sand 5-15%  
vf-f, occ burrow holes, occ manganese,  
low est K

Sandy Silt (ML) yellow brown, tan;  
damp, stiff, low med plast, sand 20-35%  
vf-med, clay 10-20%, occ burrow  
holes, trace manganese, low med est K

Sandy Clay (CH) red brown,  
damp, v. stiff, high plast, sand 10-25%  
f-med SR-R, silt 0-10%, occ manganese,  
occ gravel f to 1/2" dia SR-R, low est K









