Pre-Dynamic Stripping Underground Demonstration Project Hydrogeochemical Characterization of the Gasoline Spill Area, Lawrence Livermore National Laboratory, Livermore Site, Livermore, California

by Charlie Noyes

Introduction

A detailed hydrogeochemical characterization of the Gasoline Spill Area (GSA) at the Lawrence Livermore National Laboratory (LLNL) Livermore Site was conducted between October 1991 and September 1993 as part of the Dynamic Underground Stripping Demonstration Project (DUSDP). Thirteen hydrogeologic and hydrogeochemical cross-sections were constructed that incorporated geologic, geophysical, hydraulic, chemical, and well completion data. These cross-sections provided the basis for preparing structure, isopach, and isoconcentration maps for the DUSDP steam zones and adjacent confining layers. A discussion of the objectives, methodology, and results of the hydrogeochemical characterization conducted is presented below.

Study Objectives

The study objectives were to:

1. Assess the hydrogeochemical setting of the GSA to critically evaluate the effectiveness of the Dynamic Stripping process as an in-situ fuel hydrocarbon (FHC) remedial technology. This effort included volumetric estimation of pre-DUSDP fuel hydrocarbons-in-place, as well as characterizing and predicting the potential steam migration pathways prior to the commencement of actual steam injection at the GSA; and

2. Assist in the final design of the DUSDP well field, including contributing to the steam injection and extraction well completion design (e.g., screen length and location, filter pack, and screen slot size) and identifying steam injection and extraction well locations.

Gasoline Spill Area Site Background

The releases, areal extent of gasoline, and pre-DUSDP remedial activities are summarized below.

Gasoline Releases

Between 1952 and 1979, a records review indicates that about 17,000 gallons of leaded gasoline may have been lost from the southernmost of four underground storage tanks in the GSA (Figure 1) (Dresen *et al.*, 1986; Nichols *et al.*, 1988; Thorpe *et al.*, 1990; and Isherwood *et al.*, 1990). The apparent inventory deficit is suspect since measurement accuracy is not known and undocumented removals may have occurred. Subsequent investigation indicate that the leak had occurred at the western edge of the southernmost tank and gasoline has contaminated unsaturated sediments to a depth of about 100 ft and saturated sediment and ground water to a depth of about 135 ft. All four tanks were removed from service, drained of gasoline, and filled with sand in 1980 (Isherwood *et al.,* 1990).

Rough estimates of FHC (as gasoline) mass in-place as gasoline prior to any remedial activities were based on chemical analyses of saturated and unsaturated soil and ground water, and indicated that about 6,000 gallons existed in the vadose zone, about 11,000 gallons were present in saturated sediments, and about 100 gallons were dissolved in ground water (Nichols *et al.,* 1988). Concentrations of as high as 5,100 ppm in saturated soil samples near the center of the release site indicate that free phase gasoline exists below the present water table (Dresen *et al.,* 1986; Hunt *et al.*, 1988; Udell and Hunt, 1987). Free phase gasoline below the present day water table is attributed to a 10 to 30 ft lower water table during the time of the releases (Alameda County Flood Control and Water Conservation District, 1982). As the water table rose in the 1980s, free phase gasoline was trapped within and against fine-grained, low permeability sediments (Nichols *et al.*, 1988).

Areal Extent of FHCs

The pre-DUSDP distribution of FHCs at the GSA was characterized in several investigations summarized in Isherwood *et al* (1990). The distribution of total aromatic hydrocarbon concentrations above 1 ppm in the vadose zone appeared to be limited to an area less than about 30 to 35 ft from the leak point, decreasing to 0.1 ppm within 40 to 45 ft horizontally of the leak point. Total fuel hydrocarbon (TFH) concentrations exceeding 10 ppm in ground water appeared to be restricted to the immediate vicinity of the gasoline leak point and to decrease significantly in all directions away from the spill center. In 1990, benzene concentrations above the 0.001 ppm State of California Maximum Contaminant Level (MCL) were restricted to an area within about 300 ft from the leak point. FHCs in ground water are not present below a depth of about 140 ft.

Pre-DUSDP Remedial Activities

A gasoline skimmer, soil vapor and ground water extraction wells, a thermal oxidizer vapor treatment unit, and an ultraviolet/hydrogen peroxide water treatment unit are among the remedial technologies used intermittently for pilot tests at the GSA since September 1988. Vacuum-induced soil venting was considered by Macdonald *et al.* (1991) to have removed about 2000 gallons liquid-equivalent gasoline vapor between September 1988 and December 1991. In addition, at least 100 to 150 gallons of fuel hydrocarbons were removed by skimming free product from the top of the water table, during pumping tests, and during routine sampling (Isherwood *et al.,* 1990). A microbiological study by Krauter and Rice (1991) indicated that microbiological populations at the GSA are much larger than those in nearby uncontaminated areas suggesting that additional gasoline constituents may have been metabolized by microbes. Isherwood *et al.* (1990) and Macdonald *et al.* (1991) contain additional details concerning the history and results of the remedial techniques tested at the GSA.

Previous Hydrogeochemical Characterization

The local GSA hydrogeology and the subsurface distribution of the FHCs have been studied

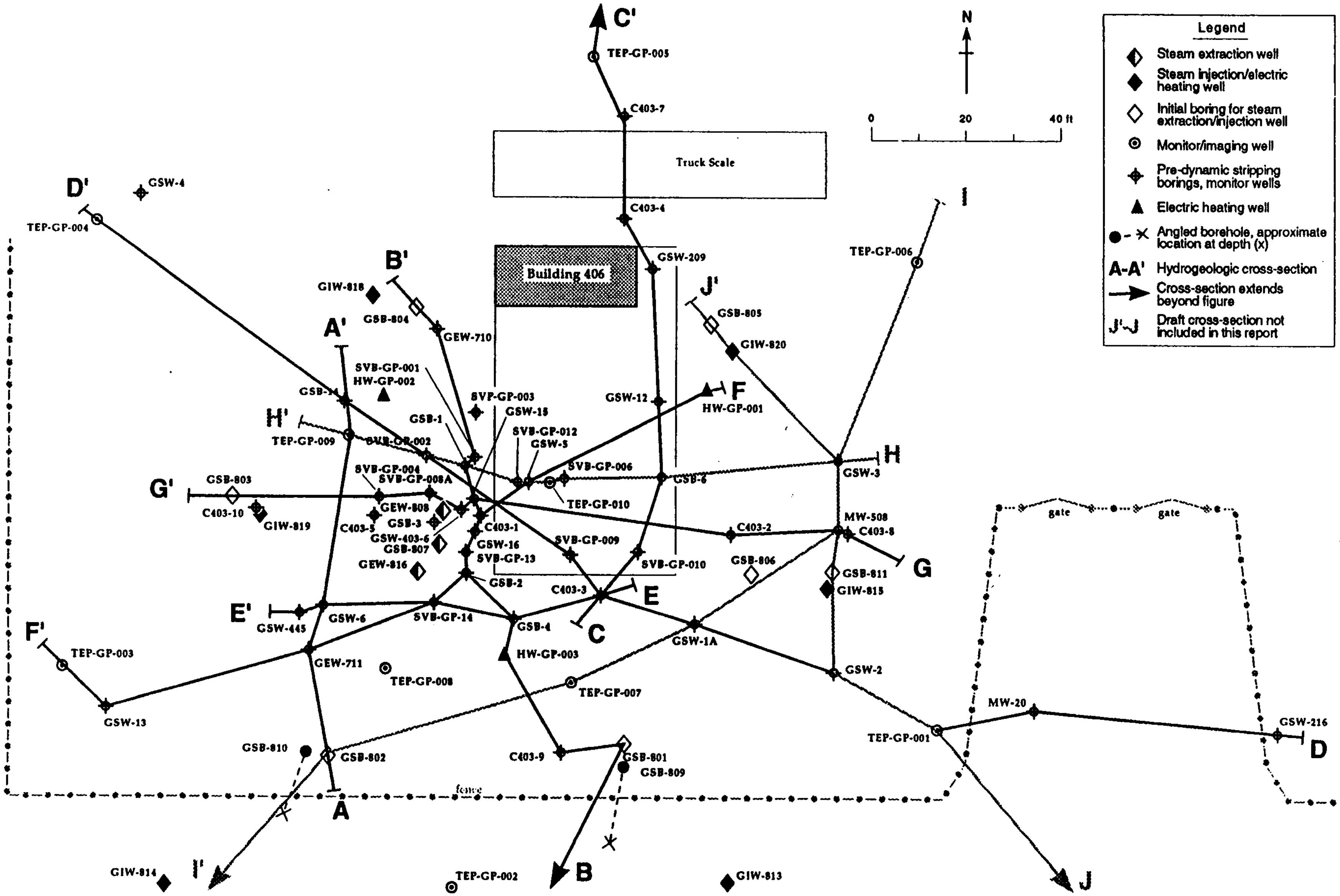

Figure 1. Hydrogeologic Cross-Section Index Map, Lawrence Livermore National Laboratory, Gasoline Spill Area.

since 1984 when two monitor wells and nine soil borings were drilled and sampled in the Building 403 area (Carpenter, 1984). An additional six soil borings were drilled and five monitor wells were installed by O.H. Materials (1985). Thirteen monitor wells were installed in the Building 403 area by Weiss Associates in 1985 and 1986 (Dresen *et al.*, 1986). Since that time, twelve additional pre-DUSDP wells and three vadose zone monitor wells were drilled to further define the vertical and horizontal extent of FHCs in soil and ground water, and for vacuum-induced vapor extraction and monitoring (Nichols *et al.*, 1988; Isherwood *et al.*, 1990, Cook *et al.*, 1992). Following the pre-DUSDP hydrogeologic characterization described in this report, additional hydrogeologic analyses have been conducted at the GSA and adjacent areas for Remedial Design Report #2 for Treatment Facilities C and F (Berg *et al.*, 1993a), and Remedial Design Report #3 for Treatment Facilities D and E (Berg *et al.*, 1993b).

General Hydrogeology of the LLNL Livermore site

The LLNL Livermore site lies within the Mocho 1 and Spring hydrologic subbasins (California Division of Water Resources, 1974). The site is underlain by up to 1000 ft of unconsolidated sediments of late Tertiary to Holocene age, which are subdivided into the Plio-Pleistocene Livermore Formation and undifferentiated late Pleistocene to Holocene alluvium (Isherwood *et al.*, 1990). The Livermore Formation is divided locally into an upper member composed of inter-fingered gravel, sand, silt, and clay, and a lower member consisting of more laterally-continuous layers of silt and clay with lesser gravel. The sedimentary sequence described herein consists of the Upper Member of the Livermore Formation and overlying Undifferentiated Alluvium.

Two ground water systems underlie the LLNL area, a shallow system composed of predominantly heterogeneous alluvial deposits and a deeper system composed of fluvial and lacustrine sediments (Isherwood *et al.*, 1990). The GSA hydrostratigraphic section and ground water described herein is within the shallow system. Regional ground water flow is generally westward, locally stratified, and primarily horizontal, but the flow paths deepen gradually westward toward the center of the basin. The upper and lower ground water systems are separated by a regional confining layer in the upper part of the Lower Member of the Livermore Formation that locally dips westward. Depth to ground water at the LLNL Livermore site varies from about 120 ft in the southeast corner of the site near the GSA, to 30 ft in its northwest corner. Ground water gradients vary from relatively steep (0.02 ft/ft) in the northeast corner to fairly flat (0.001 ft/ft) toward the west of this site. The ground water gradient in the GSA is generally to the south but nearly flat.

Pumping tests and the distribution of volatile organic compounds (VOCs) have demonstrated a relatively high degree of horizontal communication in the Livermore site subsurface (Isherwood *et al.*, 1990). Calculations of hydraulic conductivity and ground water gradients, along with history matching of VOC migration, indicate an average horizontal ground water velocity of about 30 ft/yr in permeable sediments (E.M. Nichols, oral communication, October, 1993). Although downward vertical hydraulic gradients exist over much of the site, the layered nature of the alluvium generally prevents rapid downward migration of VOCs.

Hydrogeologic Setting of the Gasoline Spill Area

Hydrostratigraphic correlations in the saturated and unsaturated zones at the GSA were based on a combination of hydrogeologic, hydraulic, and pneumatic (vapor flow) data, which are described below.

Hydrogeologic Database

Geologic and Geophysical Data

Forty-seven pre-DUSDP geologic borehole logs were used to construct (1) a total of ten hydrogeologic cross-sections (Figures 2 to 11), (2) isopach maps of the upper steam zone (USZ) and lower steam zone (LSZ) and adjacent confining layers (Figures 12 to 15), and (3) structure maps of the USZ and LSZ (Figures 16 and 17). All the boreholes used in this analysis are listed in Appendix A. Many of these boreholes were continuously cored, and all include textural descriptions using the Unified Soil Classification System (USCS). Other parameters described by the well-site geologist include sediment color, grain size, sorting, density, odor, moisture content, and an estimate of relative permeability (low, moderate, or high). Gamma ray and resistivity geophysical logs are available for twenty-two of the 47

GSA pre-DUSDP borings (Appendix A).

Logs from all twenty-six DUSDP pilot boreholes (Appendix A) were also used to construct the hydrogeologic cross-sections and maps presented in Figures 2 to 17. All DUSDP pilot boreholes were continuously-cored, sampled for FHCs, and logged for lithology (geology) as described above. Ten of the 26 boreholes were also geophysically logged using an induction tool to assist hydrostratigraphic correlations (Appendix A).

Hydraulic Data

Estimates of the degree of vertical and horizontal hydraulic communication between hydrostratigraphic intervals in the saturated zone at the GSA, as well as the integrity of adjacent aquitards, were made using pre-DUSDP hydraulic data from three long-term (greater than 24 hours in duration) tests performed on GSW-6, GSW-16, and GEW-710 (Figure 1; Isherwood *et al.*, 1990), and one 2-hour drawdown test performed on GSW-1A (Figure 1). Additionally, the results of a seven-hour DUSDP extraction test performed on GEW-816 and one-hour injection tests performed on GIW-813, GIW-814, GIW-815, GIW-818, GIW-819, and GIW-820 in August 1992 (Lee *et. al,* 1994) were also reviewed.

Pneumatic Data

To evaluate possible vadose zone steam migration pathways at the GSA, pneumatic data collected at three soil vapor monitoring boreholes during extended soil vacuum-induced extraction tests on GSW-16 (Cooke *et al.*, 1992) were reviewed and integrated with the geologic and geophysical data described above.

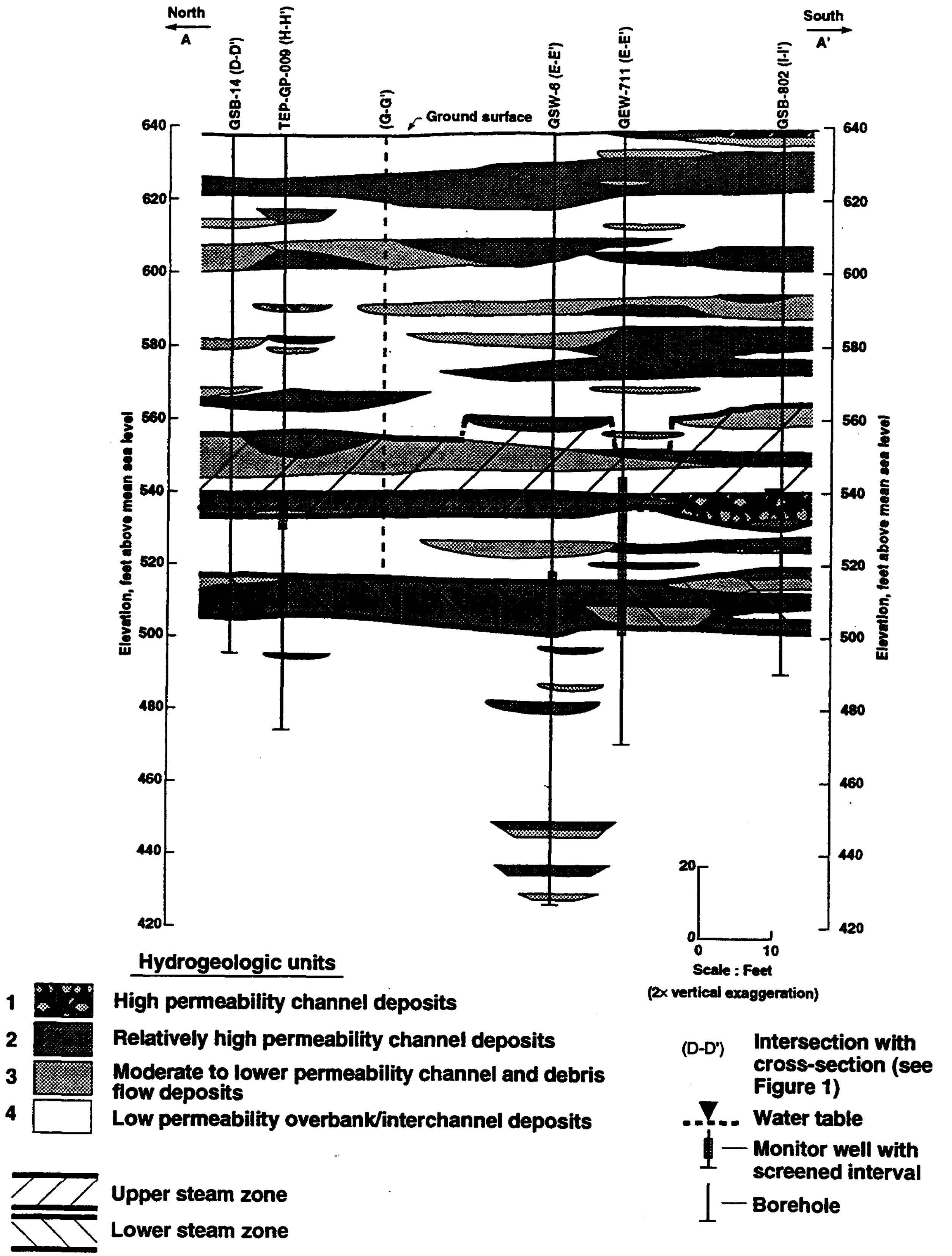

Figure 2. Hydrogeologic cross-section A-A', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

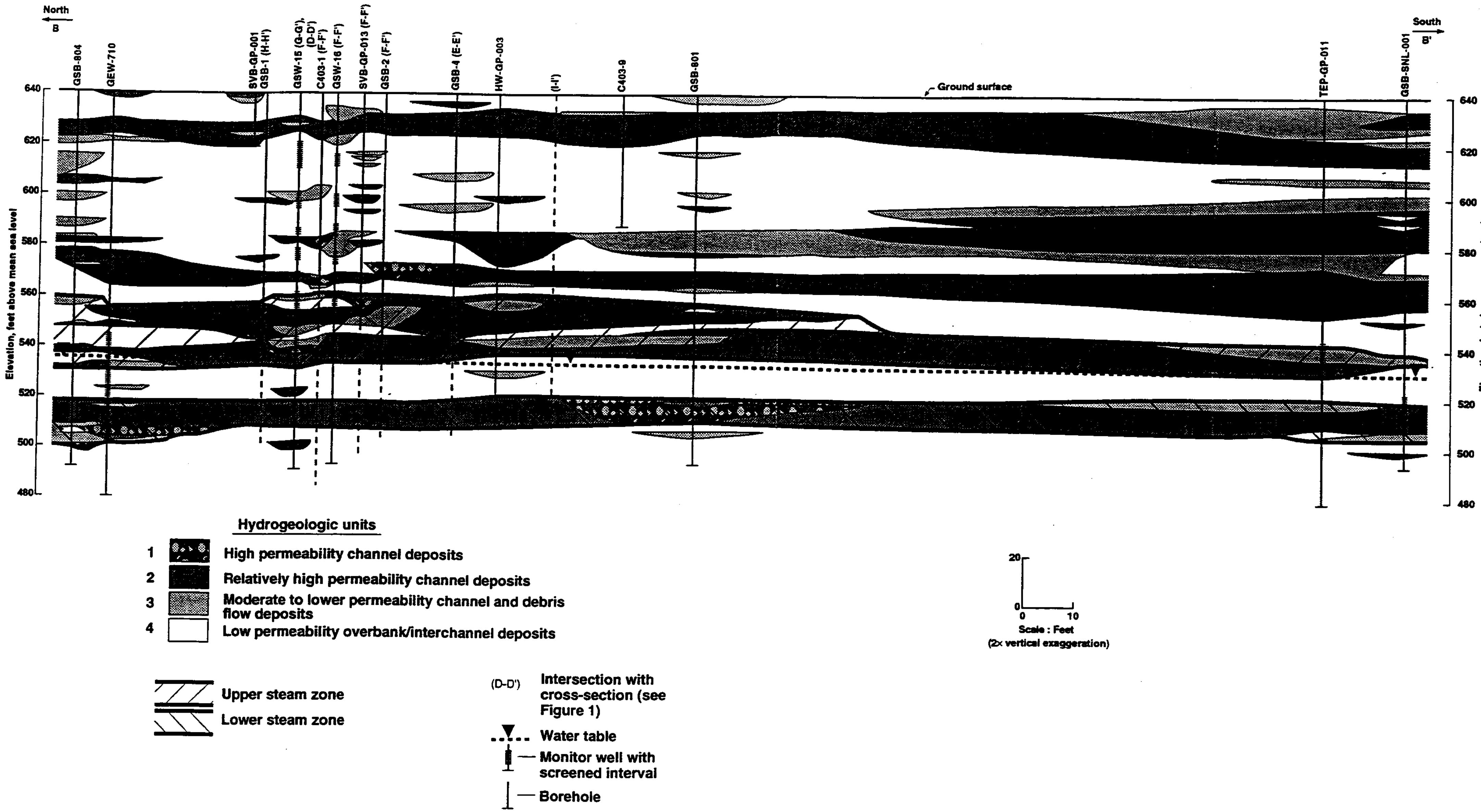

Figure 3. Hydrogeologic cross-section B-B', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

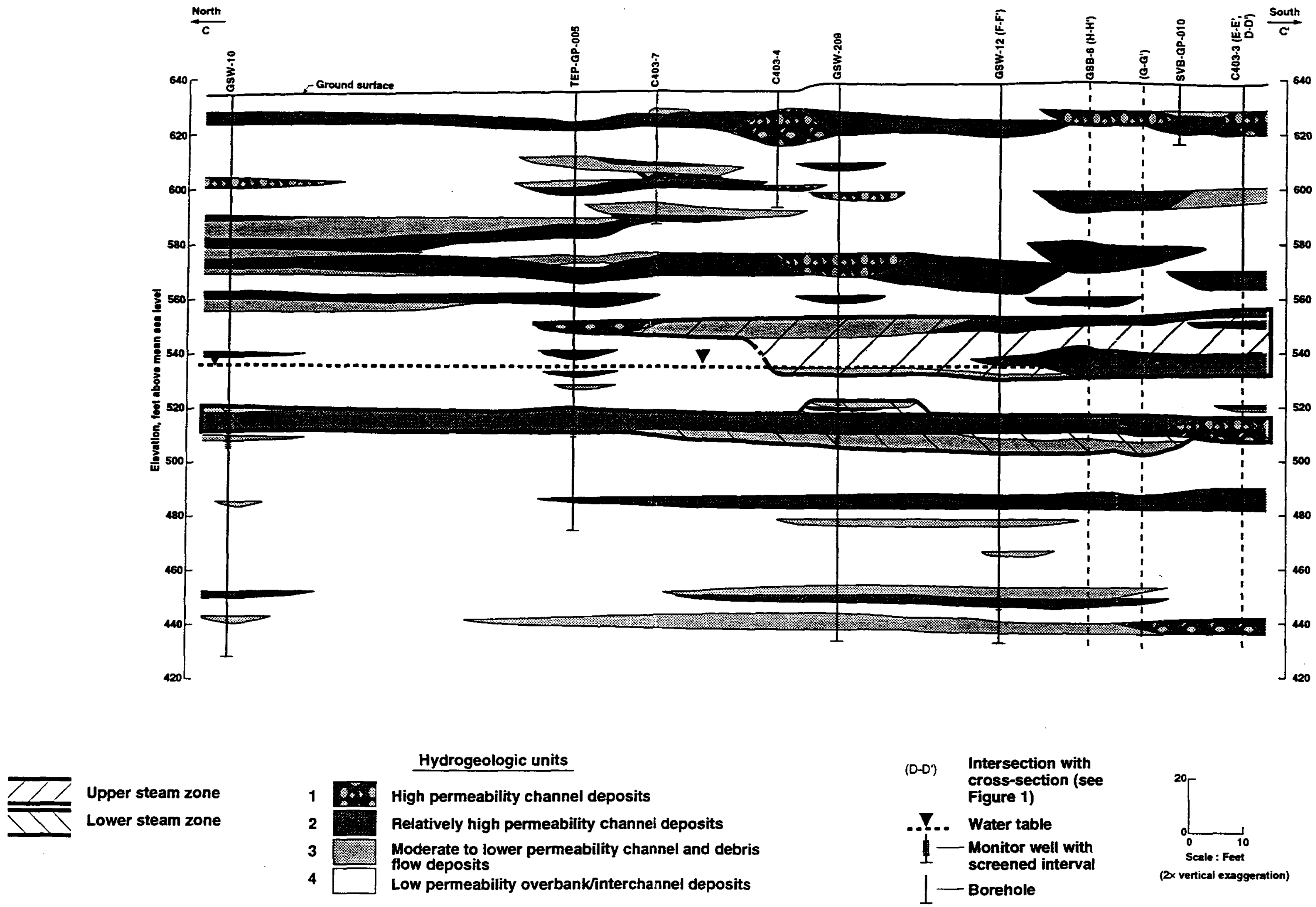

Figure 4. Hydrogeologic cross-section C-C', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

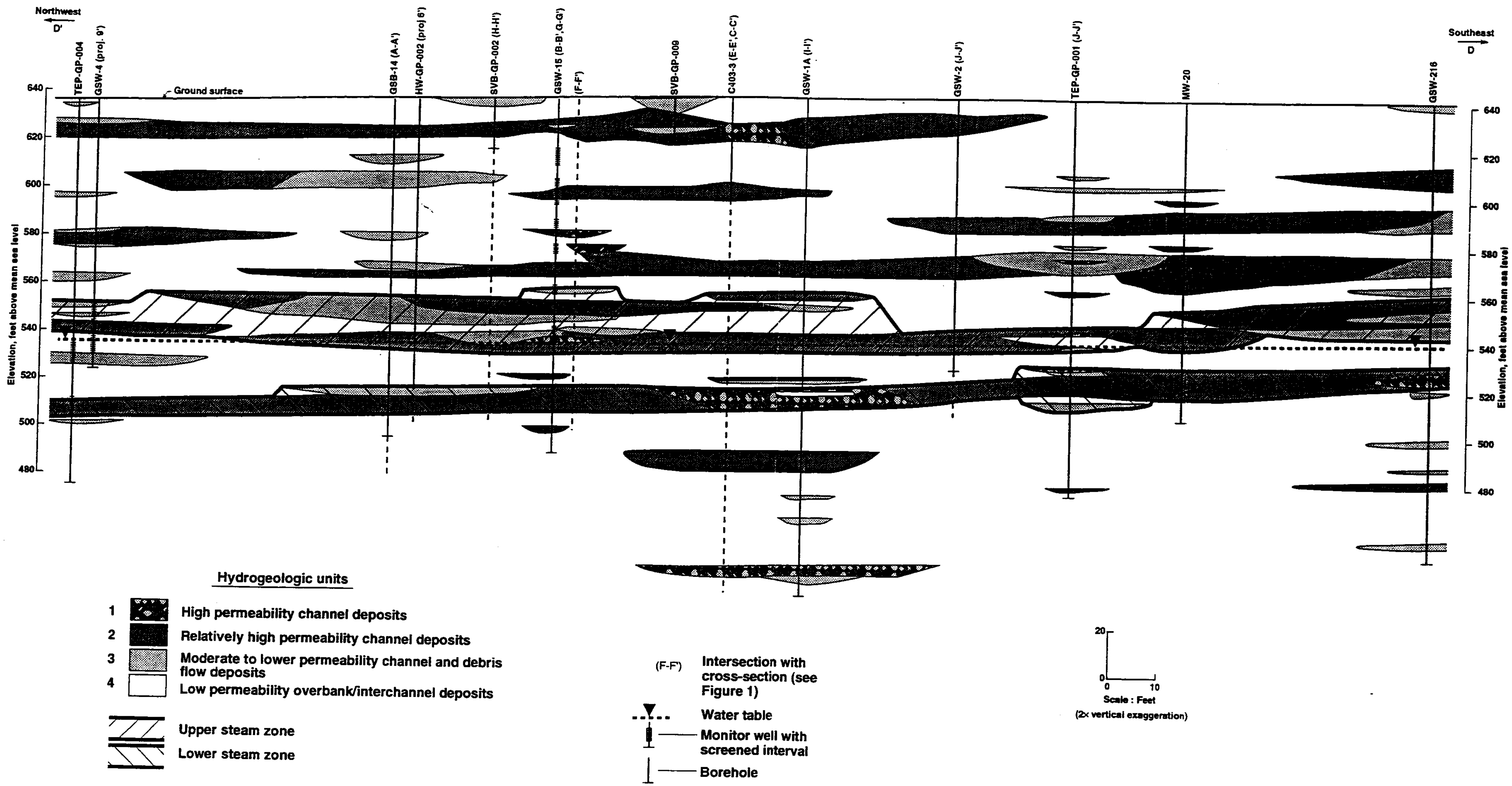

Figure 5. Hydrogeologic cross-section D-D' Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

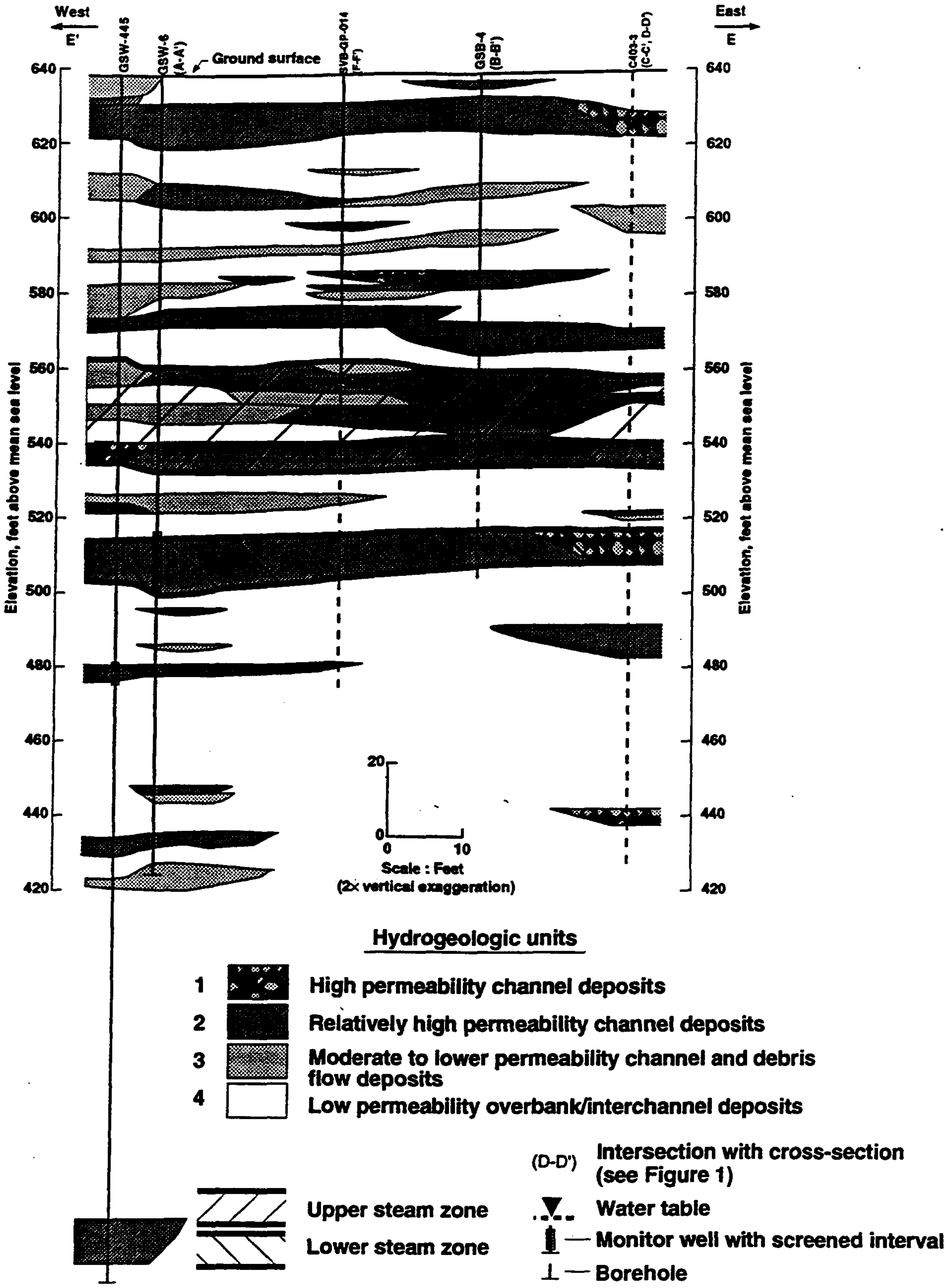

Figure 6. Hydrogeologic cross-section E-E' Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

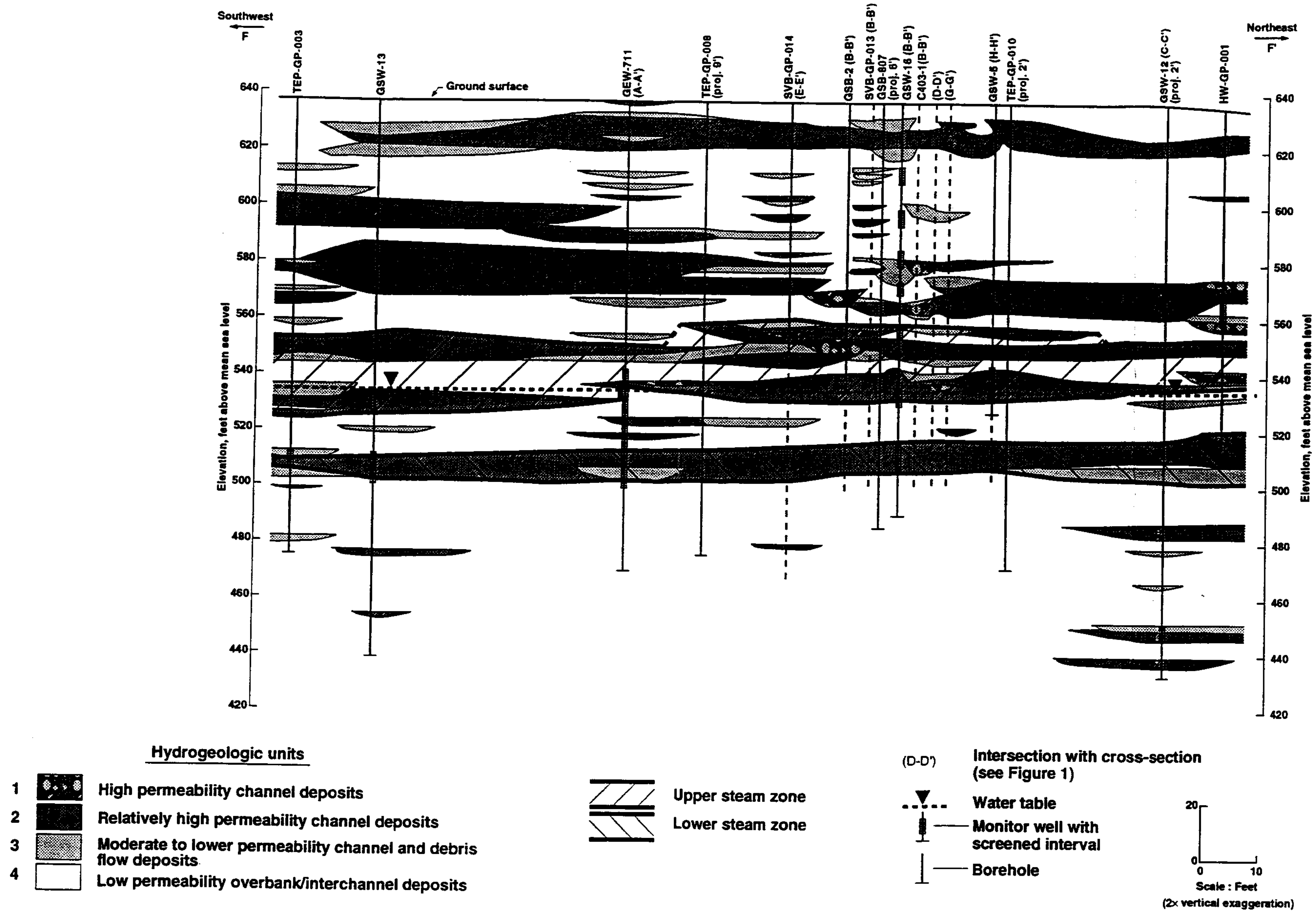

Figure 7. Hydrogeologic cross-section F-F', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

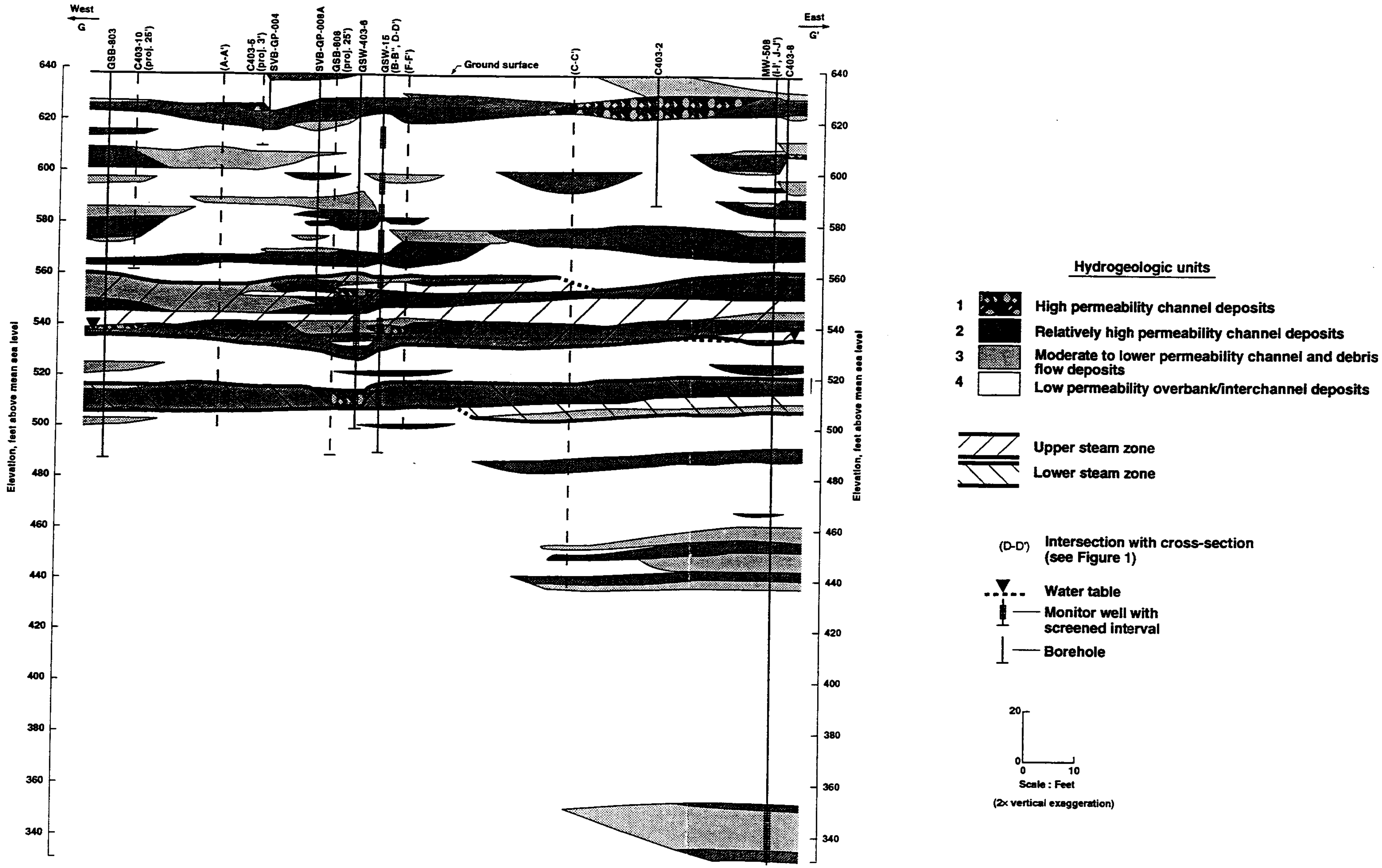

Figure 8. Hydrogeologic cross-section G-G' Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of GSA hydrogeologic units, refer to Section 2.2.

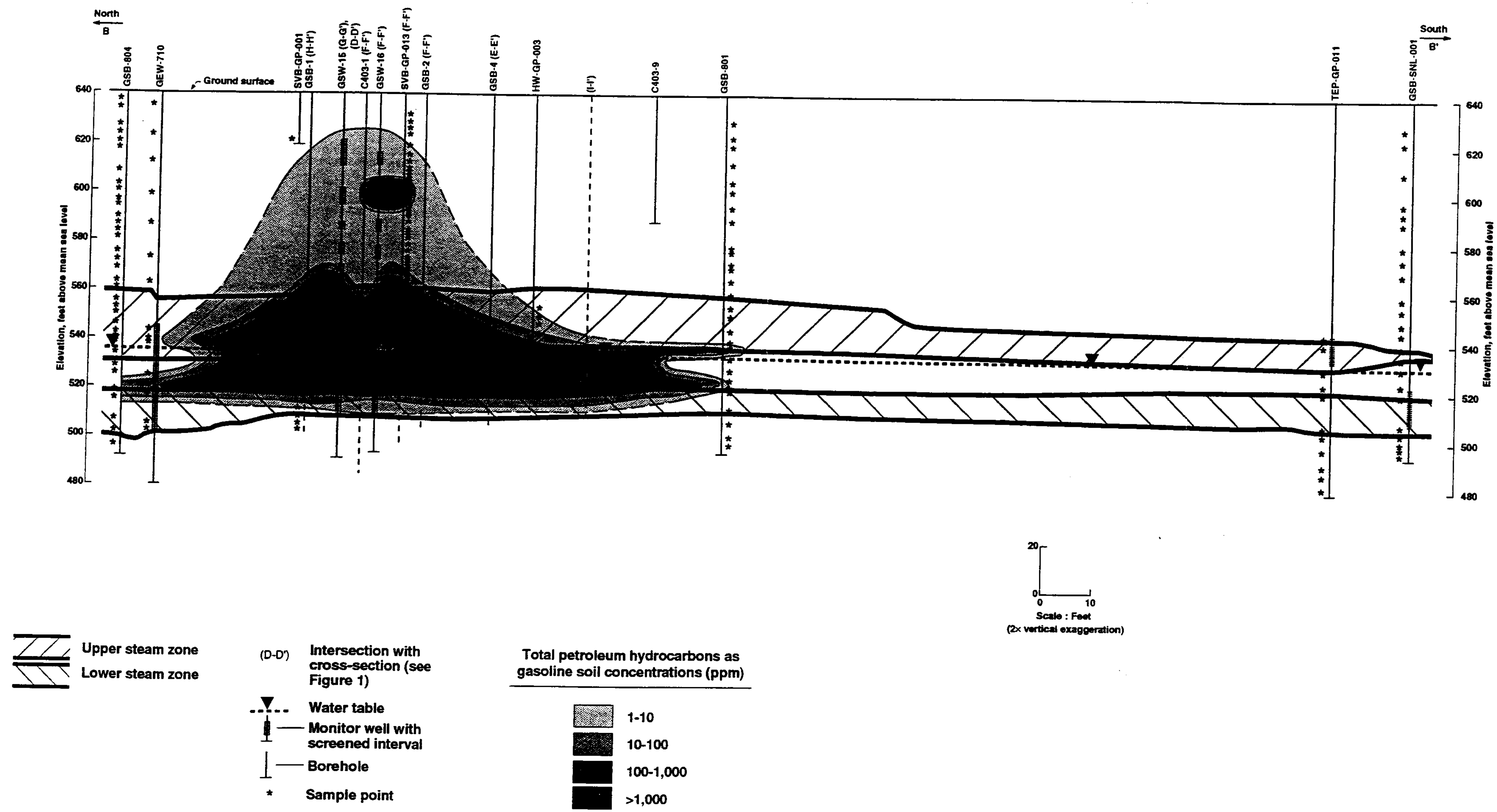

Figure 9. Hydrogeochemical cross-section B-B', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of the chemical data used in contouring, refer to Section 4.1, see Figure 3 for designation of hydrogeologic units.

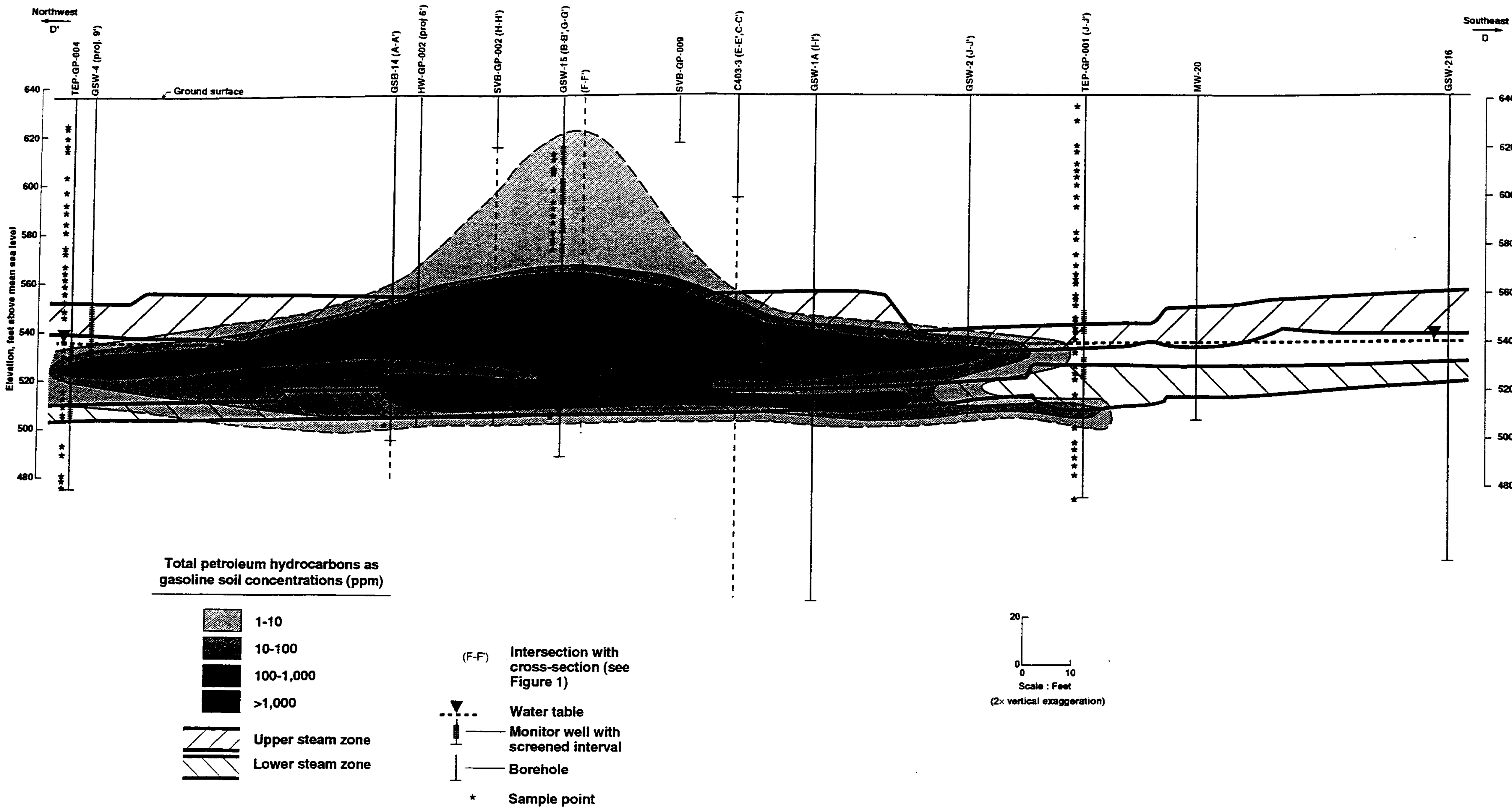

Figure 10. Hydrogeochemical cross-section D-D', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of the chemical data used in contouring, refer to Section 4.1, see Figure 5 for designation of hydrogeologic units.

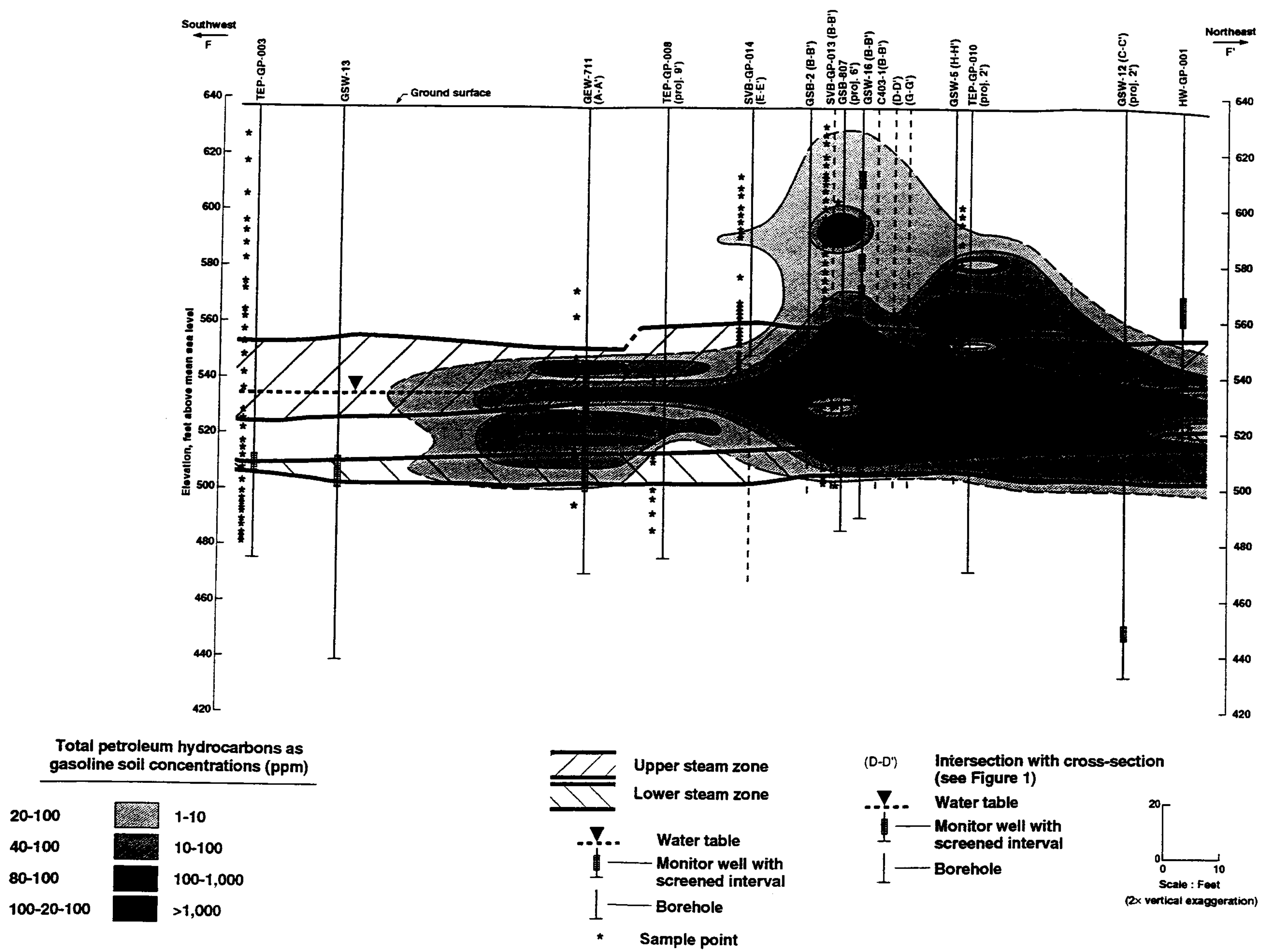

Figure 11. Hydrogeochemical cross-section F-F', Lawrence Livermore National Laboratory, Gasoline Spill Area. For discussion of the chemical data used in contouring, refer to Section 4.1, see Figure 8 for designation of hydrogeologic units.

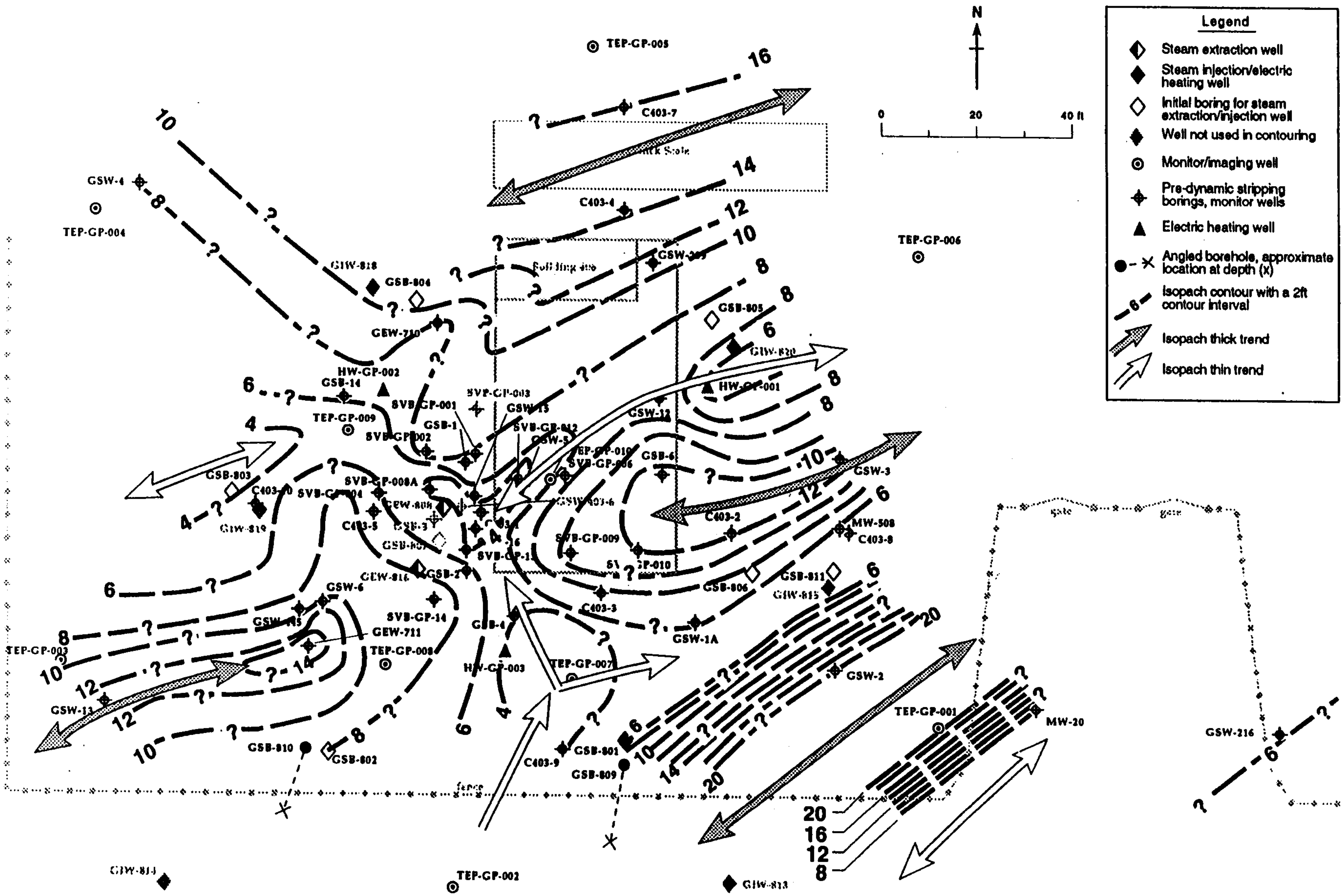

Figure 12. Isopach map of the confining layer above the Upper Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

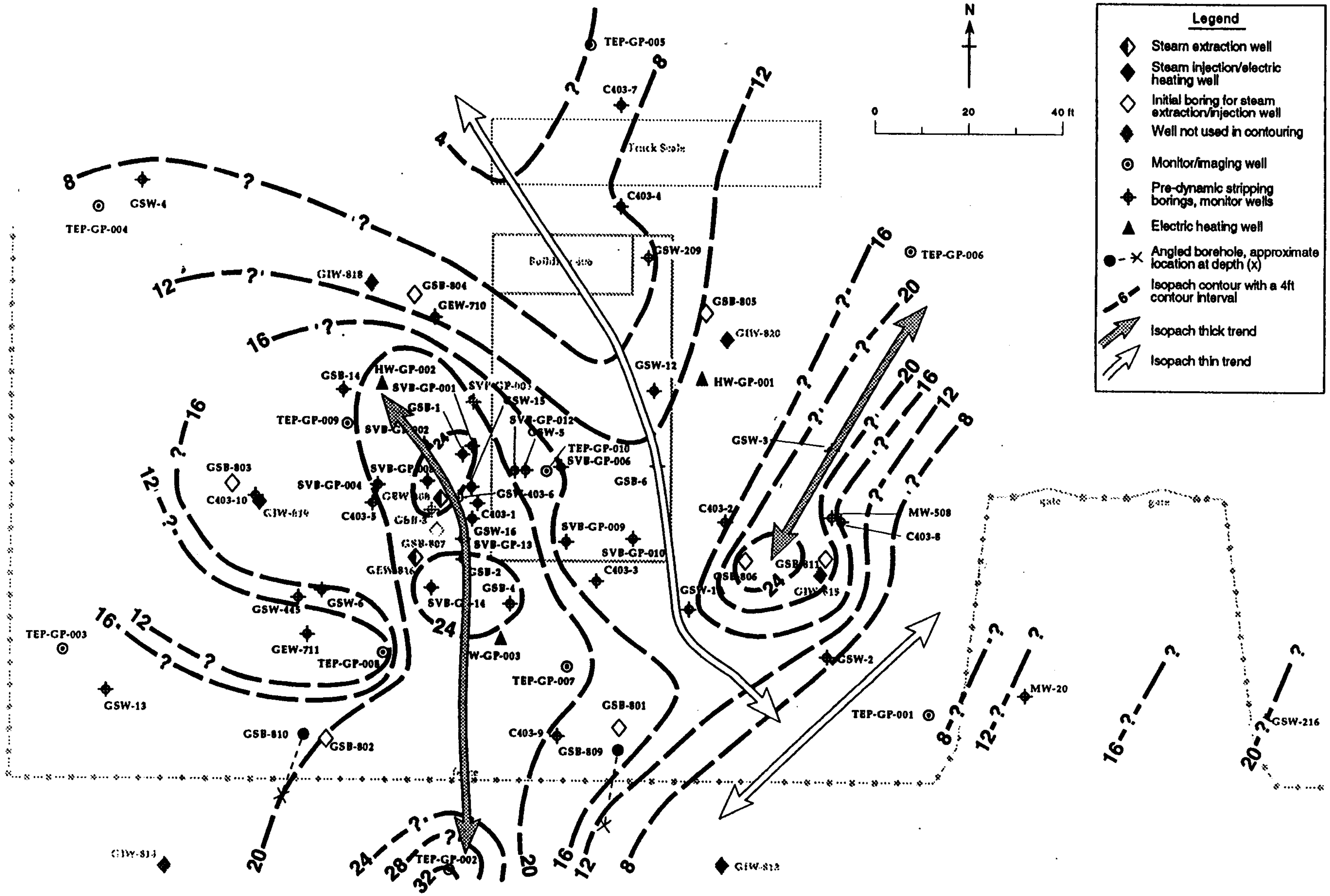

Figure 13. Isopach map of the Upper Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

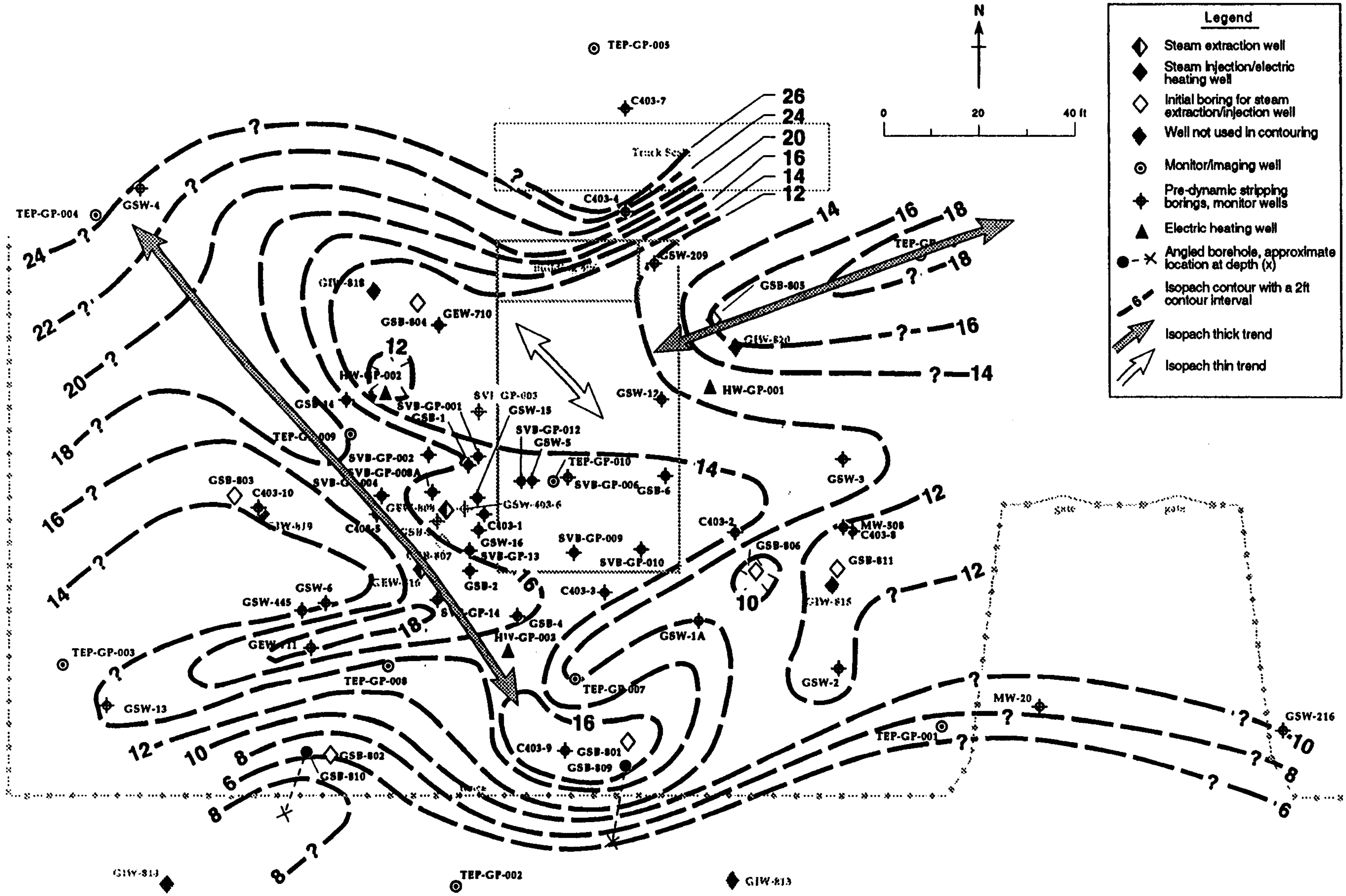

Figure 14. Isopach map of the confining layer between the Upper and the Lower Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

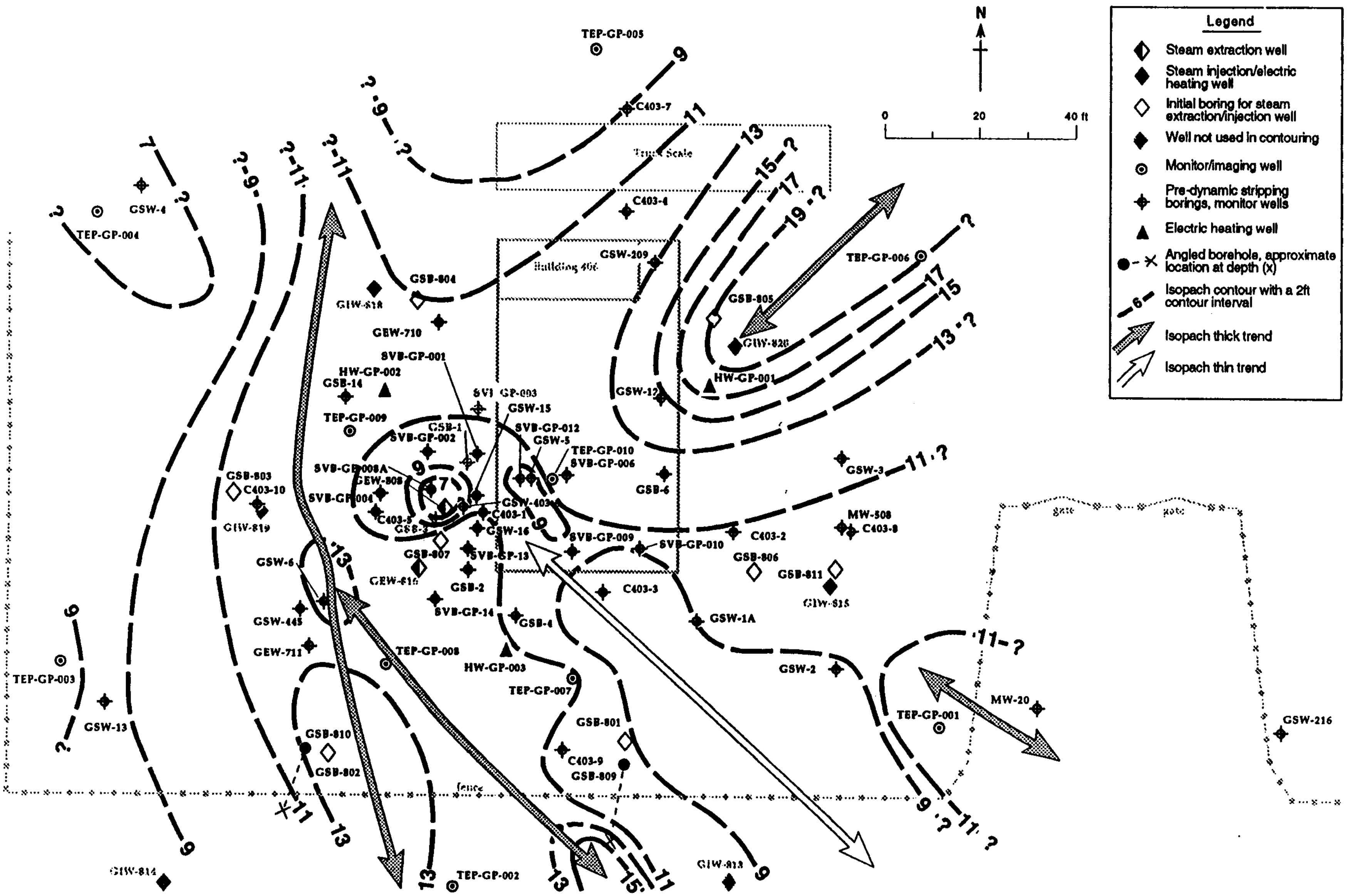

Figure 15. Isopach map of the Lower Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

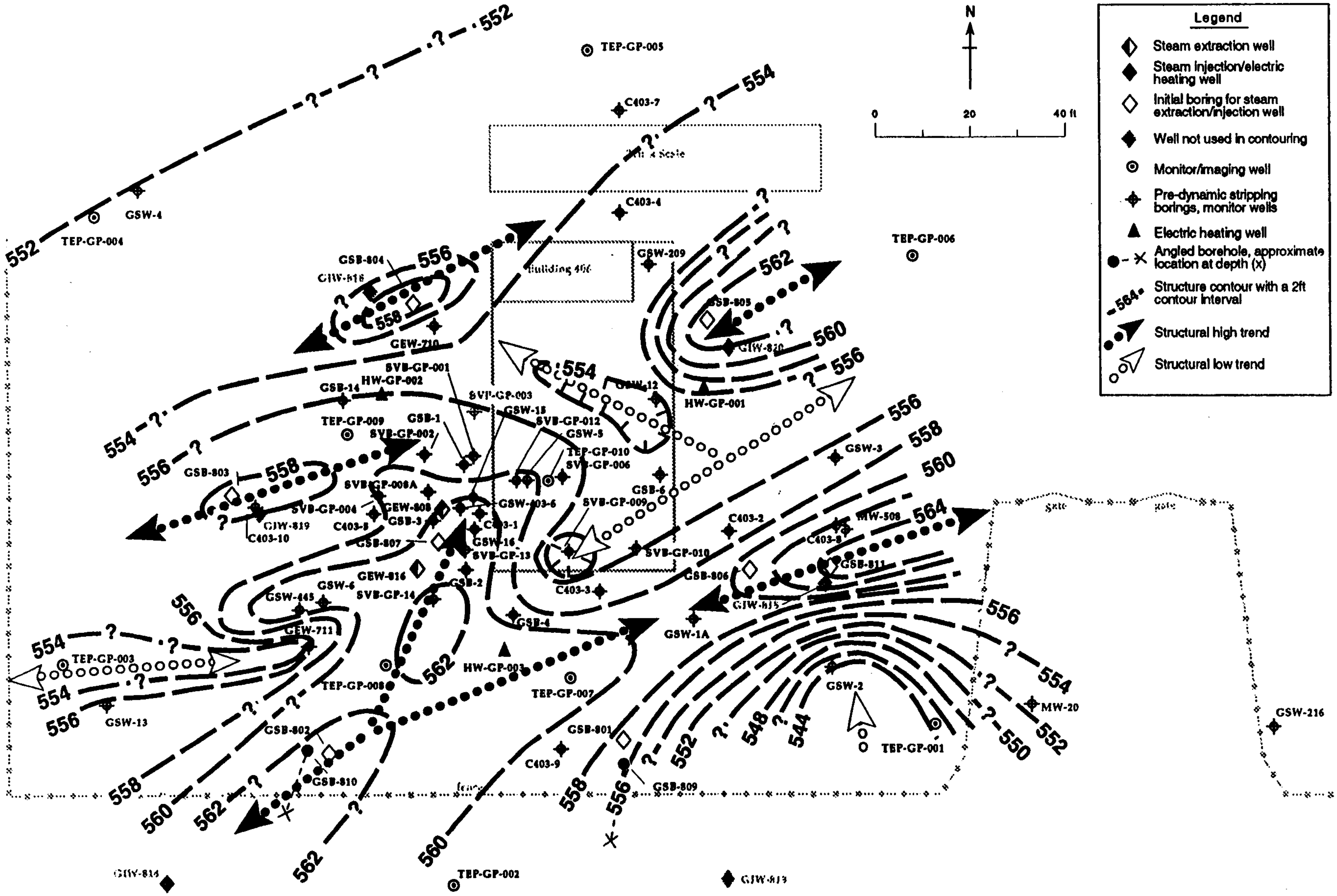

Figure 16. Structure map of the top of the Upper Steam Zone, Gasoline Spill Area, Lawrence Livermore National Laboratory, Gasoline Spill Area.

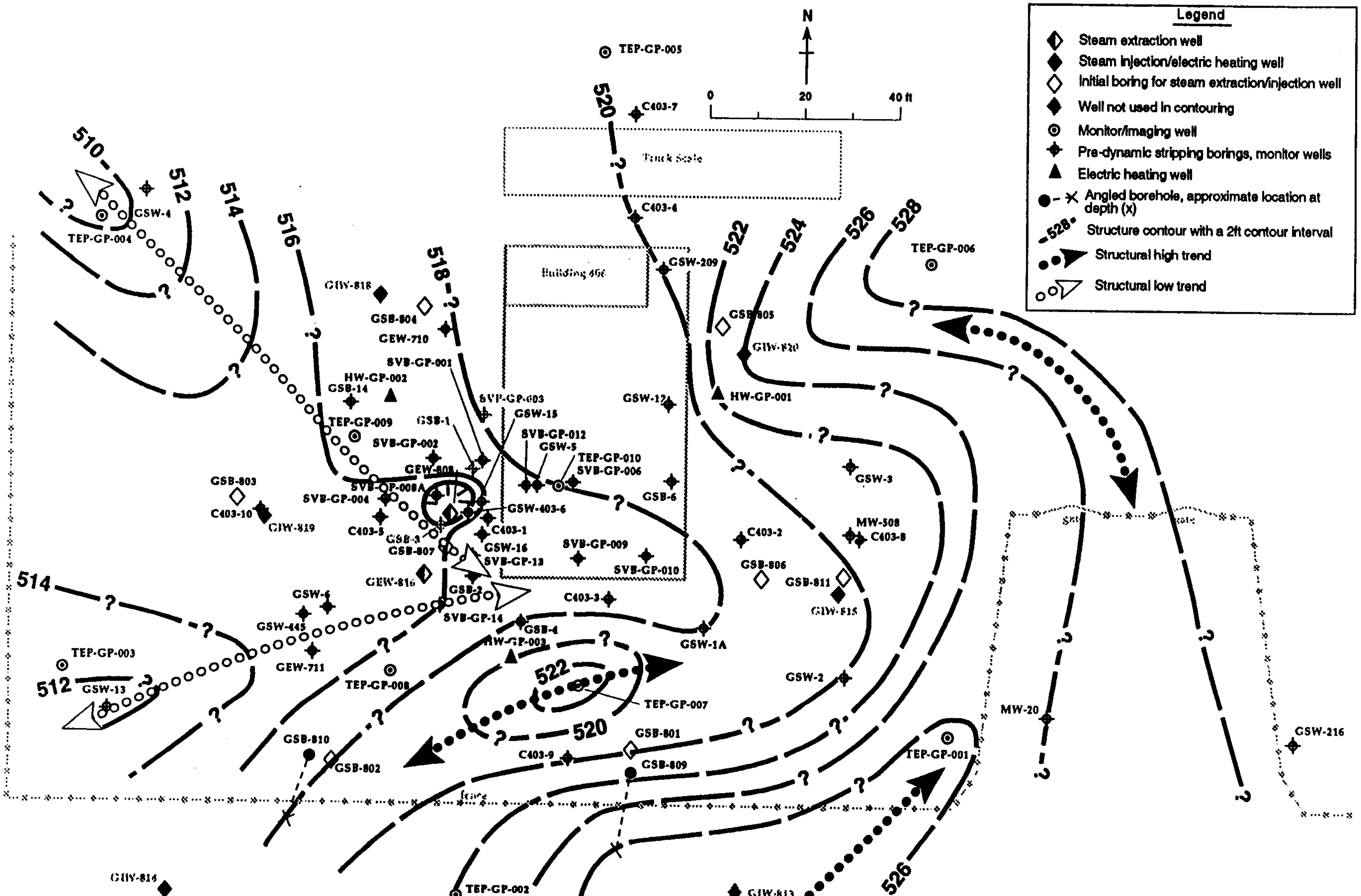

Figure 17. Structure map of the top of the Lower Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

Definition of Hydrogeologic Units

Sediments at the GSA were divided into four hydrogeologic units based on a previous study relating sediment type, sediment texture, depositional environment, and hydraulic conductivity (Noyes, 1991). In this study, the four hydrogeologic units were shown to have a characteristic hydraulic conductivity range and to be mappable on the basis of core descriptions and geophysical logs. Thus, hydrogeologic cross-sections constructed using this approach depict not only an interpretation of subsurface hydrostratigraphy, but also an interpretation of the vertical and lateral distribution of hydraulic conductivity.

A similar approach was used to characterize the hydrostratigraphy and hydraulic conductivity distribution at the GSA. Since Noyes (1991) showed that the hydraulic conductivity of a given sediment type appears to be primarily a function of sorting, the sediment types (gravelly sand, silty clay, etc.) constituting the four hydrogeologic units were re-ranked accordingly. Coarsest-grained, well-sorted deposits were ranked as having the highest hydraulic conductivities, while very fine-grained, poorly-sorted deposits were ranked as having the lowest hydraulic conductivities. This classification is shown in Table 1. The four hydrogeologic units, which represent distinct depositional environments within an arid alluvial fan setting, are presented below along with the hydraulic conductivity ranges defined by Noyes (1991):

Hydrogeologic Unit 1. Coarse-grained, well-sorted sandy gravel and gravelly sand. These sediments are interpreted as braided stream channel deposits (channel lag, channel bar, etc.) with relatively high permeabilities. Hydraulic conductivities range between 15 and 1,070 gpd/ft^2 (7.08×10^{-4} cm/sec to 5.05×10^{-2} cm/sec), with an arithmetic mean of 280 gpd/ft^2 (1.32×10^{-2} cm/sec).

Hydrogeologic Unit 2. Coarse- to finer-grained, moderately well-sorted sandy gravel, gravelly sand, silty sand and gravel, and sand. These deposits are interpreted as braided stream deposits and coarse-grained gravelly debris flow deposits with relatively high to moderate permeabilities. Hydraulic conductivities range between 13 and 1,000 gpd/ft^2 (6.14×10^{-4} cm/sec to 4.72×10^{-2} cm/sec), with an average of 154 gpd/ft^2 (7.27×10^{-3} cm/sec).

Hydrogeologic Unit 3. Predominantly coarse-grained, poorly-sorted clayey gravel, gravelly sand, gravelly silt and clay, and silty sand. These deposits are interpreted as debris and mud flow deposits and less well-sorted, finer-grained channel deposits with moderate to low permeabilities. Hydraulic conductivities range between 16 and 170 gpd/ft^2 (7.55×10^{-4} cm/sec to 8.02×10^{-3} cm/sec), with an average of 116 gpd/ft^2 (5.47×10^{-3} cm/sec).

Hydrogeologic Unit 4. Finer-grained, poorly-sorted clayey sand and silt, silt, and silty clay. These deposits are interpreted as overbank and interchannel deposits with relatively low permeabilities. Hydraulic conductivities range between less than 5 and 18 gpd/ft^2 (2.36×10^{-4} cm/sec to 8.50×10^{-4} cm/sec), with an average of 11 gpd/ft^2 (5.19×10^{-4} cm/sec).

Hydrostratigraphic Intervals

These hydrogeologic units constitute seven hydrostratigraphic intervals which are found at the GSA. These hydrostratigraphic intervals are described below.

GSA

Seven distinct hydrostratigraphic intervals are recognized at the GSA based on core descriptions, geophysical log response, and hydraulic data (Figures 2 to 8). Detailed descriptions of these intervals are presented in Appendix B. These intervals, which were deposited in an alluvial fan setting in response to climatic and/or tectonic changes, are significant for the DUSDP because they may act as either barriers or preferential flow pathways for steam migration. The seven intervals consist from surface downward of: (1) an upper permeable zone, (2) a thick aquitard zone containing thin, discontinuous lenses of higher-permeability channel deposits, (3) a sequence of laterally-continuous interbedded channel deposits and aquitard deposits, including the confining layer above the USZ, (4) the USZ, (5) a confining layer between the two steam zones, (6) the LSZ, and (7) a confining layer beneath the LSZ.

Hydrostratigraphic intervals 4 (USZ) and 6 (LSZ) were identified for steam injection and extraction because:

1. Most ground water with elevated FHC concentrations resides within these two zones;

2. Most higher-permeability deposits with elevated TPH-g soil concentrations are within these two zones; and

3. The two zones appear to be hydraulically isolated from adjacent hydrostratigraphic intervals, thereby limiting the potential for steam-breakthrough to the ground surface.

Sections 3.1.1 and 3.1.3 discuss the hydrogeochemistry of the USZ and LSZ.

Adjoining Areas

Although the lateral extent of most hydrostratigraphic intervals beyond the immediate GSA vicinity (300 ft radius) is not currently known, hydraulic response data from aquifer tests performed on MW-292, MW-276, and MW-364 (Thorpe *et al.*, 1990) indicate that the LSZ extends at least 1,500 ft north of the GSA. The lateral extent of this zone in other directions beyond the GSA has not yet been determined.

Hydrogeology of the Steam Zones and Adjacent Confining Layers

The hydrogeology of the two steam zones and adjacent confining layers is described in detail below.

Geology

Upper Steam Zone

As shown in hydrogeologic sections A-A' to G-G' (Figures 2 to 8), the USZ consists of a three-dimensional network of permeable, lenticular channel deposits (hydrogeologic units 1, 2, and 3; Table 1) separated vertically by fine-grained sediments (hydrogeologic unit 4; Table 1). The channel deposits are hydraulically connected where higher-permeability channel sequences incise similar underlying deposits.

The USZ varies from 0 to over 30 ft thick and consists of a heterogeneous mixture of high to lower-permeability sandy to clayey gravel and gravelly to silty sand interpreted as braided stream and debris flow deposits. The top of the USZ occurs between about 75 and 95 ft below ground surface (bgs), while the base of the unit varies between about 110 and 95 ft bgs. Only the lower few feet (0 to 10 ft) of this zone are currently below the water table. Because of the slight westward structural dip of the USZ, the section becomes progressively more unsaturated to the east. This partially-saturated sequence consists largely of a single, discrete interval of channel deposits which wedges out to the southwest, northeast, and probably north of the GSA.

A structure map of the top of the USZ (Figure 16) shows a series of northeast-southwest trending structural highs and lows. The structural highs, which are interpreted as the uppermost, hydraulically-connected channel sequences, are considered to represent the upper limits of steam migration in the GSA, and may represent areas of steam accumulation.

An isopach map of USZ permeable sediments shows the axes of the thick and thin trends oriented generally north-south (Figure 13). Since these trends represent the cumulative thickness of several stacked channel sequences, their utility in predicting steam migration pathways in the USZ is questionable.

An isopach map of the confining layer above the USZ is shown in Figure 12. The northeast-southwest trending axes of the thick and thin sequences which constitute this confining layer parallel structural trends shown on the USZ structure map (Figure 16). These isopach thicks are interpreted as fine grained, low permeability overbank sediments which were deposited between the highest USZ channel deposits (Figure 3). This confining layer varies in thickness from over 20 ft to less than 4 ft. Structural highs in the USZ which coincide with confining layer thins (e.g., near GSB-803 and HW-GP-001; Figure 12) may be potential sites for steam breakthrough into overlying, higher-permeability channel deposits.

Confining Layer Separating the Two Steam Zones

Figure 14 is an isopach map of the confining layer separating the USZ and the LSZ. The confining layer varies in thickness from less than 6 ft in the south to over 26 ft in the north. Hydraulic testing at the GSA indicate that there is no communication between wells screened in the USZ and LSZ, demonstrating that the confining layer forms a laterally continuous, hydraulic barrier between the two steam zones (Section 3.2.2).

Thin, laterally discontinuous channel deposits occurring in the confining layer constitute the second water-bearing zone (Figures 3 and 5) at the GSA (Isherwood *et al.*, 1990). Based on GSA borehole and water level data, these lenses of higher permeability sediments appear to be either hydraulically isolated or in communication with the underlying third water-bearing zone defined herein as the LSZ.

Lower Steam Zone

Unlike the USZ, the LSZ (Figures 2 to 8) consists of a single, discrete unit composed of higher-permeability, coarse-grained, sandy gravel to gravelly sand (hydrogeologic units 1 and 2; Table 1). The top of the LSZ occurs between about 112 and 130 ft bgs and varies between 7 and 19 ft in thickness, averaging about 11 ft. The LSZ is interpreted to be a braided stream or braided plain deposit which forms a very laterally continuous, sheet-like interval. An isopach map of the LSZ (Figure 15) shows that, within this sheet-like deposit, a series of generally northwest-southeast and northeast-southwest oriented thick and thin trends are present. The seven-hour pumping test conducted on GEW-816 (Section 3.2.4) shows that, although very good lateral communication exists within the LSZ, the drawdown pattern observed during the pumping test parallels the northwest-southeast trend observed in the isopach map (Figure 18). This may indicate a northward depositional gradient for the LSZ. During steam flooding, preferential steam flow may therefore be northwest-southeast.

A structure map of the top of the LSZ shows that this surface forms a shallow, westward-dipping synclinal fold (Figure 17). After steam flooding ceases, up-dip steam migration may occur.

The LSZ is underlain by a laterally-continuous confining layer at least 20 ft thick. Chemical data indicate that FHCs do not occur below this layer (see Section 4). Immediately below the LSZ in the eastern portion of the GSA, a laterally continuous interval of clayey gravel to gravelly clay (hydrogeologic unit 3) is present that is up to 10 ft thick (Figure 20). These moderate- to lower-permeability, poorly-sorted sediments, interpreted as a large debris flow deposit, form a northwest-southeast trending sequence which most likely parallels the LSZ depositional gradient. Based on soil chemical data, FHCs do not appear to occur within this deposit. The steam stripping process is not likely to affect the low permeability sediments which constitute the confining layer below the LSZ.

The structure maps and isopach maps of the USZ, LSZ, and adjacent confining layers were used to determine the appropriate screened intervals for the DUSDP extraction, injection, and electrical heating wells at the GSA.

Hydrology

Hydraulic data from pumping tests of LSZ and USZ wells are discussed below.

The Upper Steam Zone

No pumping tests have been performed on wells screened solely in the USZ due to the partial saturation and low hydraulic conductivity (0.2 to 41 gpd/ft^2) of most of the constituent sediments. Pumping tests performed on GSW-16 and GEW-710, screened in both the USZ and LSZ (Appendix A), showed insignificant responses in USZ observation wells. As shown in Figures 2 through 8, the heterogeneous nature of the USZ sediments appears to limit lateral hydraulic communication within the zone. We anticipate that steam migration pathways within the USZ will be difficult to predict, and that steam flooding may be limited to interconnected, higher permeability units within the USZ (hydrogeologic units 1 and 2).

Confining Layer Between the Two Steam Zones

As discussed previously, the integrity of the confining layer separating the two steam zones was evaluated during several pumping tests on wells screened only in the LSZ (GSW-6 and GSW-1A; Appendix A). In these instances, no hydraulic response was noted in USZ observation wells, indicating that the confining layer forms a laterally continuous hydraulic barrier between the two steam zones.

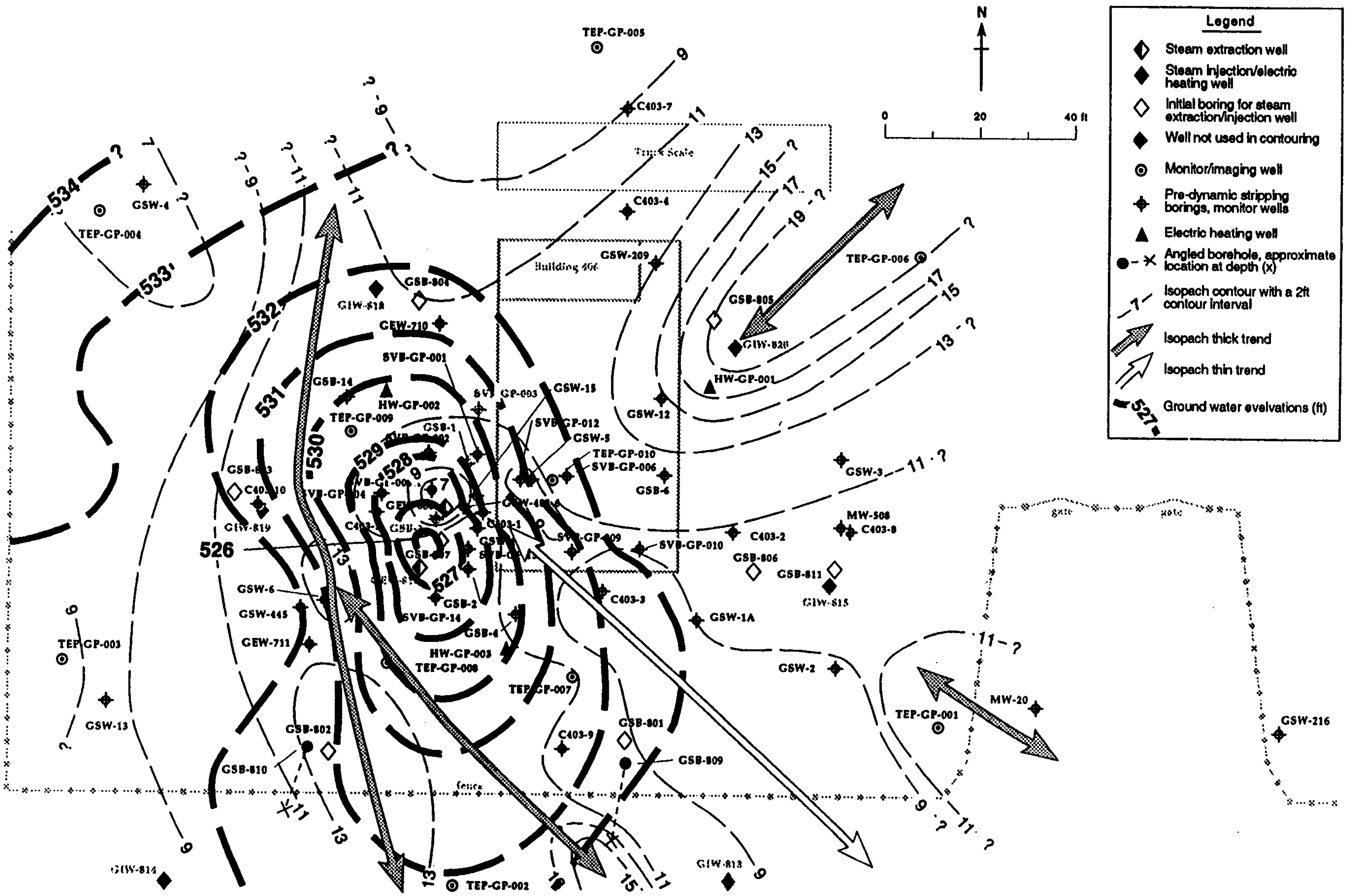

Figure 18. Isopach map of the Lower Steam Zone, with superimposed GEW-816 pumping test drawdown map, Lawrence Livermore National Laboratory, Gasoline Spill Area.

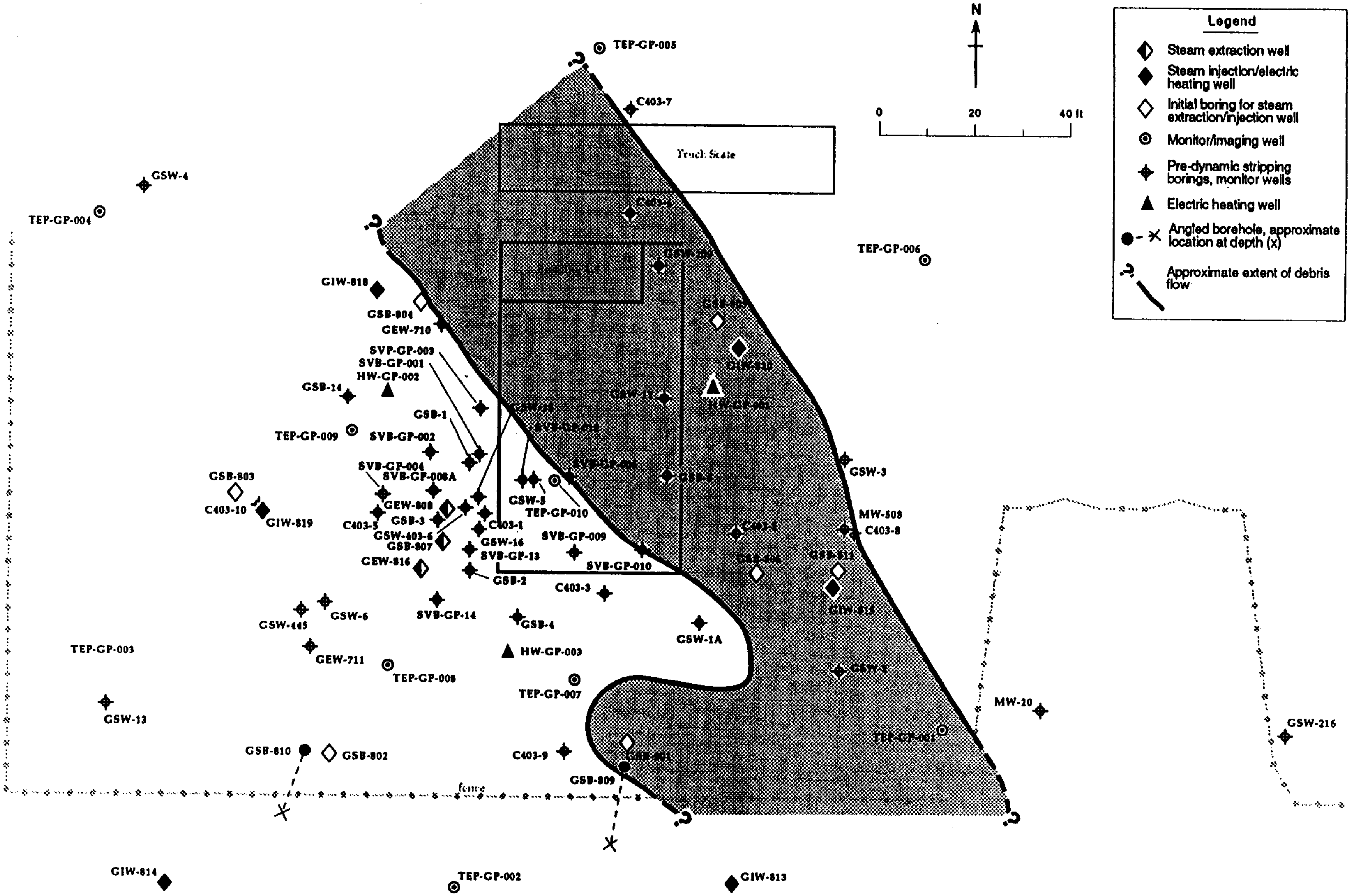

Figure 19. Areal distribution of the debris flow occurring at the base of the Lower Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

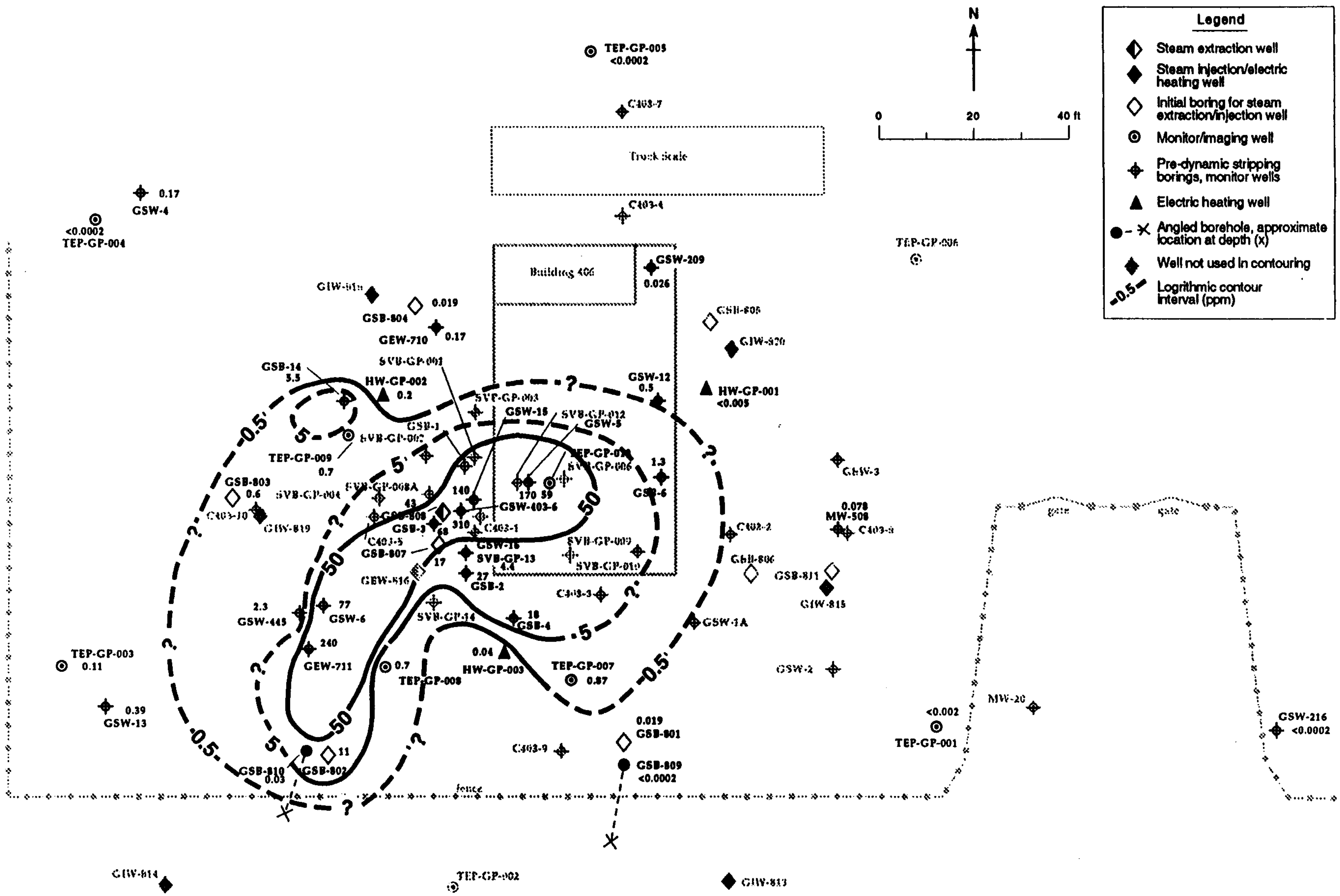

Figure 20. Maximum soil benzene concentration (ppm) in the Upper Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

The Lower Steam Zone

During pre-DUSDP pumping tests performed on wells completed in the LSZ (GSW-16, GSW-6, and GEW-710; Appendix A), all LSZ observation wells within the zone of hydraulic influence of the pumping well exhibited a strong response. Based on these data and the high sustainable flow rates of the pumping wells (25 to 36 gpm), the LSZ is highly transmissive and laterally extensive in the GSA.

Comprehensive DUSDP Pumping Test

Between August 6 and 15, 1992, seven one-hour injection tests and one seven-hour extraction test were conducted to further characterize the LSZ and to help identify preferred steam migration pathways at the GSA (Lee *et al.*, 1994). These tests confirmed previous pumping test results indicating that (1) there is no or little communication between the two steam zones, (2) the USZ is characterized by lower hydraulic conductivities than the LSZ, and (3) that the LSZ is highly transmissive and exhibits very good lateral communication. An average LSZ transmissivity of 12,000 gpd/ft was calculated assuming an 11 ft average thickness and a hydraulic conductivity of 1,090 gpd/ft^2. Analysis of the long-term test data also suggested that less-transmissive LSZ sediments may be present to the east and west outside of the GSA.

Although these hydraulic test analyses indicate that the LSZ is laterally continuous in all directions, there appears to be a preferred ground water flow direction. Figure 18 is an isopach map of the LSZ with the drawdown map for the GEW-816 pumping test superimposed. Both show an northwest-southeast elongation, indicating preferred flow is occurring within higher permeability channel deposits oriented northwest-southeast. The inferred preferential flow direction may also be due to the presence of less transmissive or thinner LSZ sediments to the east and west.

Distribution of Fuel Hydrocarbons in the Subsurface

The distribution and estimated volume of FHCs-in-place at the GSA prior to the DUSDP are discussed below.

Chemical Data

Three vintages of chemical data defined relative to GSA vapor extraction activities (Section-1.2.2) were used to characterize the vadose and saturated zone pre-DUSDP FHC distribution and to estimate FHC volume:

Pre-Vapor Extraction Data - Soil and ground water chemical data from GSA boreholes and monitor wells drilled and installed from 1984 to 1987.

Contemporaneous Vapor Extraction Data - Data collected during vapor extraction activities at the GSA, beginning in August 1988 and continuing until December 1991. Chemical data include soil data from soil vapor borings SVB-GP-008A, SVB-GP-013, and SVB-GP-014.

Post-Vapor Extraction/Pre-DUSDP Data - Ground water data from previously installed monitor wells collected after vapor extraction ceased and prior to the initiation of electrical resistance heating and dynamic stripping. This data set also includes soil and ground water data from boreholes and wells drilled after December 1991, which includes the DUSDP TEP-GP, GSB-800, GEW-800, and HW-GP series.

Comparisons of pre-venting and post-venting soil chemistry data indicate that vapor extraction was effective in the upper 85 feet of the vadose zone. However, below this depth inconsistent changes in concentrations indicate that vapor extraction was not effective (Isherwood *et al.*, 1990; Macdonald *et al*, 1991). Accordingly, only contemporaneous extraction and post-venting soil data were used to characterize FHC contaminant distribution in the upper 85 feet of the vadose zone. All three categories of soil data were used to contour FHCs in the vadose zone below 85 feet and in the saturated zone.

FHC Distribution

Three hydrogeochemical cross-sections showing TPH-G concentrations in soil (Figures 9 to 11) and five isoconcentration maps showing soil and ground water benzene concentrations in the vadose and saturated zone (Figures 20 to 24) were completed using post-vapor extraction/pre-DUSDP data. These maps, along with the isopach maps of the USZ and LSZ (Section 3.1) were used to help position the DUSDP steam injection and extraction wells at the GSA.

The Vadose Zone Above the Upper Steam Zone

The distribution of TPH-G in the vadose zone is shown in Figures 9 to 11. TPH-G and benzene soil concentrations generally increase with depth and decrease laterally away from the center of the spill. Concentrations of TPH-G range from non-detectable (less than 0.5 ppb) near the ground surface to 100 ppm just above the top of the USZ (Figure 9).

The Upper Steam Zone

From the top of the USZ (75 to 95 ft bgs) to the water table, FHC concentrations range from 100 ppm to 1,000 ppm beneath the release point (Figures 9 to 11). At the water table, the extent of FHCs increases laterally. In both soil and ground water, benzene concentrations decrease concentrically away from the spill area in the USZ (Figures 20 and 23). At a radial distance of about 60 ft from the release point, benzene soil concentrations in the USZ decrease to approximately 0.5 ppm. The distribution of benzene in USZ ground water is shown in Figure 21. Based on site-specific empirical evidence, free-phase hydrocarbons appear to be present within the area enclosed by the 1 ppm benzene contour. USZ wells where free-phase FHCs were detected are identified in Figure 21.

The Confining Layer Between the Two Steam Zones

As shown in Figures 9 to 11, concentrations of TPH-g in the confining layer separating the two steam zones generally exceed 100 ppm close to the central portion of the spill. FHC concentrations in the confining layer do not extend laterally as far as in the USZ and LSZ, suggesting that the initial spill geometry has been modified by ground water flow through the more permeable USZ and LSZ sediments. The elevated soil benzene concentrations present at TEP-GP-005 suggest a secondary FHC source north of the GSA (Figure 21). An attempt to

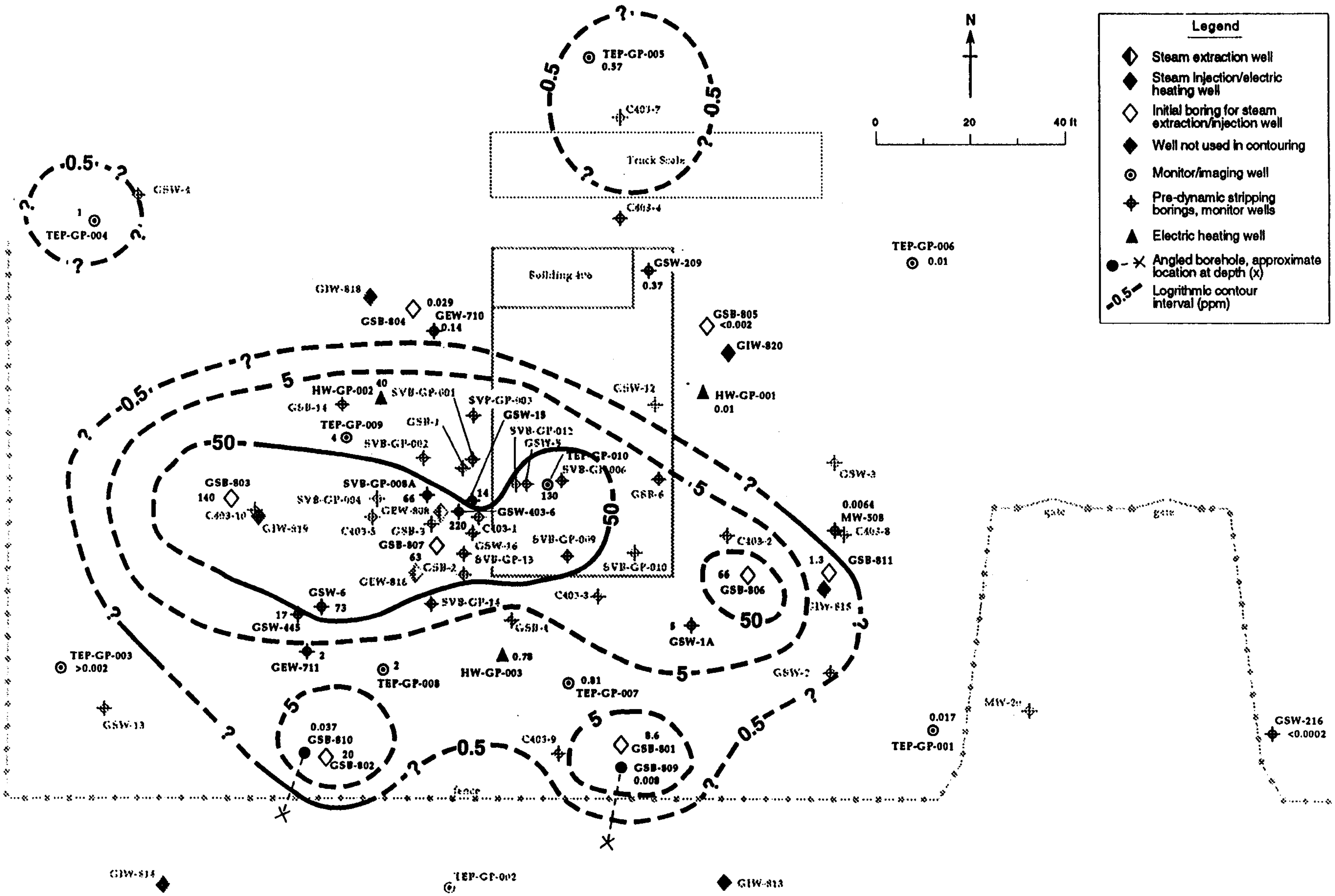

Figure 21. Maximum benzene soil concentrations (ppm) in the confining layer between Upper and Lower Steam Zones, Lawrence Livermore National Laboratory, Gasoline Spill Area.

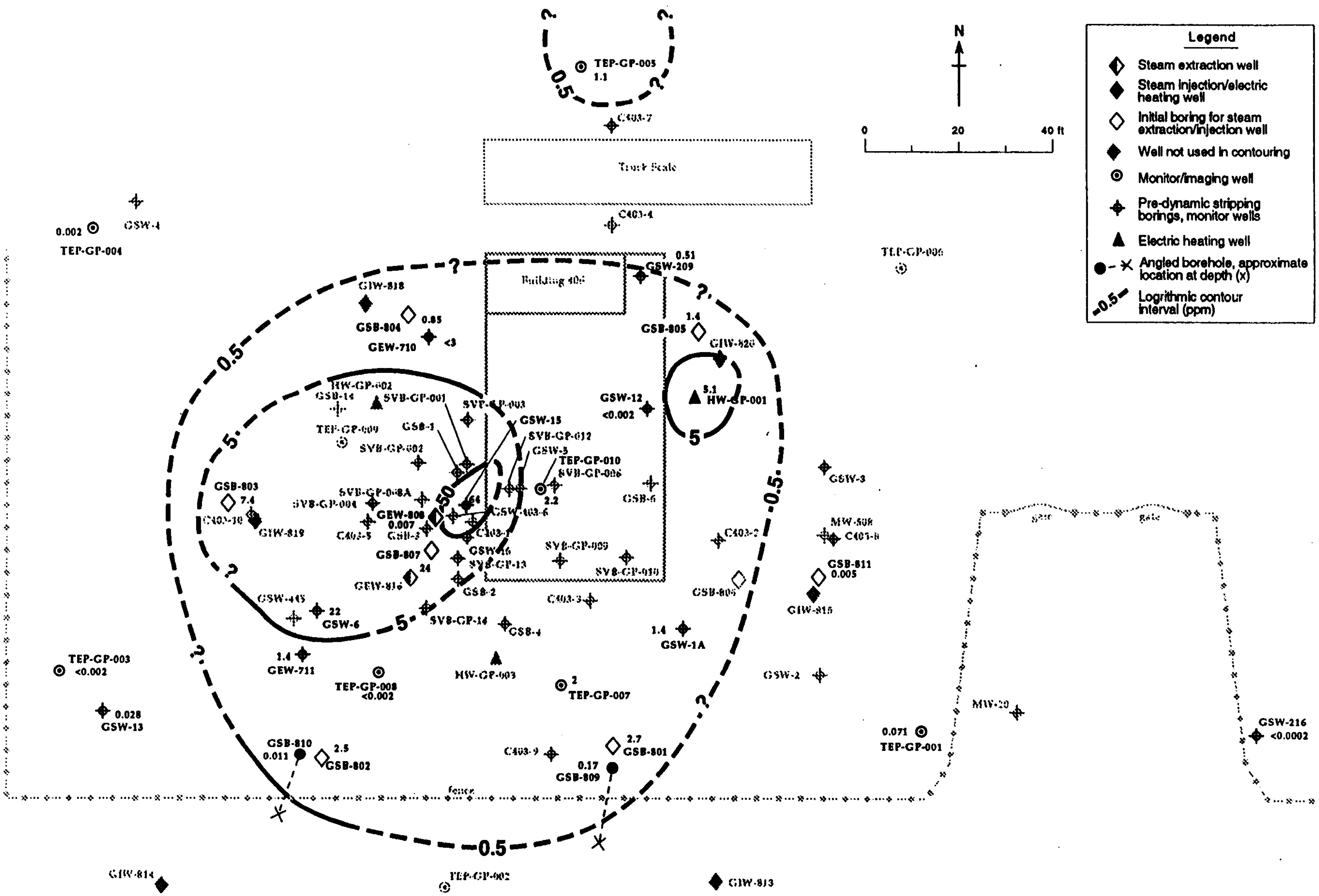

Figure 22. Maximum benzene soil concentration (ppm) in the Lower Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

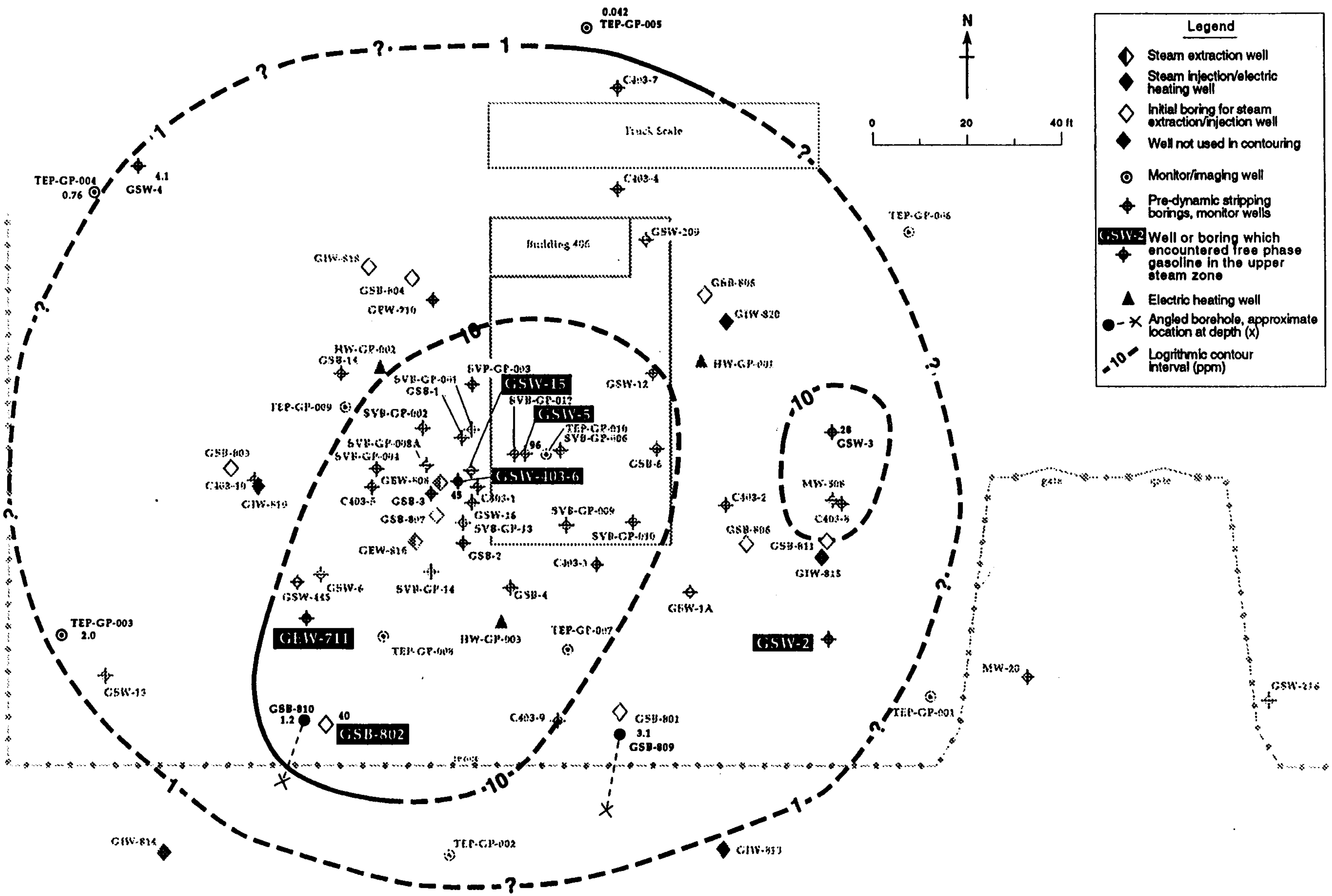

Figure 23. Maximum ground water benzene concentrations (ppm) in the upper steam zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

chemically fingerprint the two areas of elevated FHC concentrations yielded equivocal results (Devany and Noyes, 1992).The Lower Steam Zone

As in the USZ, soil and ground water benzene concentrations within the LSZ decrease concentrically away from the spill center (Figures 9 to 11, 22 and 24). At a radial distance of about 70 ft from the spill center, soil benzene concentrations decrease to approximately 0.5 ppm (Figure 24). Elevated soil and ground water benzene concentrations at TEP-GP-005 again suggest the presence of a second gasoline source area proximal to the GSA, as described in Section 4.2.3.

Only minor TPH-g soil concentrations (less than 20 ppm) are present in the confining layer beneath the LSZ. These concentrations are believed to result from borehole conduit effects (i.e. introduced from shallower zones during drilling) and have therefore not been contoured.

Volumetric Gasoline Estimates

To assist in evaluating the effectiveness of DUSDP as a remedial technology, the distribution, mass, and volume of gasoline in the subsurface at the GSA prior to the onset of DUSDP were estimated using the Interactive Volume Modeling (IVM) software by Dynamic Graphics, Alameda, California. The methodology, results, and limitations of these estimates are discussed in Devany, 1993.

IVM uses a spline-type algorithm to interpolate scattered data onto a regular three-dimensional grid (called gridding) and generates 3-dimensional depictions of surfaces of equal concentration called iso-shells. The user can "slice" and rotate the contour model to observe the details of the iso-shells and corresponding spatial distribution of a property such as concentration or porosity. IVM also calculates associated volumes of iso-shells in user-specified regions. The mass in each iso-shell (M_{is}) can be determined using the following equation:

$$M_{is} = V * D * C$$

where

V = iso-shell volume

D = bulk density at the *in situ* moisture content

C = geometric mean of the iso-shell concentration range

Total plume mass is the sum of all iso-shell masses. The pre-DUSDP GSA TPH-g volumes were calculated using a density of 0.75 g/cm3

The GSA chemical data set consists of soil sediment concentration data from 66 boreholes and wells drilled between April 1985 and April 1992 (Appendix A). As discussed in Section 4.1, vadose zone sediment concentration data collected prior to January 1991 were omitted from these calculations since a significant volume of gasoline (i.e., about 2,000 gal) was removed by the vapor extraction pilot study (Section 1.2.2).

To constrain the interpolations made in the GSA IVM volumetric determinations, the aforementioned hydrogeochemical data set was combined with digitized isoconcentration

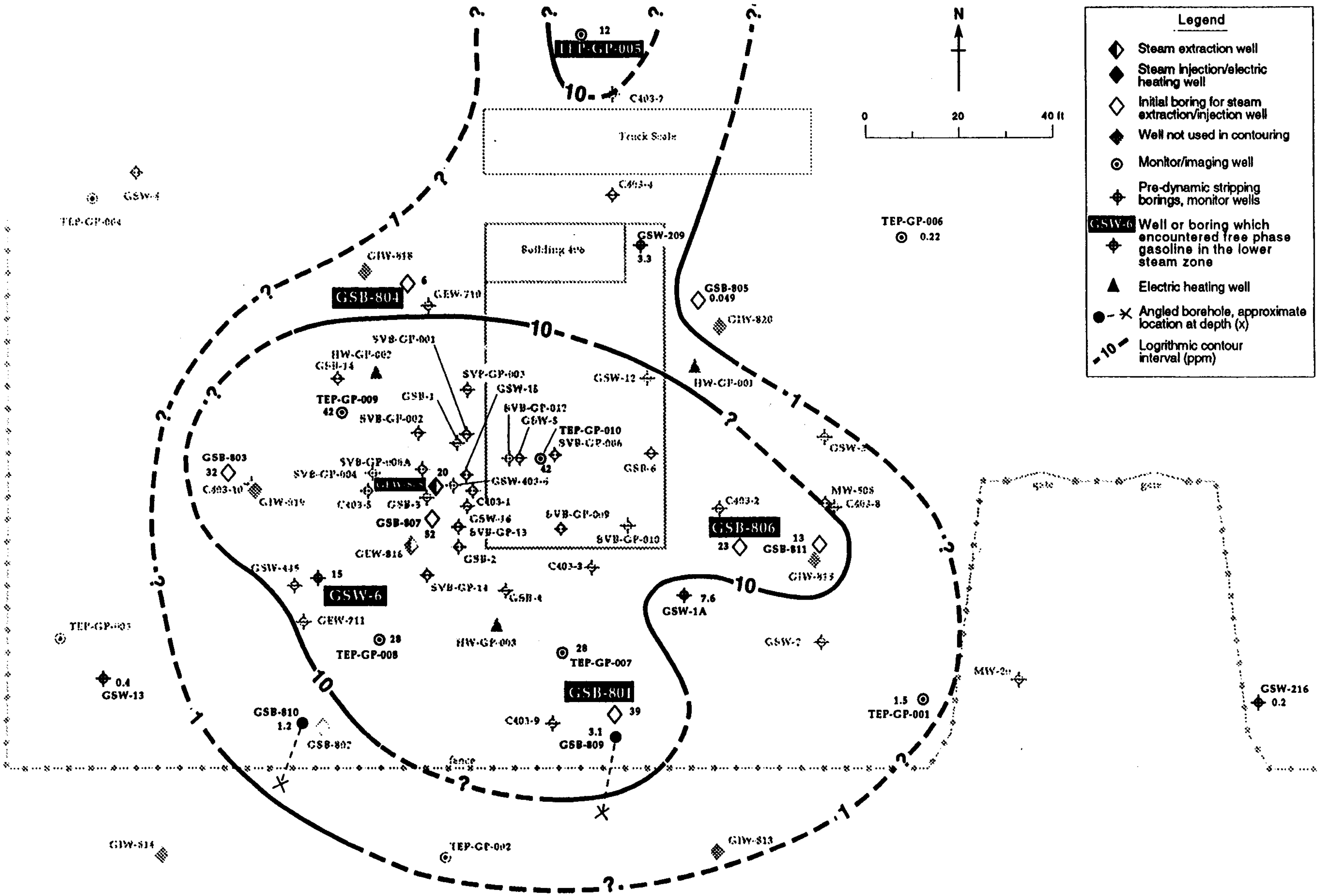

Figure 24. Maximum ground water benzene concentrations (ppm) in the Lower Steam Zone, Lawrence Livermore National Laboratory, Gasoline Spill Area.

contour lines from the eight hand-contoured hydrogeochemical cross-sections discussed in Section 4.1. This approach significantly increased the number of data points in critical areas (i.e., > 1 ppm), and reduced the role of the computer-assisted interpolation, while still utilizing IVMs volumetrics capabilities.

The total calculated pre-DUSDP GSA TPH-g volume is about 7,400 gallons. This volume represents the gasoline in the GSA subsurface inside as well as outside the DUSDP injection well ring. This is only a semi-quantitative estimate since an estimate of potential error of the IVM software interpolation cannot be determined at this time.

The amount of TPH-g in each GSA hydrostratigraphic unit potentially affected by DUSDP (units 2 through 6) was also estimated. These volumes, which represent the amount of gasoline in each unit in the area enclosed by the electrical heating/injection wells, are estimated to be:

1) 20-50 ft depth (unit 2) = 311 gal

2) 50 ft to the top of the USZ (unit 3) = 642 gal

3) The USZ (unit 4) = 3,153 gal

4) Confining layer between the USZ and LSZ (unit 5)= 1,963 gal

5) LSZ (unit 6) = 480 gal

The total amount of gasoline within the DUSDP injection ring is estimated to be about 6,500 gallons.

Summary

Data from 47 pre-DUSDP boreholes and 26 DUSDP boreholes were used to construct hydrogeologic and chemical cross-sections (Figures 2 to 11) and isopach, structure, and isoconcentration maps (Figures 12 to 24) to characterize the pre-DUSDP hydrogeochemical environment at the GSA.

The USZ, which occurs between about 80 to 110 ft bgs, consists of a complex network of interconnected higher- and moderate-permeability channel deposits interbedded with low-permeability overbank deposits (Figures 3 and 5). Since only the lower few feet of this zone are saturated, most of the USZ occurs within the vadose zone. Steam flooding in this interval is expected to be limited to interconnected higher-permeability deposits. Several structural highs in the USZ may represent traps for steam accumulation (Figure 16). Areas where these structural highs coincide with thin zones in the confining layer above the USZ represent potential sites for steam breakthrough into overlying higher-permeability channel deposits. However, the thick confining layer between 20 and 50 ft bgs should prevent steam breakthrough to the surface.

The LSZ, which occurs between about 120 and 135 ft bgs, consists of a higher-permeability, sheet-like deposit of relatively homogeneous braided stream deposits which are well-interconnected hydraulically. Both the USZ and LSZ exhibit a slight northwestward dip towards the center of the depositional basin (to the west). Due to upward heat flux in the subsurface, the potential for some eastward, up-dip migration of steam exists.

Hydraulic testing performed at the GSA for the DUSDP indicates that there is little if any hydraulic communication between the USZ and LSZ. The transmissivity of the LSZ, based on an average thickness of 11 feet, was calculated to be about 12,000 gpd/ft. Hydraulic testing suggests better hydraulic communication northward and southward within the LSZ (Figure 18). Accordingly, we anticipate that preferential steam flow may occur to the north and south. The transmissivity of the USZ could not be measured since most of this zone is unsaturated.

Isoconcentration maps and cross-sections of TPH-g and benzene (Figures 9 to 11, 22 to 24) indicate concentrations decrease concentrically away from the spill center, located near well GSW-16. Free-phase gasoline appears to be largely confined to the area enclosed by the 1 ppm benzene ground water contour (Figures 23 and 24). To optimize the DUSDP well field design, steam injection wells were located proximal to the margin of the 1 ppm ground water benzene contour in the USZ and LSZ.

A volumetric estimate of subsurface gasoline at the GSA was made using interactive volume modeling software and hand-contoured hydrogeochemical cross-sections. The total volume of gasoline estimated to be within the DUSDP injection well ring was semi-quantitatively estimated to be about 6,500 gallons.

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J. Chiu of Weiss Associates performed final development, initial sampling, hydraulic tests, and preliminary interpretation of hydraulic data.

D. Underwood interpreted chemical and geologic data and provided editorial support.

K. Heyward of LLNL prepared the graphics.

Hydrogeologic Unit	Sedimentary Texture (USCS)[1]	Symbol on Cross-Sections	Description/ Depositional Environment	Hydraulic Conductivity Range (gpd/ft^2)	Interpreted Permeability
1	Sandy Gravel(GP) Gravelly Sand(SP) Sand(SP)	1SG(GP) 1GS(SP) 1SP(SP)	Well-sorted, coarse-grained channel deposits	15 to 1070 (mean = 280)	Very high to high
2	Sandy Gravel(GW) Gravelly Sand(SW) Sand(SW) Sandy Gravel(GM) Gravelly Sand(SM) Silty Sand(SM) (Fines<20%) Silty Gravel (GM)	2SG(GW) 2GS(SW) 2S(SW) 2SG(GM) 2GS(SM) 2SLS(SM) 2SLG(GM)	Moderately well-sorted, coarse-grained channel deposits and coarse-grained debris flow deposits	13 to 1000 (mean = 154)	High to moderate
3	Clayey Gravel(GC) Silty Sand(SM) (Fines>20%) Gravelly Clay(CL) Gravelly Silt(ML)	3CLG(GC) 3SLS(SM) 3GCL(CL) 3GSL(ML)	Debris flow deposits and fine-grained, less well-sorted channel deposits	16 to 170 (mean = 116)	Moderate to low
4	Clayey Sand(SC) Sandy Silt(ML) Silty Clay(CL) Clay(CL) Clayey Silt(ML) Sandy Clay(CL) Silt(ML)	4CLS(SC) 4SSL(ML) 4SLCL(CL) 4CL(CL) 4CLSL(ML) 4SCL(CL) 4SL(ML)	Fine-grained, poorly-sorted overbank and interchannel deposits	<5 to 18 (mean = 11)	Low

Table 1 -Hydrogeologic Units Defined in the Gasoline Spill Area

Notes: 1. Unified Soil Classification System

2. Pumping-test-derived hydraulic conductivity values from Noyes, 1991.

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