Argonne's Expedited Site Characterization: An Integrated Approach to Cost- and Time-Effective Remedial Investigation

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INTRODUCTION

Argonne National Laboratory has developed a methodology for remedial site investigation that has proven to be both technically superior to and more cost- and time-effective than traditional methods. This methodology is referred to as the Argonne Expedited Site Characterization (ESC). Quality is the driving force within the process. *The Argonne ESC process is abbreviated only in time and cost and never in terms of quality*. More usable data are produced with the Argonne ESC process than with traditional site characterization methods that are based on statistical-grid sampling and multiple monitoring wells.

A principal difference between the Argonne ESC process and traditional remedial investigation approaches is the heavy emphasis within the Argonne ESC on understanding the geologic/hydrogeologic framework of a site through the integration of multiple scientific disciplines, before investigations on contaminant distribution and migration begin. This framework is then combined with historical information on contaminant type and usage at the site to generate multiple working hypotheses that guide selection of investigation techniques and sampling locations. In addition, existing data are evaluated for quality and used whenever possible to reduce the need for field activities and avoid duplication of effort and data. The Argonne ESC approach has streamlined remedial site investigations by greatly decreasing the number of monitoring wells and samples required to completely define site features for selection of remedial options.

The Argonne ESC process has been successfully implemented at multiply contaminated landfills for the Bureau of Land Management and at former grain storage facilities in Kansas and Nebraska for the Commodity Credit Corporation (CCC) of the United States Department of Agriculture (USDA). Within the CCC/USDA program, the costs of Argonne ESC field programs are 1/10 to 1/5 those of traditional approaches. In addition, the field time required within the CCC/USDA program is as little as 1/30 of that needed in traditional approaches involving random sampling and multiple wells. The Argonne ESC is presently being implemented by the Department of Energy (DOE) at the Pantex Plant at Amarillo, Texas, and by the Department of Defense in the base closure and realignment program. The goal of all these efforts is to generate cost- and time-effective remedial characterization programs that permit accelerated implementation of technically correct remedial actions.

This paper gives an overview of the Argonne ESC process and compares it with traditional methods for site characterization. Two examples of implementation of the Argonne ESC process are discussed to illustrate the effectiveness of the process in CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) and RCRA (Resource Conservation and Recovery Act) programs.

THE ARGONNE ESC PROCESS

The Argonne ESC process emphasizes the use of the scientific method to solve site investigation problems with technically defensible data. The basic features and steps of the Argonne ESC process are discussed below.

An experienced technical manager with a broad base of expertise and a team of scientists with diverse expertise and strong field experience are required to make the process work. The Argonne team is composed of geologists, geochemists, geophysicists, hydrogeologists, chemists, biologists, computer scientists, health and safety personnel, and regulatory staff, as well as technical support staff. Of the geoscience staff, seven scientists are at the Ph.D. level, two are at the master's level, and one is at the bachelor level. They have a combined total of 170 years of experience in various aspects of the geosciences. Other disciplines within the team follow approximately the same distribution in terms of degree level and experience. The technical team works together throughout the process. In other words, the team that plans the program also implements the program in the field and writes the reports. The more experienced scientists do not remain in the office while individuals with lesser degrees or experience carry out the field work.

The technical team first *critically* reviews and interprets existing data for the site and contaminants to determine which data sets are technically valid and can be used in initially designing the field program. One of the most basic mistakes in the site characterization process is failure to use technically sound available data to form working hypotheses on hydrogeology, contaminant distribution, etc. for initial testing.

After assembling and interpreting existing data for the site, the entire technical team visits the site to identify as a group the site characteristics that may prohibit or enhance any particular technological approach. Logistic and community constraints are also identified at this point.

After the field visit, the team selects a suite of technologies appropriate to the problem and completes the design of the field program. No one technique works well at all sites, and a suite of techniques is necessary to delineate site features fully. In addition, multiple technologies are employed to give greater confidence in conclusions about site features. Noninvasive and minimally invasive technologies are emphasized to minimize risk to the environment, the community, and the staff. In no case is the traditional approach of installing a massive number of monitoring wells followed.

A *dynamic* work plan that outlines the program is produced for the sponsoring and regulatory agencies. The word dynamic is emphasized because the work plan is viewed as a guide, subject to modification, for the site characterization activity rather than a document that is absolute and unchangeable. Therefore, the health and safety plan and quality assurance/quality control plan must be broad and encompass all possible alterations to the work plan. The cooperation of the regulating agency is essential in successful implementation of this process.

The entire team participates in the technical field program. Several technical activities are undertaken simultaneously. These may range from different surface geophysics investigations to vegetation sampling. Data from the various activities are reduced and interpreted each day by the technical staff. Various computer programs are used to visualize and integrate the data. However, *people* do the data interpretation and integration, not computers. The computers are just one more tool in use at the site.

At the end of the day, the staff members meet, review results, and modify the next day's program as necessary to optimize activities that are generating overlapping or confirming site details. Data are not arbitrarily discarded — each finding must be explained and understood. Anomalous readings may be due to equipment malfunctions, laboratory error, and/or the inability of a technique to work in a given setting even though theoretically it should.

The end result of this process is the optimization of the field activity to produce a high-quality technical product that is cost- and time-effective. The Argonne ESC process is normally divided into two phases referred to as Phase I and Phase II. The Phase I effort is normally the most staff- and technology-intensive phase, with several individual programs operating simultaneously. The Phase II programs are normally smaller in effort and are designed to measure final parameters for a site, in order to set the feasibility program in action.

Table 1 presents a summary comparison of the Argonne ESC process with traditional site characterization methods.

EXAMPLES OF IMPLEMENTATION OF THE ARGONNE ESC PROCESS

Two examples of the successful implementation of the Argonne ESC methodology are discussed below. The CCC/USDA Waverly, Nebraska, site illustrates the importance of critically evaluating existing data in forming working hypotheses for site characterization. In addition, the Waverly program demonstrates the benefits of integrating multiple technologies to interpret site hydrogeology and contaminant movement. The second example is taken from the ongoing Argonne ESC program at the DOE Pantex Amarillo site. This program represents the first effort to apply the methodology within a large facility with a somewhat lengthy history of environmental investigations. The Pantex program also illustrates the benefits to be gained in the Argonne ESC by maximizing the use of existing data and employing the multidisciplinary problem-solving approach to formulate viable geologic/hydrogeologic concepts before data gathering begins in the field.

WAVERLY, NEBRASKA, SITE

Site Setting and History

At the CCC/USDA Waverly site in southeastern Nebraska, carbon tetrachloride was found in a public supply well (1,100 ppb and 710 ppb) in 1986. Site investigations in 1987 by the Region VII U.S. Environmental Protection Agency (EPA) established that carbon tetrachloride soil contamination at the former CCC/USDA grain storage facility was responsible for the groundwater contamination.[1] Site characterization studies conducted by a private contractor concluded that the groundwater regime at the Waverly site consisted of a single aquifer in a sand unit with an intermittent clay layer. Groundwater flow was estimated to be toward the north-northwest (Figure 1). The contaminated public and domestic wells were located northeast of the former CCC/USDA site. Pumpage from the public well was thought to be responsible for drawing the contamination to the northeast.

On the basis of this site characterization study,[1] a groundwater extraction well (GWEX) and a vapor extraction system (VES) were installed by the EPA at Waverly as part of an emergency removal action in 1987-1988. In 1988, operation of the GWEX and the VES system was turned over to the CCC/USDA. The remedial systems have significantly decreased the carbon tetrachloride concentrations in the soil vapor and groundwater at the former CCC/USDA site. In addition, groundwater contamination in a public supply well and monitoring wells located on and northeast of the site has fallen below detectable levels. However, a domestic well located farther northeast of the site and estimated to be within the capture zone of the GWEX continued to show carbon tetrachloride contamination (Figure 1). Because the groundwater flow direction was thought to be to the northwest from the site, continued contamination in the domestic well was difficult to understand, especially since contaminant levels in monitoring wells located between this domestic well and the site had fallen below the detection limit.

A Record of Decision (ROD) for Waverly was issued by the EPA in 1990. Among other items, the ROD required an explanation of the contamination in the domestic well northeast of the site and reevaluation of the area of influence of the existing GWEX. The CCC/USDA requested Argonne's assistance in addressing these two issues.

The Argonne ESC Process at Waverly

Evaluation of Existing Data. The first step in the Argonne ESC process for Waverly was critical review and evaluation of existing data. Although the private contractor performing the initial site investigation had compiled all existing well data, no effort had been made to use these data to understand the geology and hydrogeology of the site.[1] A review of the available geologic logs of monitoring wells, irrigation wells, and public supply wells, coupled with geologic reconstructions based on these well data, indicated that two sand aquifer units separated by a continuous clay layer were present immediately beneath the Waverly site (Figure 2). This concept is directly opposed to the conclusions reached in the previous site investigation, in which one aquifer was postulated for the Waverly site. In addition, evaluation of major ion chemistry in groundwater samples from monitoring wells installed at the site indicated significant differences between the upper and lower sand units (Figure 3).

Use of these existing data led to the conclusion that the groundwater flow direction for the upper aquifer was most likely to the north-northeast and not the north-northwest (Figure 4). The mistake in determining the flow direction occurred because the previous contractor assumed that one aquifer was present and mixed water level measurements from the upper and lower aquifers. (Only the upper aquifer is contaminated at the Waverly site.)

To substantiate the northeasterly flow direction of the upper aquifer, groundwater levels were recorded before the field investigations began by using monitoring wells installed in the upper and lower aquifers during the previous site characterization efforts at Waverly. These measurements indicated that the groundwater flow in the upper aquifer was to the northeast, not to the northwest as determined in the previous study (Figure 4). The water level elevation in the lower aquifer was about 1 ft lower than that in the upper aquifer. Nevertheless, water levels in the lower aquifer were not influenced by pumpage in the upper aquifer, indicating a lack of hydraulic connection between the two aquifers.

However, as Figure 2 shows, the behavior of the aquifer systems about 3,000 ft north of the former grain storage facility could not be stated with any degree of certainty (line A-A', Figures 1 and 4). Well logs in this area indicated a one-aquifer system. Whether the two aquifers beneath the former grain storage site merged or one was pinched out was unknown.

The Argonne ESC field program was designed to answer specific questions in light of this new model for the aquifer systems. The major objectives were (1) to verify the presence of two aquifers north of the site and determine if they merge or if one aquifer is pinched out and (2) to determine the extent of any previously unmapped contamination in the upper aquifer.

As a reference point for the field studies, a type geologic section with data from immediately beneath the former grain storage site was established for comparison with and interpretation of field data from north-northeast of the site (Figure 5). Geologic data along line A-A' (Figure 4) were gathered from soil borings (made with a hollow-stem auger or a mud-rotary drill). Groundwater samples were obtained with a HydroPunch for analysis of major ions, isotopes, and carbon tetrachloride, for comparison with known aquifer chemistries immediately beneath the former CCC/USDA site. A surface time domain geophysics investigation was conducted along line A-A' to help map and substantiate or disprove the continuous nature of the clay layer separating the two aquifers. The use of data from these three different methodologies to reach conclusions on hydrogeologic features at Waverly increased the credibility of the results generated by the Argonne ESC process without requiring a large number of monitoring wells.

Use of Geology. Six soil borings were drilled to the northwest, north, and northeast of the site to evaluate the continuity of the two sand units and the intervening clay layer. Geologic logs of the soil borings indicated the presence of clay and sand units away from the site (Figure 6). However, the geologic data could be interpreted to indicate either that both of the sand units and the intervening clay were continuous across the area of investigation or that the upper aquifer was pinched out to the north. Therefore, the geologic data could not be used alone to delineate the exact hydrogeologic relationships north of the site.

Use of Groundwater Geochemistry. Groundwater samples were collected with a HydroPunch from the six soil borings drilled for the geology study along line A-A'. Comparison of the major ion and tritium isotopic compositions of groundwater samples collected from these soil borings to the reference geochemical data (Figure 7) provided strong evidence that the upper aquifer is absent away from the Waverly site (Figure 8). The ionic tritium concentrations of groundwater samples collected above and below the clay layer intersected in soil borings about 2,000 ft north-northeast of the site were low and less variable, similar to those of samples from the lower aquifer at the site (Figure 7). This result indicates that the upper aquifer is absent north of the site. The geochemical data further indicate that the hydraulic separation between the two aquifers is maintained away from the site and that contamination is not migrating to the lower aquifer. The geochemical data, therefore, allowed questions left from the geologic interpretation to be answered and the interpretation of the aquifer system to be further refined.

Use of Surface Geophysics. Additional evidence for the absence of the upper aquifer north of the Waverly site was obtained from surface geophysical surveys. A time domain electromagnetic (TDEM) survey was performed along line A-A' (Figure 4) in the areas of soil boring investigations. Data reduction using traditional techniques produced a subsurface profile (Figure 9) that was inconsistent with the known geologic relationships at the site (Figure 5). Consequently, the data were reprocessed with the more sophisticated technique of image inversion. This technique does not require a priori constraints on the number of lithologic layers, as do the traditional methods; therefore, it provides a more unbiased means of interpreting the geophysical data. Results of the image inversion processing of TDEM data are shown in Figure 10. The disappearance of the upper aquifer sand unit is indicated to the north, consistent with the geochemical data.

Use of an Integrated Model. Figure 11 shows the integrated model of the geologic and hydrogeologic relationships at Waverly, based on the geologic, geochemical, and geophysical data. As this diagram shows, the upper aquifer is pinched out to the north-northeast of the site, and only the lower aquifer is present. No merging of the two aquifers occurs.

On the basis of this hydrogeologic model, the carbon tetrachloride values obtained from the HydroPunch sampling, and the history of contamination of and pumpage from adjoining wells, the configuration of the contaminant plume was reconstructed. This reconstruction indicated that the capture zone of the GWEX installed at Waverly was insufficient to capture the entire plume. The portion of the plume not captured by the GWEX continued to migrate to the northeast, along the natural direction of groundwater flow. This portion of the plume is the cause of the continued contamination in the domestic well northeast of the Waverly site. The predicted plume configuration was confirmed by additional drilling and groundwater sampling (Figure 12).

Discussion

At the CCC/USDA Waverly site, improper use of existing data prevented full understanding of the hydrogeologic system before remedial construction began. The end result was significant additional cost to the CCC/USDA for installation of modifications to the present system (an additional GWEX, piping back to the treatment plant, additions to the treatment plant, etc.) that should not have been incurred. Furthermore, wells to the northeast of the site would eventually have been contaminated by migration of the plume, resulting in potential health threats to individuals.

The Argonne field program for the additional site investigation was brief (approximately two months including report writing) and did not necessitate the installation of permanent monitoring wells. The use of multiple methodologies allowed the aquifer system northeast of the site to be understood with only temporary intrusion into residential and agricultural areas.

The Argonne ESC has been extended to remedial investigations at several additional CCC/USDA sites in Kansas and Nebraska. The Argonne ESC process has decreased the field costs of remedial site investigations at these sites to 1/10 to 1/5 of costs for traditional approaches involving extensive use of random-grid sampling and monitoring well installation. The time required for field programs can be reduced to as little as 1/30 of that for the traditional approaches. These cost and time savings are achieved because a high-quality technical product is produced through one integrated, scientifically sound investigation rather than numerous single-task programs with little integration of scientific data.

PANTEX PLANT, AMARILLO, TEXAS

Site Setting and History

Pantex is located in the panhandle area of west Texas in Carson County, approximately 17 miles northeast of downtown Amarillo (Figure 13). The site encompasses approximately 16,000 acres comprising facility operations, safety buffer zones, security zones, and farmland. The Pantex Plant has been operated as a weapons facility since 1942 and is now used primarily for the disassembly of nuclear weapons.

Operations conducted at the Pantex Plant generate both solid and liquid RCRA-regulated waste products. The major manufacturing operation at the facility is the formulation of high explosive (HE) materials. Organic solvents and HE materials are the primary contaminants resulting from this operation. Waste has also been generated from other operations, such as chemistry laboratories, plant maintenance, and operation and maintenance of vehicles. Machining and plating operations have generated wastes with metal contamination and corrosive characteristics. Tests of weapon components have resulted in HE and heavy-metal contamination at some sites. Furthermore, HE and solvent contamination may have originated from operations dating from World War II.

The potential for surface and subsurface contamination at the Pantex Plant has been addressed by several environmental activities, including inspections, assessments, and initial sampling investigations. These studies led to the detailed environmental investigation of the facility now underway. DOE selected the Pantex site for the first application of the Argonne ESC to a DOE environmental problem. The purpose of this program is to serve as a model for future implementation of the process at Pantex by private and governmental contractors. The specific task established for Argonne's ESC for Pantex is characterization of a perched aquifer within one zone (Zone 12) at the site. The objectives of the Zone 12 Groundwater Assessment are to determine the nature and extent of groundwater contamination beneath Zone 12 and to characterize the source and rate of migration of the hazardous constituents that are present.

Zone 12, located in the southeastern portion of the Pantex Plant, covers approximately 280 acres (Figure 13). Buildings within Zone 12 house administrative and support functions, vehicle maintenance, HE machining and synthesis operations, chemical and photographic laboratories, and various other industrial operations. Groundwater contamination beneath Zone 12 may be caused in part by migration of contaminants released from activities outside Zone 12. The system of ditches and playas in and around Zone 12 provides a high potential for surface and subsurface migration of contaminants. Numerous solvents, metals, pesticides, polychlorinated biphenyls (PCBs), petroleum hydrocarbons, acids, inorganics materials, and HE are used in the operations within and near Zone 12, and known or suspected spills and discharges of these chemicals have occurred.

At Pantex, groundwater occurs at two levels, directly above bedrock and in a shallower perched zone. Although both water zones occur in the Ogallala Formation, the convention at the Pantex site is to refer to the shallow perched zone as the "perched aquifer" and the deeper zone as the "Ogallala aquifer."

Ogallala Aquifer. The Ogallala aquifer is unconfined and lies within the Ogallala Formation. Five Ogallala production wells are currently on line in the far northeastern portion of the facility. Total depths of the production wells range from 653 to 847 ft. The saturated thickness of the Ogallala in the vicinity of Pantex ranges from 200 to 400 ft and exceeds 300 ft northeast of the plant, where the Ogallala is a primary source of water for the city of Amarillo well field. This municipal well field is located within a mile of the northeast corner of the Pantex facility. The historic groundwater flow direction to the east has been modified by pumping from the city of Amarillo well field. This change can be seen in the flow direction to the northeast beneath Zone 12.

Perched Aquifer. The upper part of the Ogallala Formation (typically 150-250 ft below the surface) contains an apparently persistent zone of low-permeability fine-grained material called the fine-grained zone (FGZ). This unit provides a relatively impermeable barrier and serves to perch water above the main Ogallala aquifer in the vicinity of the Pantex Plant. The perched aquifer within the Ogallala Formation occurs beneath portions of the Pantex site, specifically in the area of Zone 12. Although water from the perched aquifer is not used, this groundwater zone is significant because of the presence of both organic and inorganic contaminants and their potential to migrate downward into the Ogallala aquifer.

The Argonne ESC Process at Pantex

Use of Existing Data. The first task for Argonne in its ESC process is assimilation, quality evaluation, and integration of all technically acceptable existing site data. A major difference between this site and others studied by Argonne for the Bureau of Land Management and the CCC/USDA was the volume of data generated by previous investigations. However, before Argonne's ESC investigation began, these databases had not been evaluated or integrated to formulate hydrogeologic models consistent with all data for the site.

After preliminary examination of the results of previous investigations, Argonne reached the conclusion that the existing database was mostly usable with certain modifications and reinterpretations. Gaps and data of questionable quality were identified in the database, but minimal field activity was apparently needed to remedy these problems. Therefore, no major field data acquisition program was required for Argonne to complete a Phase I study at Pantex. Phase I studies in the past had normally built on little more than an existing regional geologic framework and limited sampling. At Pantex, an extensive database was already available on site-specific geology, geophysics, contaminant distribution, and geochemistry.

Results of Previous Studies. A significant amount of background information about the contamination of the perched groundwater in the vicinity of Zone 12 was accumulated in conjunction with the ongoing RCRA facility investigations and the previous studies. The data used for Argonne's preliminary review were compiled primarily from publications and reports issued by the U.S. Army Corps of Engineers[2-6] and the Bureau of Economic Geology at the University of Texas at Austin.[7] These reports included data from a total of 25 monitoring wells installed for the Zone 12, Ditches and Playas, and Leaking Underground Storage Tank RCRA facility investigation studies at Pantex, as well as other monitoring wells and domestic wells in the area. The conclusions drawn from these existing studies *prior* to Argonne's analysis can be summarized as follows:

- Recharge and hence contaminant transport was postulated to occur mainly through the floors of the playa lakes. Recharge was estimated at 30-50 cm/yr through Playa 1 near Zone 12 and less than about 1 cm/yr in the interplaya areas.

- The direction of groundwater flow in the perched aquifer was thought to be dependent on and controlled by the focused recharge through the playas. In other words, the groundwater flow would be radially away from the playa centers. On the basis of data from existing wells, the general flow direction of the perched water in the vicinity of Zone 12 was thought to be southerly, away from Playa 1, but both the direction of flow and the geographic limits of the perched water were poorly constrained.

- Groundwater in the perched aquifer was thought to eventually leak through the FGZ to the underlying Ogallala aquifer. Estimates of flow through the FGZ indicated that as much as 80% of the water in the perched aquifer could leak through the FGZ before it moved 2,600 ft laterally in the perched aquifer.

- The continuity of the perched aquifer underneath the Pantex Plant was unclear, and the possibility existed that the perched aquifer was segmented. The segments might or might not be in hydraulic communication.

- The ionic and isotopic concentrations in the perched and Ogallala aquifers were not thought to be particularly useful in defining the continuity of the perched aquifer or in evaluating potential hydraulic interconnections between the perched and Ogallala aquifers.

Evaluation of Existing Data. The Argonne ESC review of the contaminant and geochemical data from Pantex indicated that these data are largely inconsistent with the conclusions drawn by previous investigations at the site and summarized above. Discrepancies found by Argonne are discussed below.

The concentrations of chromium and the high explosive HMX in the perched aquifer in the June 1993 sampling results are shown in Figures 14 and 15. The variations in the spatial distribution of the contaminants were significant. However, the concentrations all contaminants were higher directly beneath the Zone 12 area. No spatial trend of decreasing values away from Playa 1 was observed. (Playa 1, the nearest playa lake to the north of Zone 12, was considered to be the principal source of recharge for the perched aquifer in this area.) A review by Argonne of the sources of contamination and the history of waste disposal revealed that inorganic wastes (e.g., chromium) were disposed of mainly in acid pits in the southern part of Zone 12, while the explosives wastes (e.g., HMX) were placed in the ditches in the eastern part of Zone 12. Inasmuch as contaminants are transported into the aquifer at Pantex as dissolved constituents, the contaminant distributions indicated that a significant or dominant proportion of recharge in the Zone 12 area is in the interplaya region, by infiltration vertically downward. Thus, Argonne found the present contaminant distribution to be inconsistent with the previously proposed models for recharge of the perched aquifer through the playa lakes. Argonne believed that increased recharge in the interplaya region at the Pantex Plant could be due to the presence of surface ditches formerly used to dispose of liquid wastes from the plant.

Argonne performed a detailed analysis by using existing wells to evaluate geologic controls on the perched aquifer beneath Zone 12. Argonne's reinterpretation of existing well logs suggested the presence of a gravel-filled channel crossing Zone 12 and opening to the southeast. A simplified cross section of this channel is shown in Figure 16. The perched aquifer is located above the FGZ, a zone of variable thickness and lower permeability that appears to serve as a barrier to downward water movement. Insufficient data from previous studies existed to ascertain the effectiveness of the FGZ as a barrier to vertical water movement. Furthermore, previous investigations had not revealed whether the absence of water at the perched level was due to the absence of the FGZ as a discrete barrier or to lateral lithologic changes within the FGZ. Alternatively, Argonne believed that the water might be absent because the top of the FGZ was locally structurally higher than the top of the perched water.

A review of 17 miles of existing seismic reflection data for Zone 12 and adjacent areas uncovered several problems and inconsistencies in the manner in which the data were acquired, processed, and interpreted. Little information of geologic significance could be extracted from the survey. However, Argonne reprocessed a short section of one of the lines and was able to demonstrate that reprocessing of the original data could enhance the geophysical expression of the perched aquifer and possibly provide an additional piece of independent data for formulating a technically sound model for the Zone 12 perched aquifer.

Hence, Argonne was able to identify specific areas for data collection and evaluation that would minimize field activities and cost and maximize the use of existing wells and data packages for answering the Zone 12 groundwater questions. Argonne's modified Phase I program is described below.

Phase I Argonne ESC Process at Pantex. The goal of Phase I work was to develop a working model for answering technical questions about the perched aquifer by using the available data and existing monitoring wells without resorting to an extensive field program. The basic Argonne ESC principles of involving a multidisciplinary approach were followed, however. The Phase I program emphasized the integration of all data (geologic, geophysical, and geochemical) to begin solving the problem and constraining the system. The principal tasks for the Phase I study were as follows:

- Reprocess and reinterpret preexisting geophysical seismic reflection data to optimize mapping of the perched groundwater.

- Continuously monitor water levels for an extended period of time in existing monitoring wells installed in the perched and Ogallala aquifers.

- Sample existing monitoring wells in and around Zone 12 to obtain a consistent set of geochemical data for ionic and isotopic compositions of groundwater in the perched and Ogallala aquifers.

- Integrate these data with existing geologic data to formulate the optimal field program for final characterization of the Zone 12 aquifer.

Phase I Geophysics Results. The reprocessed seismic lines were characterized by strong, continuous reflections occurring at arrival times that approximately corresponded to the depth of the top of the perched aquifer. These reflections were consistent with the seismic response that would be predicted in this unconsolidated geologic section, where acoustic impedance is controlled largely by pore fluids. The perched water reflection was seen on all of the seismic lines processed by Argonne. Three of the lines, however, had segments where the reflection was partially or completely attenuated, indicating that the perched water layer was thinner than the resolution of the seismic data or was absent (Figure 17). These data, coupled with geologic constraints, indicated points where additional field testing would be required. Shallow refraction data extracted from the seismic lines also indicated that mounds of high-velocity material suggestive of saturated to partially saturated soils are present beneath most of the drainage ditches. This finding supported the Argonne theory that these ditches, rather than the playas previously proposed, could be major zones of contaminant infiltration within and adjacent to Zone 12. It also pointed to the necessity of sampling these previously unsampled zones for recharge activity.

Phase I Hydrogeology and Geochemistry Results. Geochemical and flow data collected by Argonne from existing wells suggested that the perched aquifer at Pantex may be present as at least two, and perhaps three, geochemically distinct and hydraulically separate aquifers (Figure 18). The perched aquifer beneath Playa 1 and north of Zone 12 appeared to be hydraulically separate from that beneath Zone 12. This conclusion was based on the presence of a dry hole at the location of well PTX06-1009 and differences in the stable oxygen, hydrogen, and carbon isotope compositions of groundwater samples. The apparent boundary between these two separate perched aquifers coincides with the thinning of the perched aquifer at well PTX06-1009 (seen on the geologic cross section, Figure 16) and is supported by the distribution of oxygen isotopic compositions (Figure 19). The isotopically heavier samples are all located near Playa 1 and between Playa 1 and Zone 12. A third hydraulically separate perched aquifer may lie to the northwest of Zone 12 and east of Playa 2, as indicated by the dissolved chloride and silicon concentrations and the presence of dry holes in the area of Zone 11 (Figure 20).

The groundwater flow direction was estimated to be to the southeast in the perched aquifer between Zone 12 and Playa 1 and to the south in the perched aquifer beneath Zone 12. The flow direction may be to the west in the perched aquifer northwest of Zone 12 (and east of Playa 2) if this aquifer is hydraulically separated from the other two, as the geochemical data indicate.

Geochemical data indicate that recharge and hence contaminant transport to the perched aquifer in the vicinity of Zone 12 and to the northwest of Zone 12 occur by downward percolation of rainwater in the interplaya area. Recharge to the perched aquifer beneath Playa 1 occurs mainly by infiltration of slightly evaporated water through the playa. The oxygen, hydrogen, and carbon isotopic compositions of the groundwater differentiate the sources of recharge. These differences in the isotopic geochemistry also indicate that groundwater recharged through the playa does not appear to flow under Zone 12. These data entirely contradict previous models, in which the playas were proposed to be the main source of water for the perched aquifer beneath Zone 12.

Phase I Conclusions. The Phase I investigation established a model that is consistent with most of the available data and provides an explanation for the observed distribution of contaminants. The conclusions from Phase I are summarized below.

- Contamination from Zone 12 may reach groundwater through surface infiltration in both the playa and interplaya areas.
- Contamination reaching the groundwater through Playa 1 would probably be subjected to surface evaporation and would be diluted with a greater amount of runoff water. Any contamination that reached groundwater through the playas would be unlikely to reach the perched groundwater beneath Zone 12 because of the southeasterly flow direction in this area and the possible hydraulic discontinuity of the perched aquifer just north of Zone 12.
- Contamination reaching the perched groundwater in the interplaya area around Zone 12 would migrate in a southerly direction.
- Infiltration from ditches and other source areas in the interplaya area in and around Zone 12 may have provided a significant contaminant pathway to the underlying soils and the underlying groundwater.
- Reprocessing of seismic reflection lines in the vicinity of Zone 12 showed that the perched water is present beneath all of the lines. Breaks in the seismic horizon interpreted as perched water probably represent an absence of the perched water zone.

In contrast to previous investigators, Argonne demonstrated the importance of quantifying the recharge in the interplaya area to characterize contaminant transport to and within the perched groundwater beneath Zone 12. The framework established can now be used to guide further data collection and establish a scientifically valid groundwater model for Zone 12. The model derived must be accurate to ensure that correct remediation practices are implemented at the site.

On the basis of the model developed in the evaluation of existing data and the multidisciplinary Phase I program, Argonne is currently carrying out the Phase II field program for the Zone 12 perched aquifer characterization. Field activities for Phase II include soil borings, coring, and HydroPunch sampling at locations delineated by the Phase I data integration.

Discussion

The Argonne ESC process at Pantex has drawn heavily on preexisting data and existing monitoring wells. This approach of maximizing the use of existing data is a cornerstone of the Argonne ESC process. The minimization of Argonne's Phase I field activities reduced Argonne's projected schedules and budget for the Zone 12 field investigation significantly. Reducing time and money while generating technically sound data is the main goal of the Argonne ESC. Its coordinated, multidisciplinary, scientific team approach allowed data from many different sources and site studies to be integrated for the first time, enabling the development of a geologic-hydrogeologic-geochemical model of the perched aquifer in the vicinity of Zone 12. This model is being used to guide further characterization of the aquifer outside Zone 12, and the Argonne ESC technical approach is being adopted in other on-site investigations.

SUMMARY AND CONCLUSIONS

The Argonne ESC methodology has been demonstrated to be a time- and cost-efficient process for producing high-quality preremedial site characterizations. The Argonne ESC methodology is based on a scientific approach to problem solving that allows regulatory guidance to be incorporated easily. In other words, science drives the program within a regulatory framework. This methodology differs from attempts to follow a regulatory guidance document without incorporating a scientific approach. In past environmental site investigations, such attempts have too often led to incorrect and inconclusive site characterizations that have delayed or precluded correct remedial actions.

The Argonne ESC process is flexible and neither site nor contaminant dependent. The process has been successfully tested and applied in site investigations of multiply contaminated landfills in New Mexico (for the Bureau of Land Management) and at former grain storage facilities in Nebraska and Kansas, contaminated with carbon tetrachloride (for the CCC/USDA). The Argonne ESC process is now being employed for groundwater investigations at the DOE Pantex Plant, where the multidisciplinary scientific approach has generated a technically defensible model for the contaminated perched aquifer system.

ACKNOWLEDGMENT

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2. Pantex Plant, Amarillo, Texas, Hydrological Assessment, prepared by U.S. Army Corps of Engineers for U.S. Department of Energy, 1991.

3. Final Preliminary Data Package for Zone 12 Groundwater ADS 1230 (AL-PX-06), Pantex Plant, Amarillo, Texas, prepared by U.S. Army Corps of Engineers for U.S. Department of Energy, 1993.

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5. Pantex Plant Environmental Restoration Program, U.S. Department of Energy, Amarillo Area Office, 1992.

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7. Summary of Quarterly Progress Meeting, Pantex Project, Bureau of Economic Geology, University of Texas, Austin, Texas, 1994 (unpublished).

Table 1. Comparison of Argonne's ESC process and traditional site characterization methods.

Component	Traditional Method	ESC Process
Composition of team	Mostly junior staff	Highly experienced staff in multiple disciplines
Continuity of team	Variable throughout project	Stable throughout project
Use of existing data	Little or no use; reinvention of the wheel	Critical evaluation and maximum use
Technical strategy	Heavy reliance on random statistical sampling and well installation	Use of multiple convergent technologies; nonrandom, minimal well installation
Focus	Narrow approach with a single task	Broader approach with multiple tasks
Work plan	Rigid plan	Flexible plan to facilitate convergence on solution
Field management	Manager in office; juniors in field	Manager in field with experienced, senior staff
Data analysis schedule	Reduction and interpretation months later	Daily reduction and interpretation
Modifications during characterization	No modification of individual programs	Real-time modification of field programs
Number of field programs	Numerous separate programs	Minimal number of optimized programs

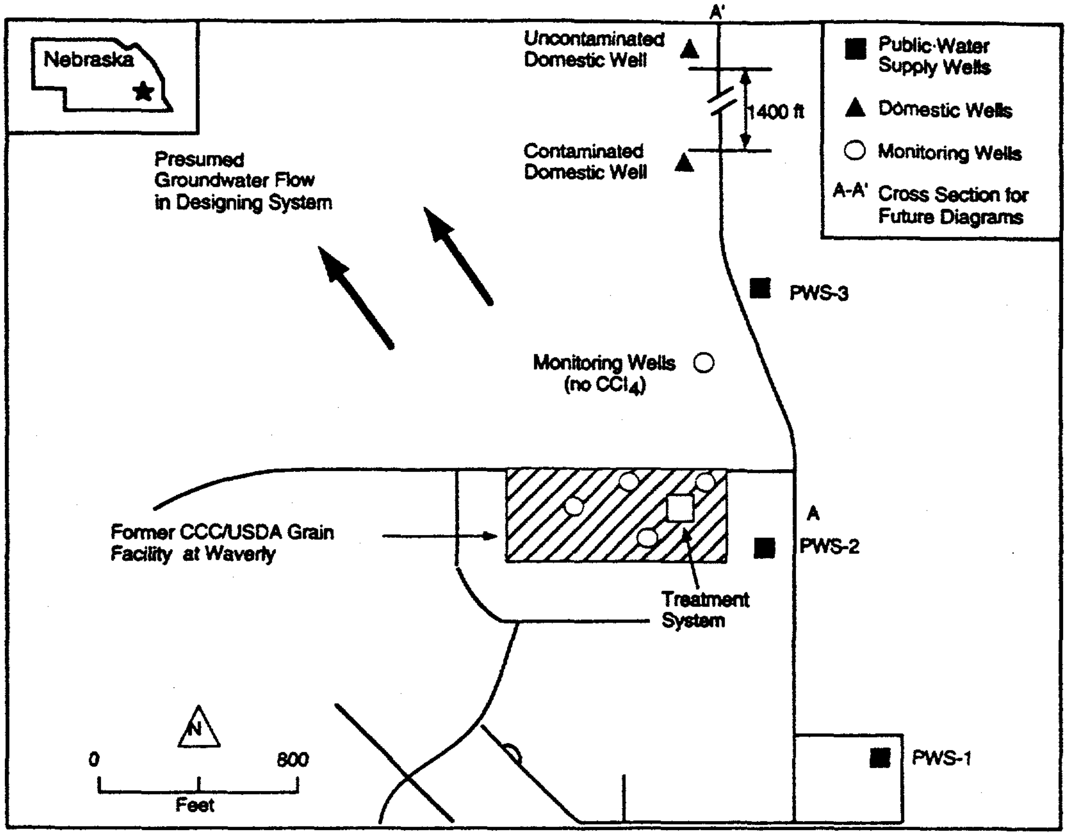

Figure 1. Waverly, Nebraska, site, with direction of groundwater flow presumed from previous investigations.

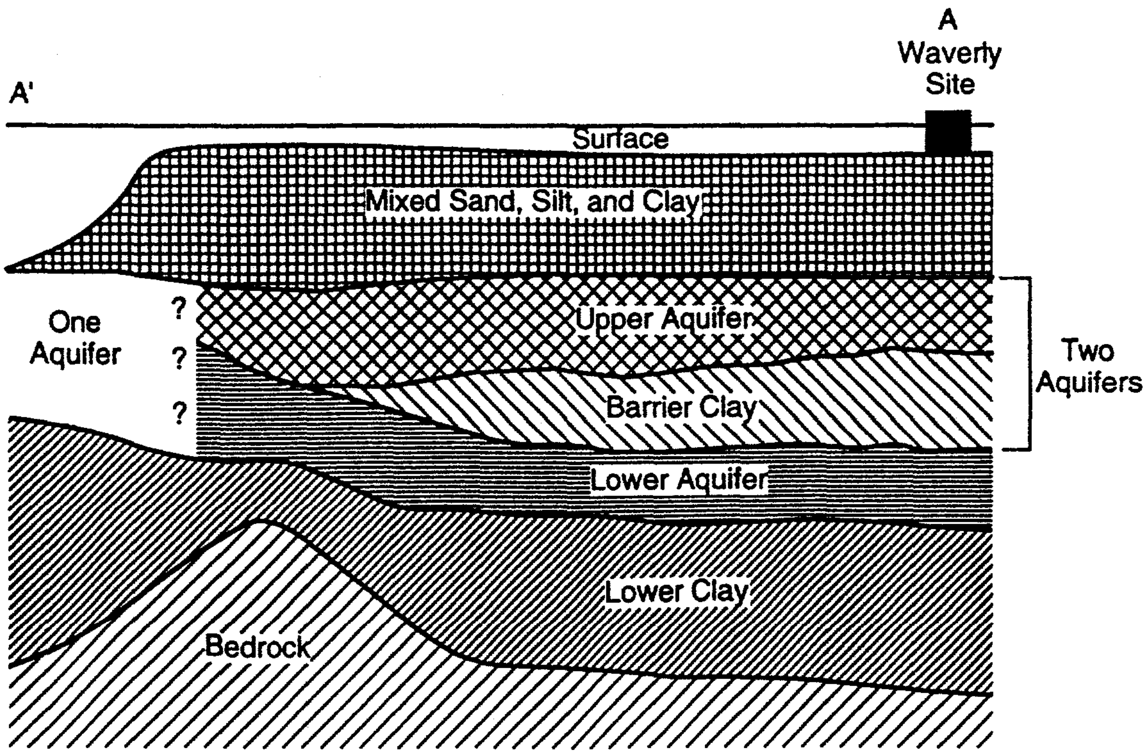

Figure 2. Revised concept of aquifer system at Waverly, produced by Argonne with a review of existing data.

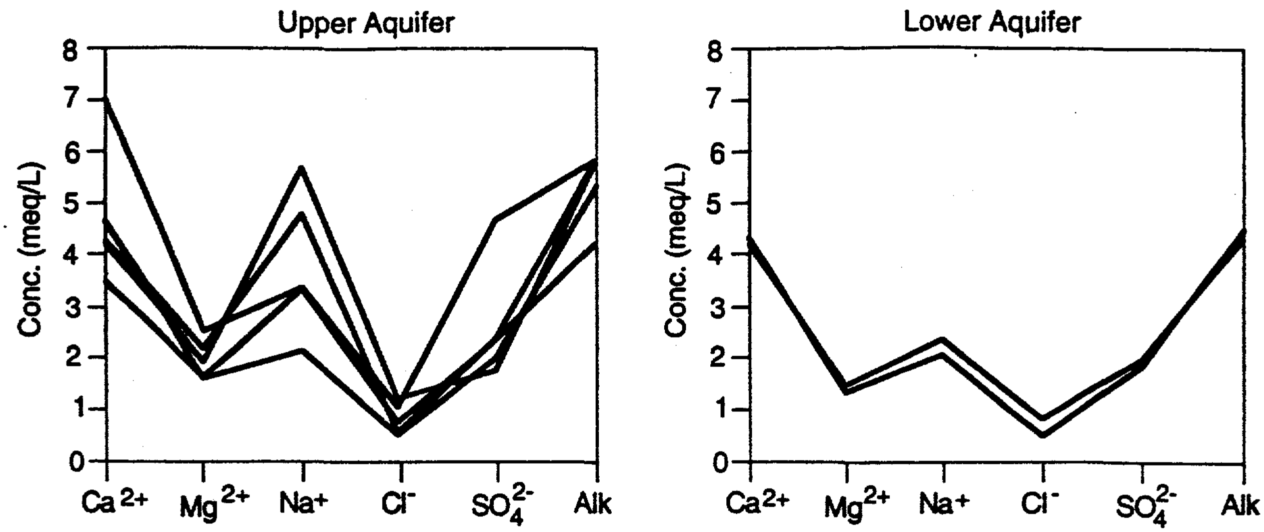

Figure 3. Major element chemistry of the two aquifers at Waverly.

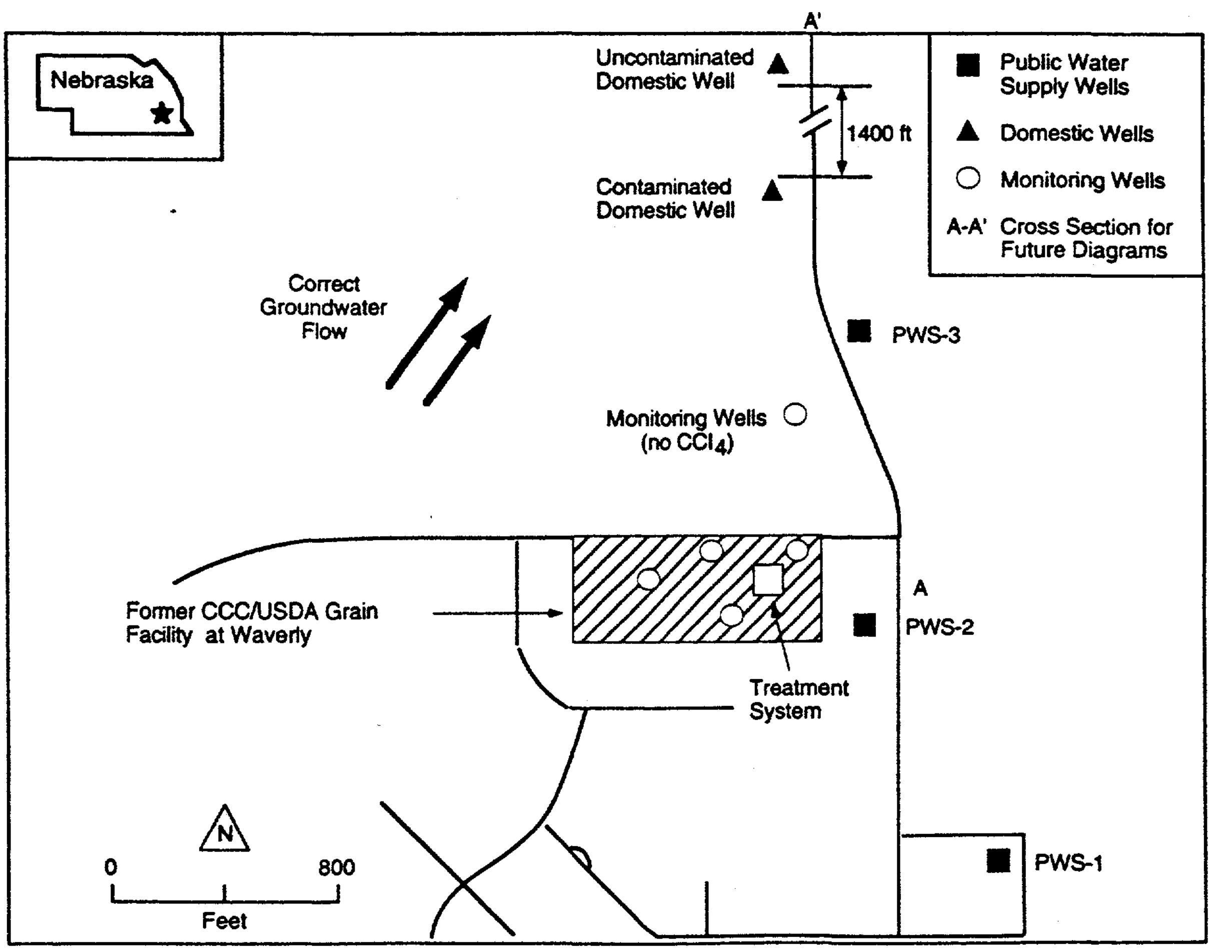

Figure 4. Direction of groundwater flow in the upper aquifer at Waverly, determined by Argonne from a review of existing data.

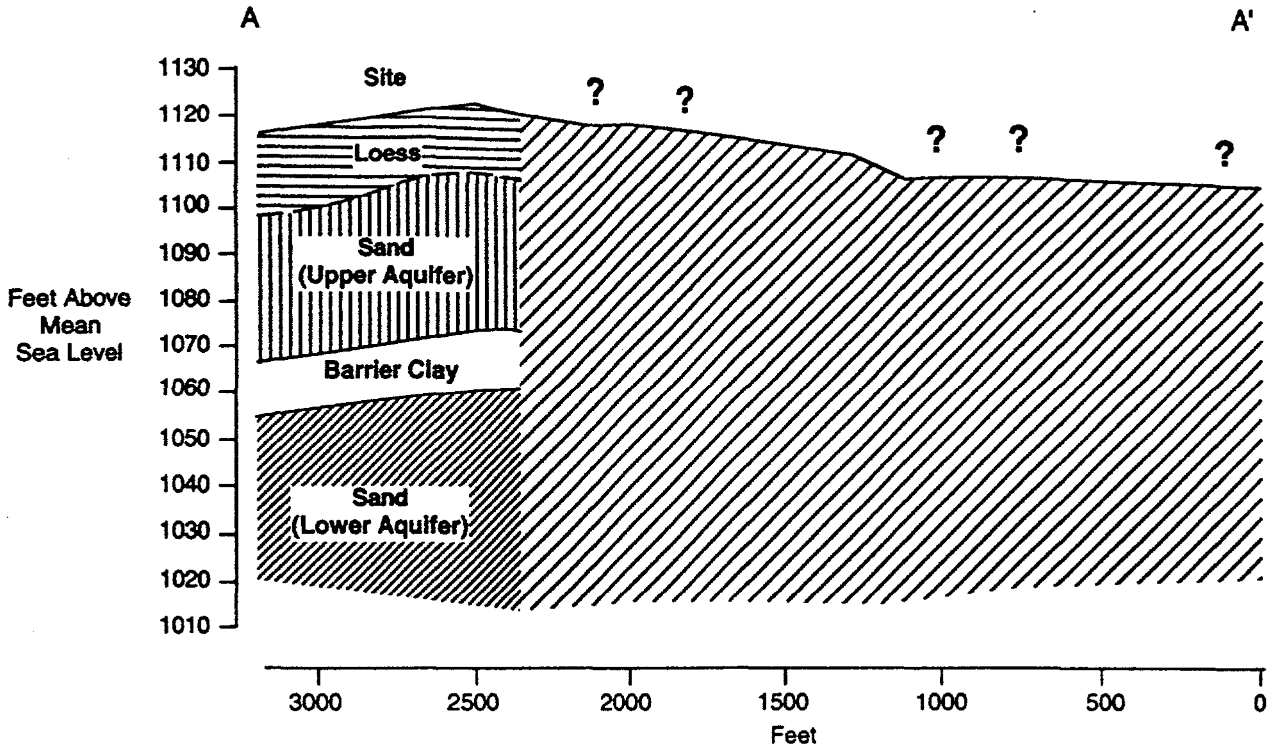

Figure 5. Type geologic section directly beneath former CCC/USDA site at Waverly.

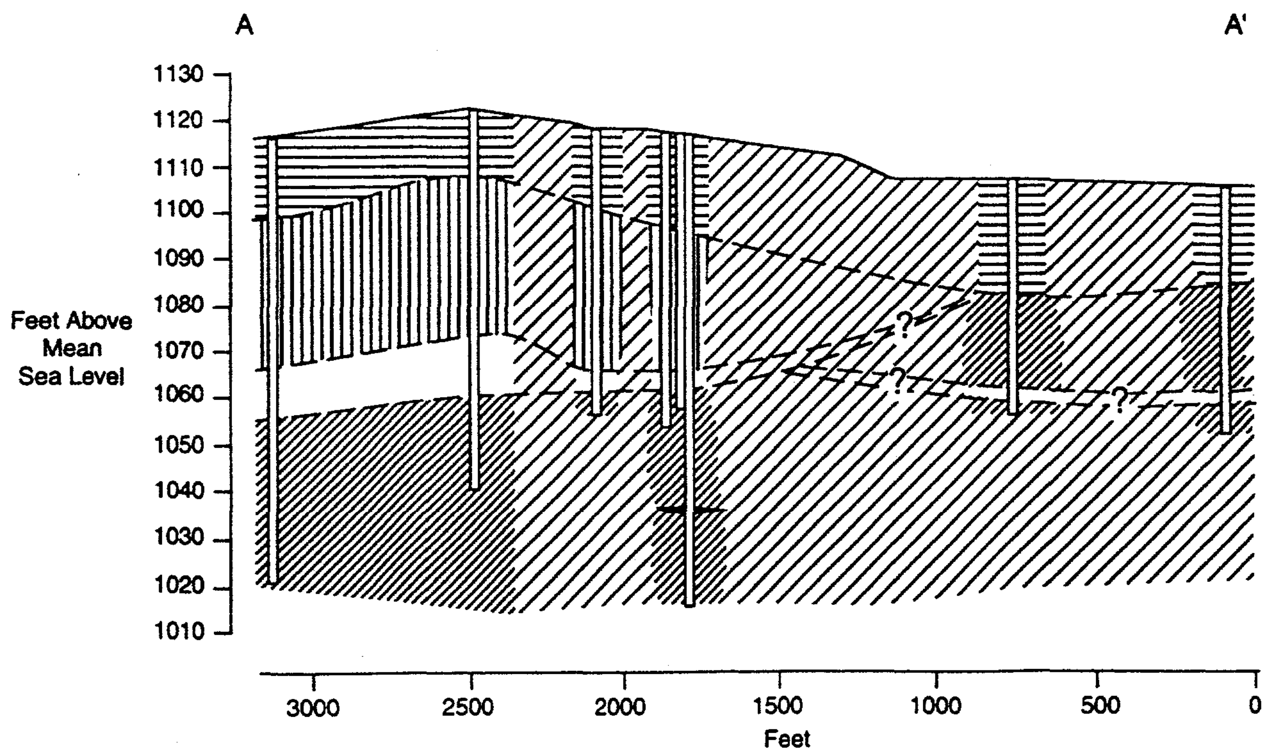

Figure 6. Geologic log data at Waverly allowed more than one possible interpretation for aquifer sand units.

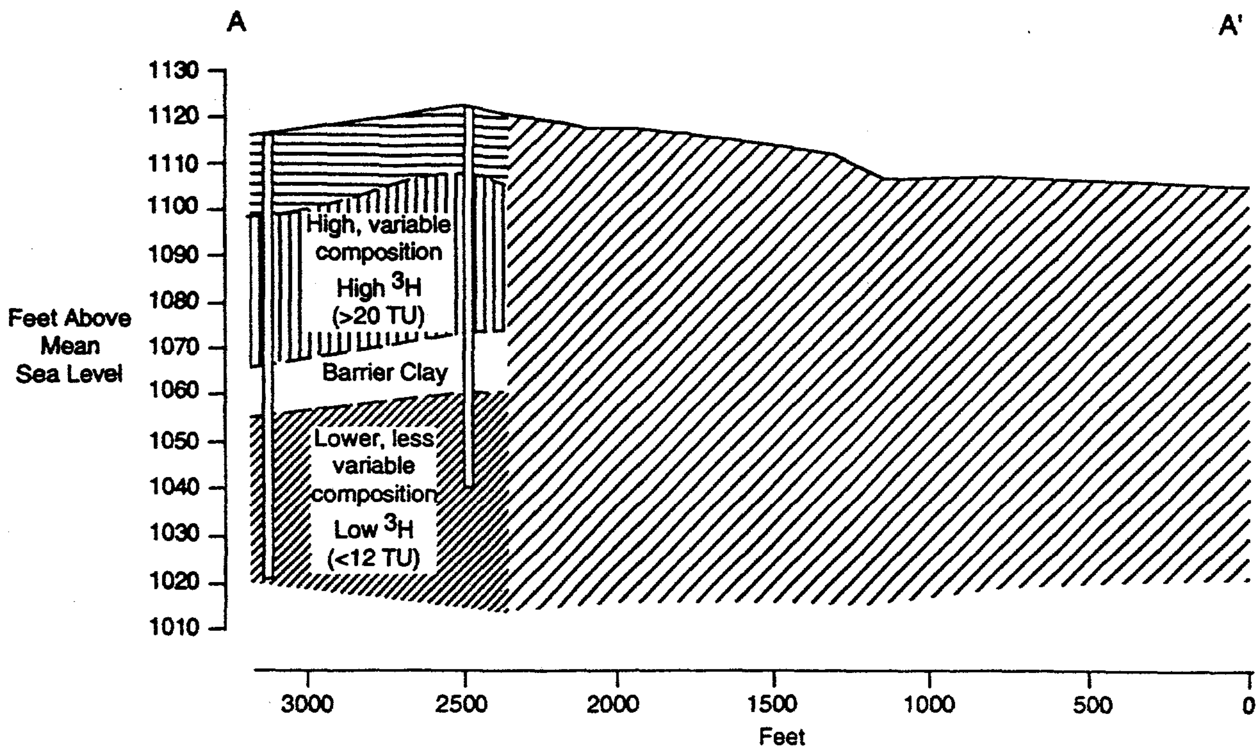

Figure 7. Geochemical data for the Waverly aquifers directly beneath the former CCC/USDA site.

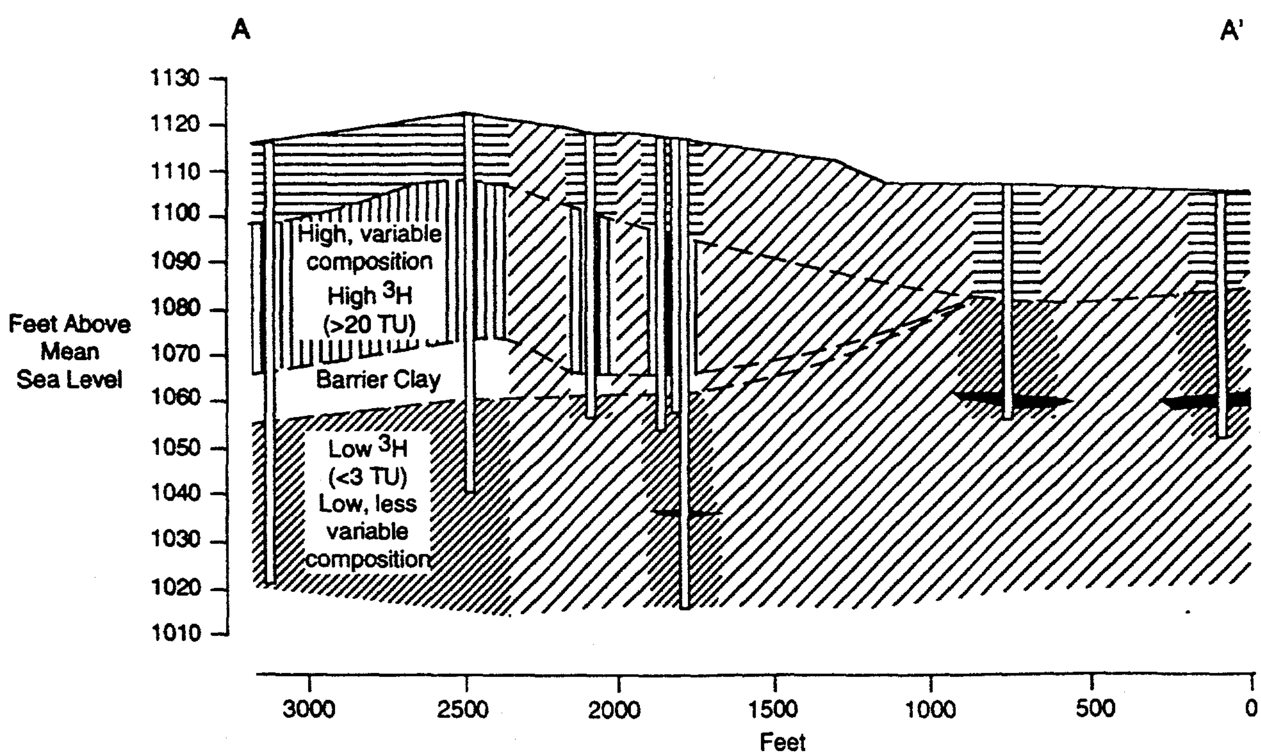

Figure 8. Geochemical data were crucial in correctly defining the hydrogeologic regime at Waverly.

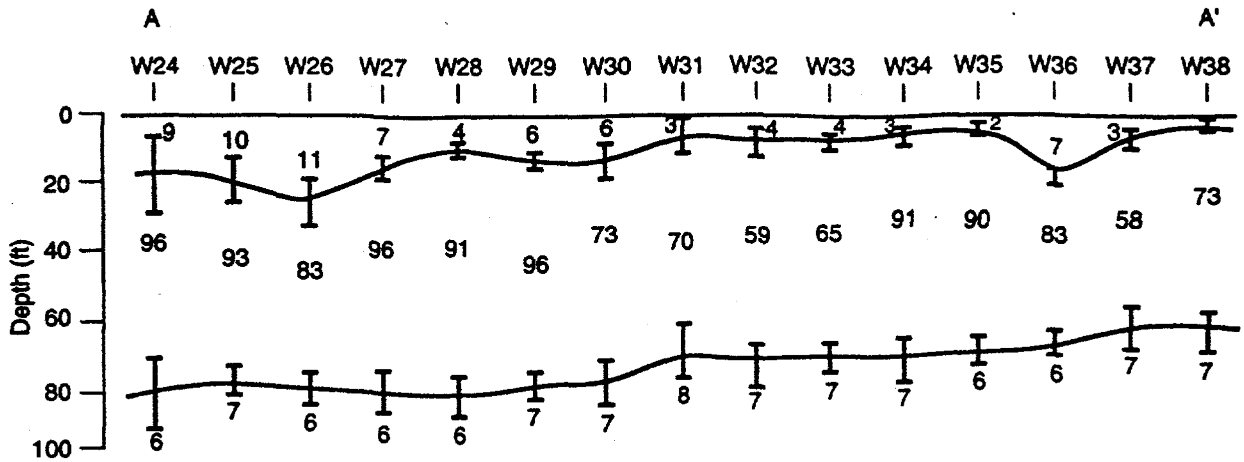

Figure 9. Conventional TDEM profile (ohm-meters) at Waverly (Section A-A').

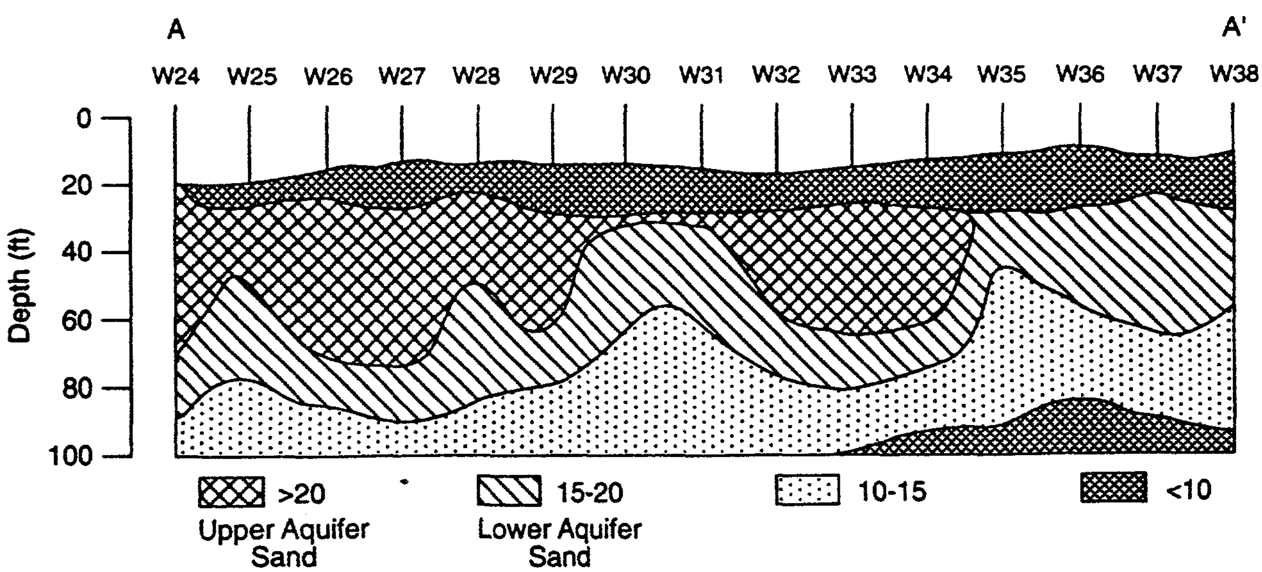

Figure 10. Image inversion TDEM profile (ohm-meters) at Waverly (Section A-A').

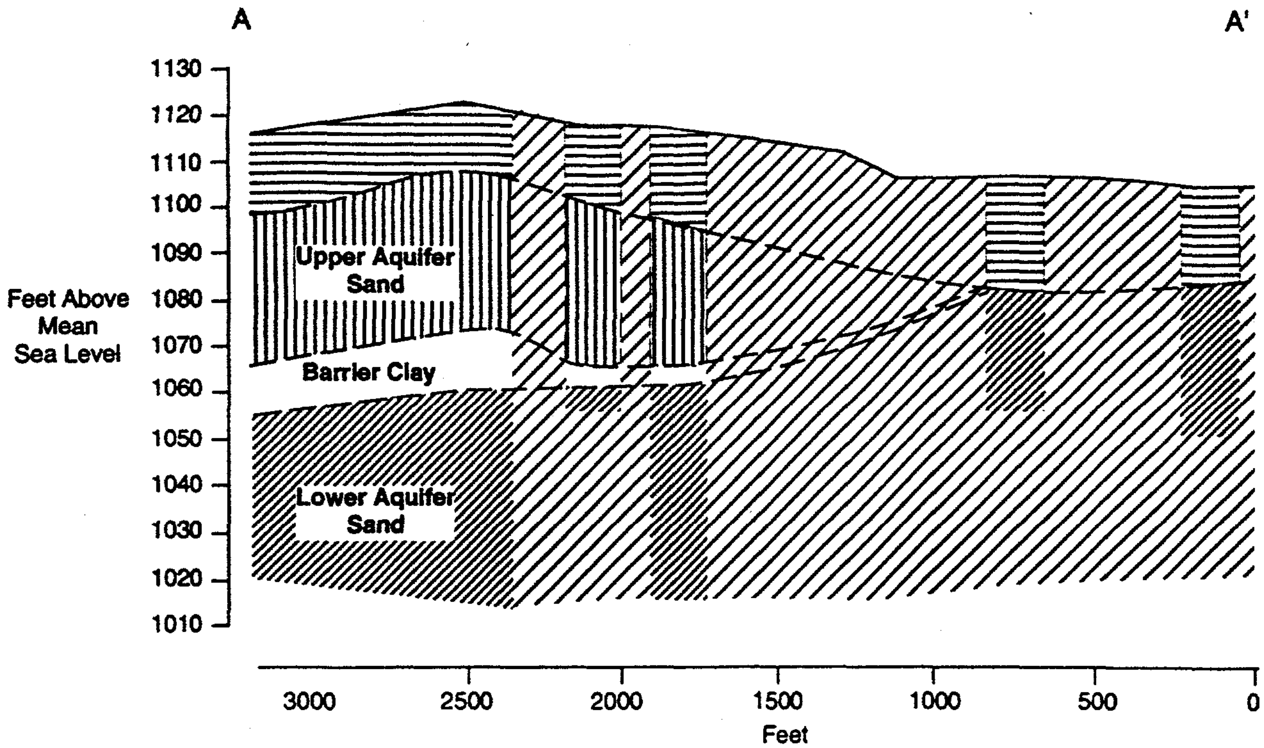

Figure 11. Pinchout of the upper aquifer at Waverly, as interpreted from TDEM data, geochemistry, and geology.

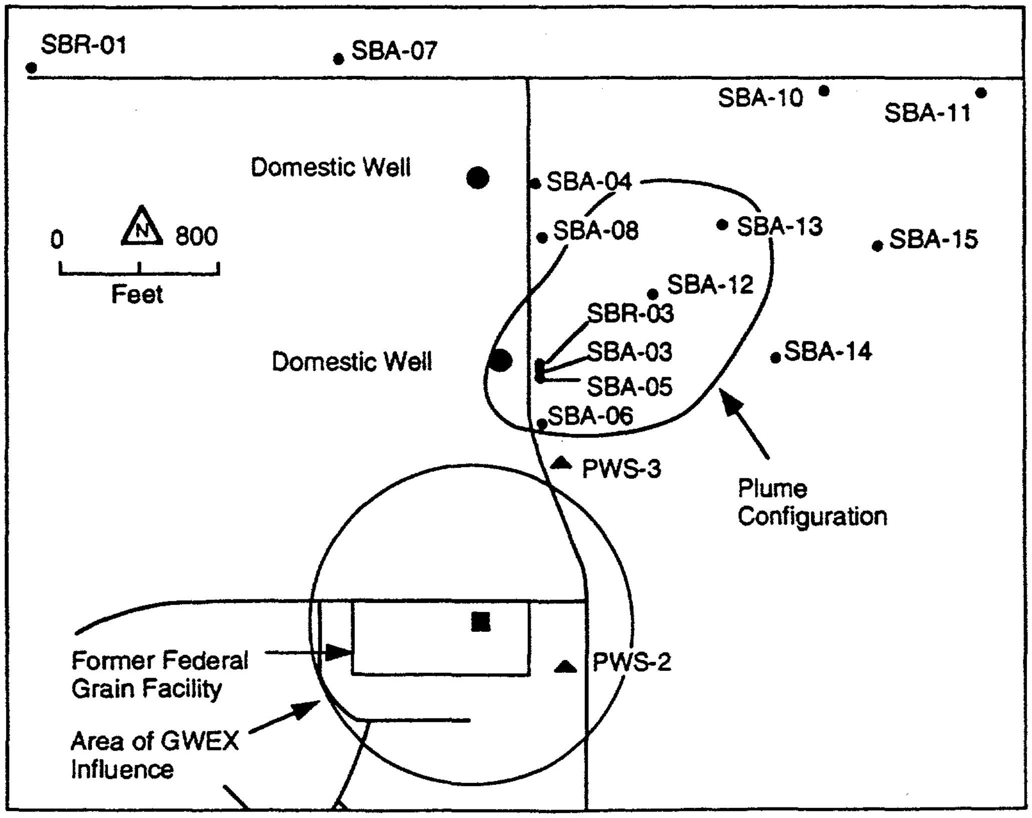

Figure 12. Configuration of the contaminant plume at Waverly.

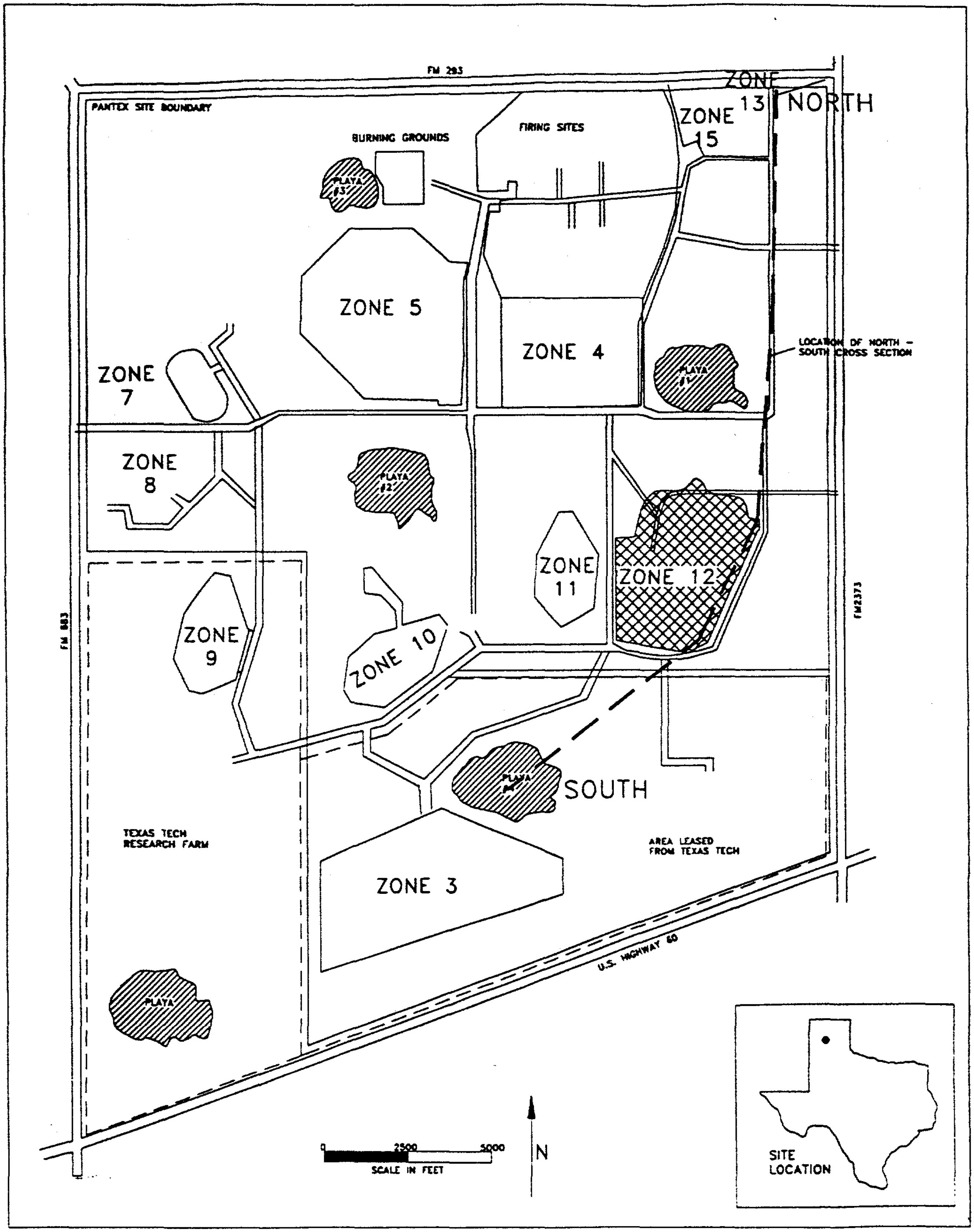

Figure 13. Location and plan of the Pantex Plant.

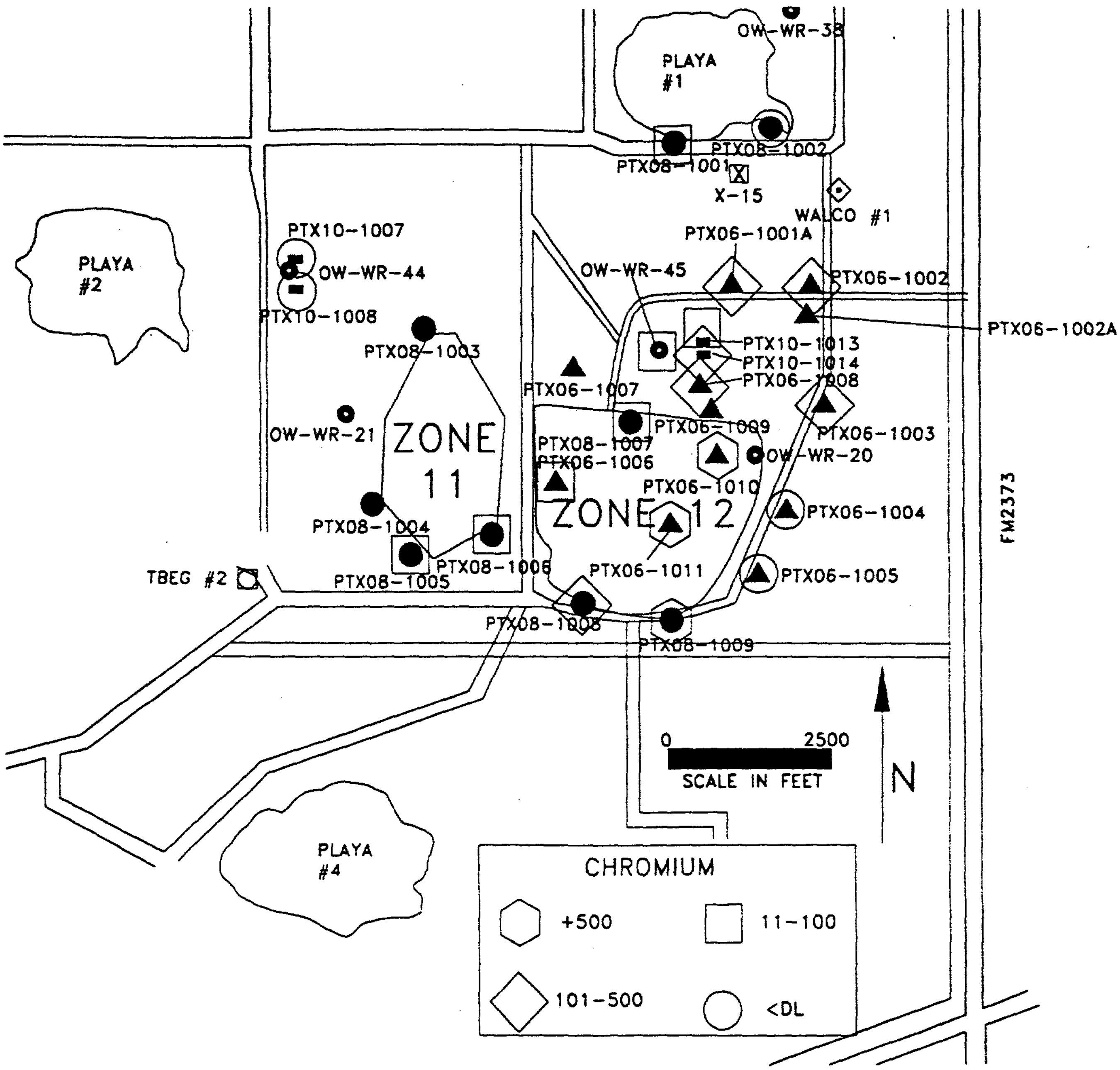

Figure 14. Concentrations of chromium (µg/L) in the Zone 12 perched aquifer in June 1993.

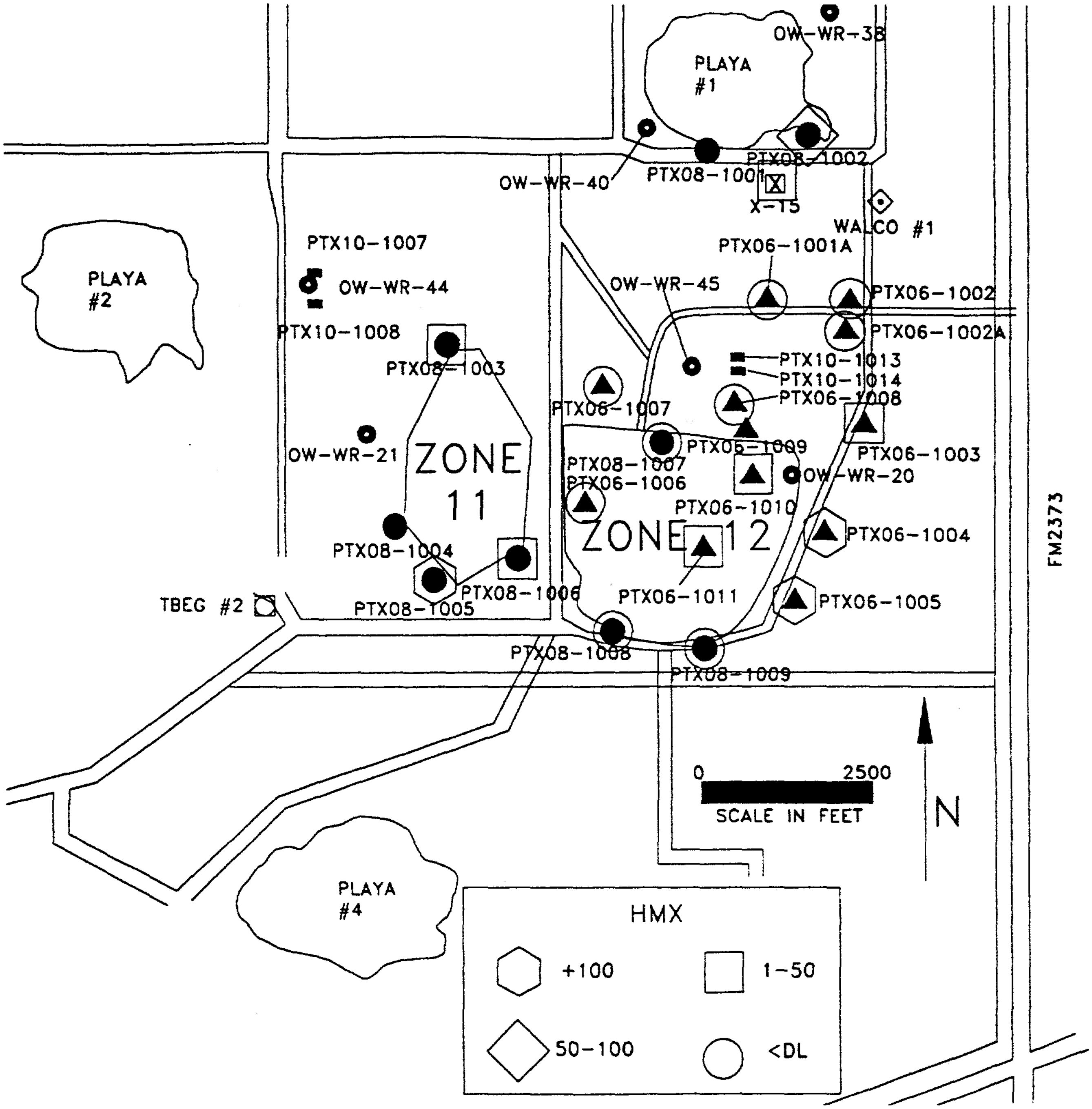

Figure 15. Concentrations of HMX (μg/L) in the Zone 12 perched aquifer in June 1993.

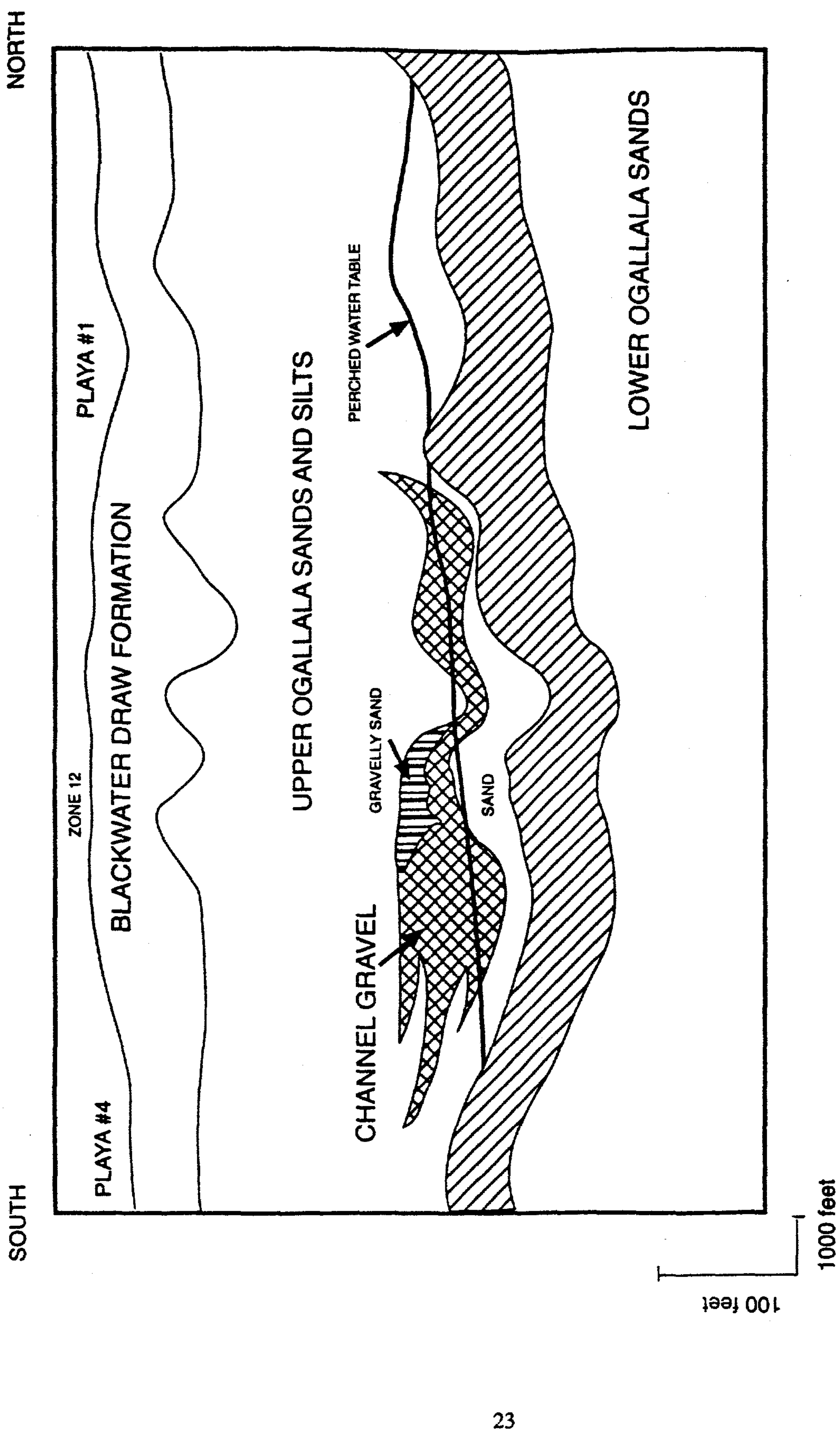

Figure 16. Simplified geologic cross section showing channel gravels. (See Figure 13 for location of cross section.)

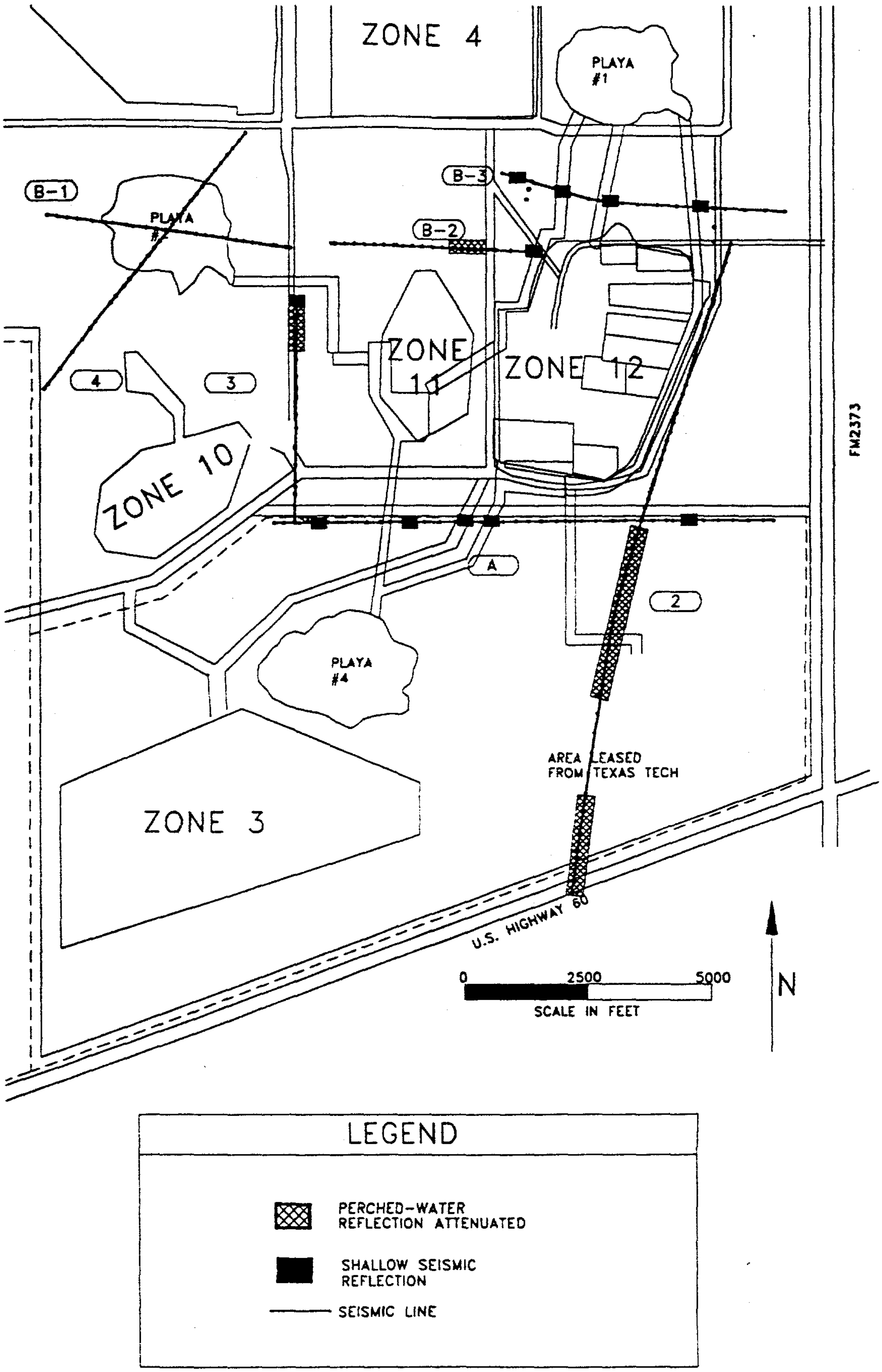

Figure 17. Locations of shallow seismic events and attenuation of perched water reflections on reprocessed seismic lines.

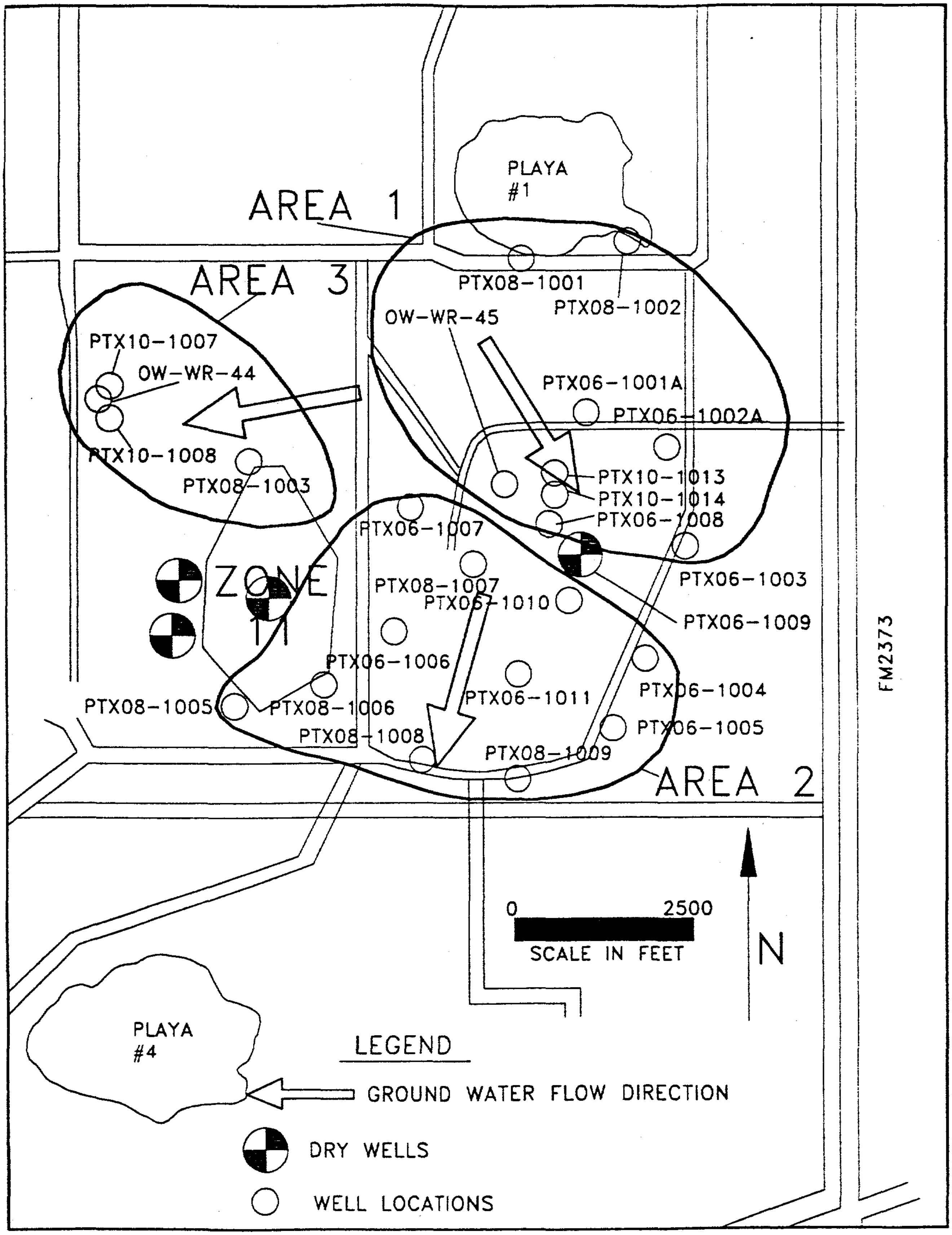

Figure 18. Location of hydraulically and geochemically separate zones (Areas 1, 2, and 3) and direction of groundwater flow in the perched aquifer at Pantex.

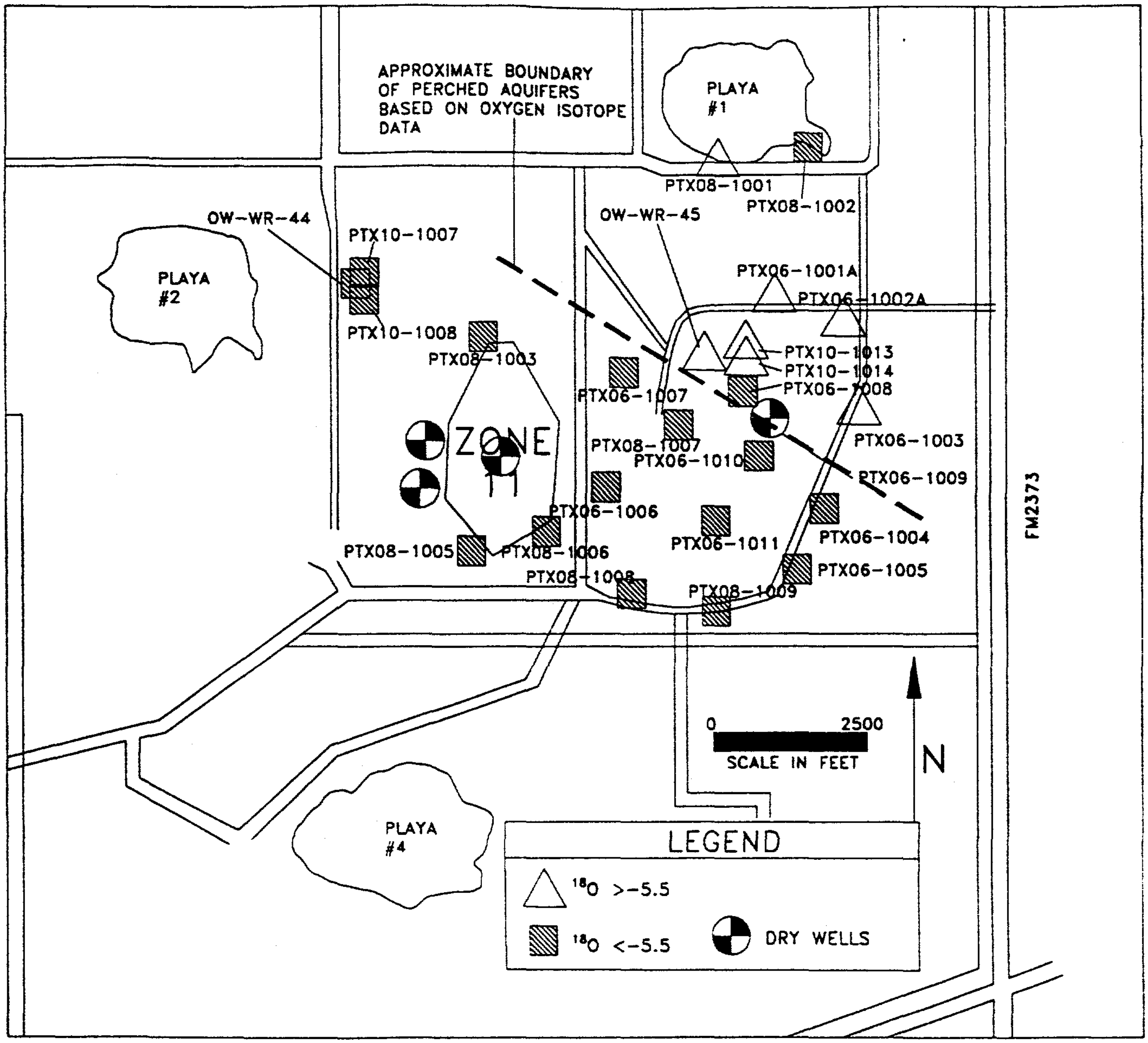

Figure 19. Distribution of Pantex groundwater samples, grouped by oxygen isotopic composition.

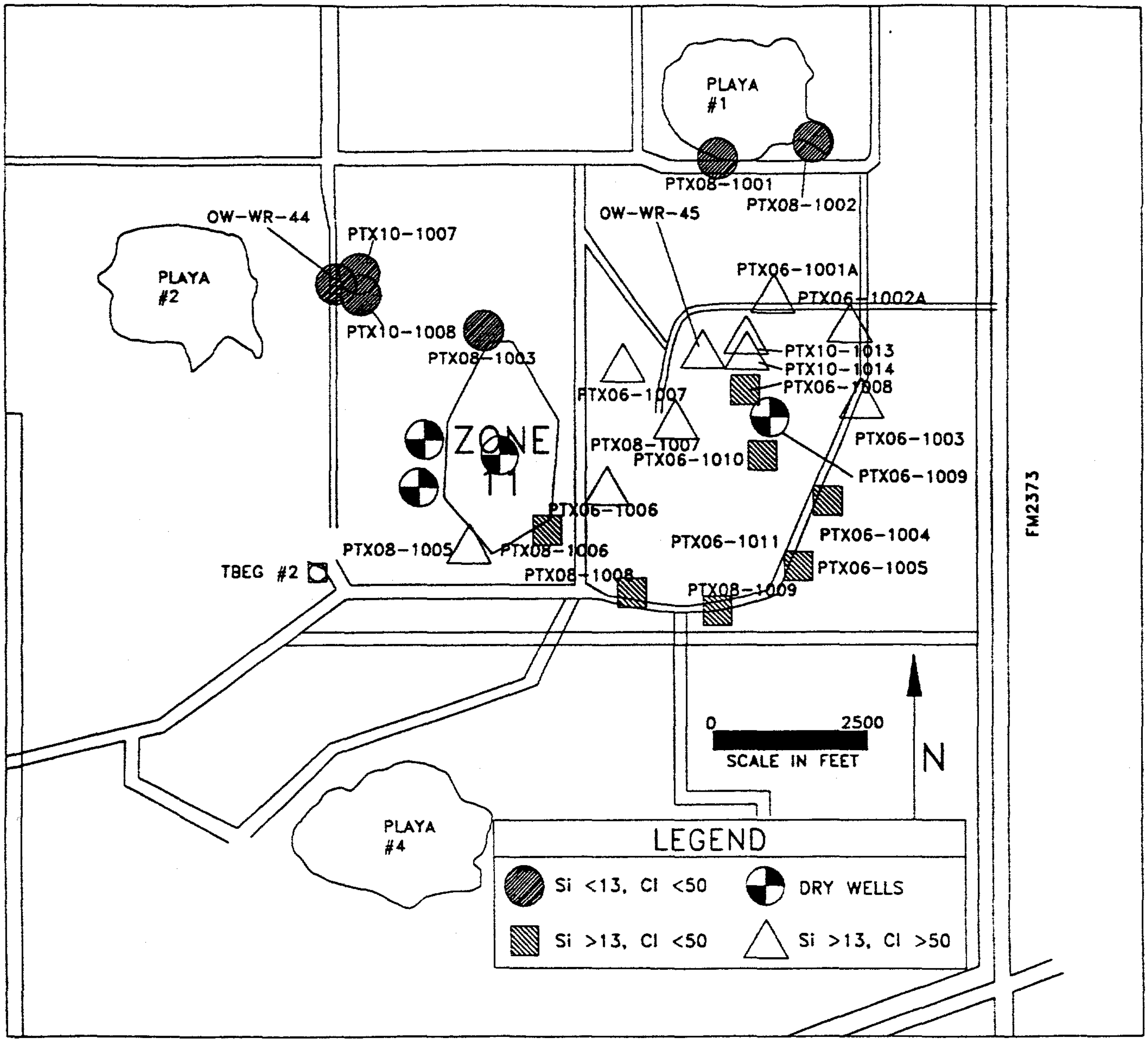

Figure 20. Distribution of Pantex groundwater samples, grouped by chloride and silicon concentrations (mg/L).