HYDROGEOLOGY OF A LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL SITE NEAR SHEFFIELD, ILLINOIS

By J. B. Foster, J. R. Erickson, and R. W. Healy

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WILLIAM P. CLARK, Secretary

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Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
4th floor
102 East Main Street
Urbana, IL 61801

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

Multiply inch-pound units	By	To obtain SI units
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4,047	square meter (m^2)
foot per second (ft/s)	18.29	meter per minute (m/min)
inch per year (in/yr)	25.40	millimeter per year (mm/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon	3.785	liter (L)
picocurie per liter (pCi/L)	0.0370	becquerel per liter (Bq/L)
nanocurie per liter (nCi/L)	37.00	becquerel per liter (Bq/L)
degree Fahrenheit (°F)	°C = 5/9 (°F-32)	degree Celsius (°C)

Geologic cross sections and maps with lines of equal altitude, and water-surface maps are referred to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). NGVD of 1929 is the geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

The Sheffield low-level radioactive-waste disposal site is located on 20 acres of rolling terrain 3 miles southwest of Sheffield, Illinois. The site covers parts of three small basins drained by three intermittent streams which empty into a tributary to Lawson Creek. Drainage divides for the basins also delineate the ground-water divides.

Precipitation that falls within the basins is the source of ground-water recharge. Precipitation averages 35 inches per year. Recharge to the saturated zone is estimated to be 2 inches per year. Runoff is estimated to be 9 inches per year and evapotranspiration 24 inches.

The shallow hydrogeologic system is composed of glacial sediments whose complex stratigraphy was defined from a study of continuous core samples from 58 test wells. A thick sequence of Pennsylvanian shale and mudstone bedrock isolates the regional ground-water aquifers below from the hydrogeologic system in the overlying glacial deposits. These deposits consist of the Glasford Formation, Roxana Silt, Peoria Loess, and Cahokia Alluvium. A continuous pebbly-sand deposit forms the most permeable unit, underlying 67 percent of the site. The pebbly sand extends across the middle of the site continuing offsite to the northeast and southwest. Two ground-water flow paths were identified. The primary path conveys ground water from the site to the east through the pebbly-sand unit; a secondary path conveys ground water to the south and east. Although the pebbly-sand unit provides the potential for rapid migration of radionuclides, it also minimizes water-level fluctuations and thus the risk of the water surface rising into the trenches.

Results of a digital computer model indicate that the areal extent of the pebbly-sand unit, hydraulic conductivity, and recharge rates are controlling factors in ground-water movement. The range in hydraulic conductivities for the various lithologic units in the hydrogeologic system prevented development of a predictive model for this site.

Tritium is the only radionuclide known to be migrating. In the southeast corner of the site, a migration rate of approximately 25 feet per year was calculated.

Water from 35 wells was analyzed for inorganic content. On the basis of the analytical results, water samples were divided into two groups. The larger group contained concentrations of inorganics typical of water found in glacial deposits in the area. The other group of samples had specific conductances, alkalinities, hardnesses, and chloride, sulfate, calcium, and magnesium concentrations which were higher than typically found in this area. The nontypical water samples also contained the highest tritium concentrations. High correlation coefficients were found between tritium and alkalinity (0.84), tritium and chloride (0.86), and tritium and silica (0.73). Moderate correlation coefficients were found between tritium and calcium (0.66), tritium and specific conductance (0.61), and tritium and hardness (0.60).

INTRODUCTION

The Illinois legislature passed the Illinois Radioactive Waste Act in 1963 which gave the Illinois Department of Public Health (IDPH) the authority to accept title to property for establishing a radioactive-waste disposal site. Under the authority of the Act, the IDPH drew up criteria in March 1965 for establishment of a site. Companies involved in radioactive-waste disposal were invited to propose possible sites. The California Nuclear Company (CNC) purchased 67 acres near Sheffield of which 20.5 acres were deeded to the State for waste burial. Site construction and waste burial began in August 1967. US Ecology Company (USEC) (formerly Nuclear Engineering Company) purchased CNC's interest in the disposal site in March 1968 and continued to bury waste until April 1978 (U.S. House of Representatives, 1978, p. 321).

In October 1981, all State responsibilities for supervision of the site were transferred to the newly formed Illinois Department of Nuclear Safety (IDNS).

This report describes the geology and hydrology of the Sheffield site and adjacent areas. The site is located on rolling terrain 3 miles southwest of the town of Sheffield, Bureau County, Illinois (fig. 1).

Purpose and Scope

The U.S. Geological Survey began a study of the hydrogeology of the Sheffield site in 1976. The purpose of the study was to determine how the glacial sediments, under existing hydrologic conditions, were functioning as containment for radionuclides. The scope of the study was to define geologic and hydrologic elements necessary to describe the hydrogeologic system. Geologic elements to be described were the stratigraphy, lithology, and mineralogy. Hydrologic elements included the hydraulic properties of the sediments and the rate and direction of water movement through both saturated and unsaturated zones within the glacial deposits. Hydrogeologic information from Sheffield and other radioactive-waste sites will be used to define the essential hydrogeologic factors necessary to quantitatively predict the concentration of radionuclides migrating in ground water from burial sites.

Acknowledgments

The authors wish to express their appreciation for the cooperation and technical support from the IDNS. We are particularly grateful to James Blackburn, David Ed, and Charles Tomlinson for the radiometric analyses of soil and water and for the health physics support in connection with tunnel construction during many long hours throughout the severe winter of 1979.

We received numerous suggestions, assistance, and technical support from a number of persons with the Illinois State Geological Survey. We would like to acknowledge Dr. Keros Cartwright, Thomas M. Johnson, Dr. Leon R. Follmer, Dr. Arthur White, and Dr. Herbert D. Glass.

The U.S. Nuclear Regulatory Commission has been most cooperative in supplying technical data and in providing funding for a part of the tunnel construction. Thanks are due to Gail Turi, who is now with the U.S. Department of Energy, and to Kitty Dragonette.

The project has received support in the form of organic and radiometric analyses of water from wells and trenches by Brookhaven National Laboratory. We wish to thank Pete Columbo, Alan J. Weiss, and A. J. Francis for their assistance in this regard.

REGIONAL SETTING

Geography

Bureau County comprises 871 square miles (mi^2) of which 4.7 mi^2 are occupied by surface-water bodies. In 1975, the county's population was 37,262 with 25,152 living in urban areas and 12,110 living on farms (U.S. Bureau of the Census, 1978).

The area near the site is sparsely populated with only 17 residences within a 2-mile radius. The closest town is Sheffield, with a population of 1,052. The unincorporated town of Mineral, population 286, is 5 miles northwest, and the town of Neponset, population 509, is 3 miles south. Bureau County population projections (Tec Search, Inc., 1969) indicate that the area surrounding the site will continue to be a sparsely populated agricultural area.

Most of the land adjoining the site is used for pasture including areas of unreclaimed land to the northeast, north, and west, that was strip mined for coal in the early 1950's. A chemical-waste burial facility is located adjacent to the northwest corner of the site separated from it by a 200-foot buffer zone.

Climate

Northwestern Illinois climate is continental, with warm summers and cold winters (State of Illinois, 1958). Long-term annual, monthly, and daily variations in precipitation and temperature are available from National Oceanic and Atmospheric Administration (NOAA) for the following stations: Kewanee, 10 miles south; Walnut, 19 miles north; and Tiskilwa, 14 miles east (NOAA, 1939-79). Evaporation data are available at Hennepin powerplant weather station, located on the Illinois River near Hennepin, 24 miles east of the site. A recording rain gage was operated at the site during the period of study.

Annual precipitation at these weather stations has reached minima of 25.43 to 29.84 inches and maxima of 45.07 to 52.37 inches, with wet years occurring at intervals of about 5 years. Average annual precipitation at the site is 35 inches based on averages of records from Kewanee, Walnut, and Tiskilwa weather stations. The distribution of precipitation during the year is characterized by a dry period, a wet period, and a moderate period. The dry period is from November through March, averaging 1.94 inches monthly. February, the driest month, averages 1.39 inches. April through July is the wet period, averaging 4.20 inches monthly. June is the wettest month, averaging 4.55 inches. The moderate period extends from August through October, averaging 3.18 inches.

The lowest monthly precipitation recorded at Kewanee was 0.06 inch in October 1964, and the highest was 13.44 inches in July 1969. Daily precipitation records show a minimum of 0.01 inch and a maximum of 5.41 inches. Figure 2 shows monthly and annual precipitation at Kewanee from 1969 through 1979, illustrating the seasonal nature of the precipitation.

The mean annual temperature at Kewanee is 50.5°F. The lowest recorded temperature was -21°F in January 1977, and the highest was 103°F in August 1953. Temperatures are commonly below freezing from December through February with normal temperatures ranging from 23.1°F in January to 27.4°F in December. The average monthly temperature for January ranged from 7.2°F in 1977 to 29.7°F in 1964. The ground is generally frozen from December through February. July is the warmest month of the year with mean monthly temperatures ranging from 71.1°F in 1979 to 80.0°F in 1955.

NOAA evaporation maps (Kohler and others, 1959) show 43 inches of annual pan evaporation in the Sheffield area. Evaporation is measured from April through September. Evaporation is highest in June and July, and lowest in April and September. Pan evaporation data for April through September are available for the period 1976 to 1978 at the Hennepin powerplant (table 1).

Table 1.--Monthly pan evaporation in inches of water at Hennepin powerplant 24 miles east of the Sheffield site

Month	1976	1977	1978
April	6.16	--	--
May	6.22	8.86	6.07
June	9.81	8.94	8.71
July	10.18	--	6.36
August	7.89	4.64	6.38
September	6.78	4.38	--

The monthly potential evapotranspiration was computed for the site (table 2) using the Blaney-Criddle equation (U.S. Soil Conservation Service, 1970):

$$E_t = (0.142\ T_a + 1.095) \times (T_a + 17.8) \times K \times d \times (0.3937)$$

where E_t is potential evapotranspiration; T_a is average air temperature (when T_a is less than 3°C, the first term in parentheses is set equal to 1.38); K is monthly consumptive-use coefficient for pasture grass; and d is the percentage of daytime hours of the year occurring during a given month. Average monthly temperature values from the Kewanee weather station were used in the computation. Potential evapotranspiration ranged from a low of 0.7 inch in November to a high of 6.9 inches in July. Annual potential evapotranspiration is 33.1 inches. The actual evapotranspiration is estimated to be 24 inches which was determined by subtracting estimated runoff and estimated infiltration from annual precipitation.

Table 2.--Average monthly potential evapotranspiration in inches of water at the Sheffield site

Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1.1	2.2	4.2	6.1	6.9	6.0	3.8	2.1	0.7

Surface Water

The Sheffield site is in the headwater tributaries of Lawson Creek, which at its nearest point is 1 mile east of the site with a drainage area at its mouth of 6.14 mi^2. Water in Lawson Creek flows to the Mississippi River by way of Abbot Ditch, Coal Creek, Mud Creek, Green River, and Rock River, a total of 55.5 river miles. Three small intermittent streams drain the Sheffield site (fig. 3). Two streams drain the south half, entering the tributary just southeast of the site. The third stream drains the north half of the site, entering the tributary about 2,000 feet east of the site. The drop in altitude from the site to Lawson Creek precludes the possibility of backwater from a flood inundating the site.

Ground Water

Ground water in northwestern Illinois is contained in sediments and rocks of Cambrian, Ordovician, Silurian, Pennsylvanian, and Pleistocene age. Four hundred and fifty feet of Pennsylvanian shale and coal measures provide a relatively impermeable barrier between the water in the glacial sediments at the Sheffield site and deeper bedrock aquifers. Most recharge to the deep aquifers occurs in an area that extends from northern Bureau County into northern Wisconsin, an area where the thick sequence of Pennsylvanian shale is missing. Some water also enters the deep aquifers in and south of Bureau County where the water table is higher than hydrostatic head in the underlying aquifers (Foley and Smith, 1954).

The direction of flow in the bedrock aquifers is generally to the south toward principal streams such as the Illinois River. Development of centers of major pumping have altered the direction of flow in some areas of the region, such as Rockford and Chicago. However, these pumping areas have not affected the direction of flow near the site.

The four largest towns within a 10-mile radius of the site (Kewanee, Neponset, Annawan, and Buda) each withdrew less than 1 million gallons of water per day from either the Cambrian-Ordovician or the Silurian aquifer in 1978 (Visocky and others, 1978).

SHEFFIELD SITE

Construction Methods and Trench Design

A cut-and-fill process was used to construct trenches ranging from 35 to 580 feet long, 8 to 70 feet wide, and 8 to 26 feet deep. The trench depth was limited by an IDNS requirement to leave at least 10 feet between the base of the trench and the top of the saturated zone. By late 1976, all available space had been used in which trenches could be excavated in natural soil, leaving 10 feet of unsaturated soil beneath the trench floor. Trenches 14 and 14A (fig. 3) were constructed later. To meet the IDNS requirement these trenches were built partly above the existing land surface at the head of the intermittent stream on the west side of the site. Trench walls were built by importing silty-clay fill and compacting the material layer upon layer.

A typical trench has sloped walls, a lengthwise sloping floor with a 2-foot by 2-foot rock filled French drain connected to a sump on the low end of the trench. A sump pipe extends from the bottom of the sump to the surface to provide access for monitoring and removing any leachate that may collect in the sump. The trenches were covered with a layer of silty-clay that has been capped by a mound of clayey-silt to silt. The cap supports a stand of brome grass as a ground cover (fig. 4).

Erosion

Runoff from precipitation forms rills and gullies in the drainageways between trenches and on the slopes steepened from building up trench walls. Mounded trench caps concentrate runoff into the small drainageways between caps. The channeling of water has resulted in deeply incised gullies.

One such gully has formed where water flows east down the steep slope between trenches 24 and 25C (fig. 3) forming a gully near the east end that on occasion reaches a width and depth of 4 feet. Other deep gullies have developed along the west end of trenches 4, 8B, and 24; below the southeast corner of trench 14; and along the south side of trench 11. These gullies have exceeded 7 feet in width and 10 feet in depth. The gully on the west end of trenches 4, 8B, and 24 has been eliminated by installation of a culvert to carry runoff from the hilltop into the northern valley. Erosion near the southeast corner of trench 14 has been remedied by routing flow into the valley over a matting installed to prevent erosion. Other smaller inter-trench-cap gullies could be avoided by restoring the surface to a more gentle slope that would allow for sheet flow over the trench surfaces and thus eliminate concentration of flow in narrow channels between caps.

Trench Structural Integrity

Precipitation falling on the open trenches moistened the trench walls thus lowering the cohesive strength of the silt layers exposed in the walls, resulting in occasional slumps. One such slump formed in the wall of trench 14 following construction and while the trench was being filled with waste.

Holes also occasionally form in trench caps when voids develop below the cap, resulting in a collapse of overlying cap material into the void. A number of holes were discovered when the snow melted in March 1979 (fig. 5). Collapse holes, varying in size from 2 to 12 feet across and 4 to 10 feet deep, formed in the caps of trenches 7, 14A, 23, 24, and 25C. Collapse holes are repaired by filling the holes with silty-clay soil and compacting the soil by running heavy equipment over the fill (Kahle and Rowlands, 1981).

Composition of Buried Waste

Records that describe physical form of the buried waste, the concentrations of specific radionuclides, and the location in trenches of specific types of shipping containers are not available. A general description of content and distribution of waste in a trench can be inferred from information on shipping papers which give the origin of the waste. Also, some records are available for dates when various parts of a trench were filled which can be compared with dates on shipping papers to determine, in general, the location of certain types of waste in a trench. Common types of radioactive waste are solidified scintillation liquids, protective clothing, tools, decontamination solutions, ion-exchange resins, general trash, experimental animal carcasses, contaminated and activated metals, glassware, and laboratory supplies from hospitals.

A total of 3,196,017 cubic feet of waste was buried. Included were 60,205 curies of byproduct material, 13,588 grams of plutonium-239, 1.7 grams of uranium-233, 40,764 grams of uranium-235, and 270,845 kilograms of source material (IDNS, written commun., 1979). A study of the origin of wastes delivered to the Sheffield site from January to June 1977 indicates that 89.7 percent of the waste was generated by nuclear fuel cycle facilities, 0.5 percent by academic institutions, 0.5 percent by medical uses, and 9.3 percent by industry (Kitty Dragonette, written commun., 1979).

The State of Illinois has limited the burial of low-level waste to solids and containerized gases at no more than one atmosphere of pressure whose concentration cannot exceed 1 curie per cubic foot. All free liquids were required to be either immobilized or solidified before disposal.

Waste material was buried in cardboard boxes, wooden boxes, steel barrels, large steel boxes, and concrete containers. Most waste was randomly piled in the trench, with the exception of large wooden boxes, concrete containers, and steel boxes which were stacked. After the trench was excavated, it was filled with waste starting from one end and covered with soil as successive segments of the trench were filled with waste. Burial progressed until the entire trench was filled and covered. Waste containing higher concentrations of radioactivity was placed next to the trench walls and covered immediately.

DRILLING AND SUBSURFACE EXPLORATION

Drilling and Sampling Methods

A total of 282 test holes were drilled on and adjacent to the site between April 1967 and December 1979. Of the 282 test holes, 151 were completed as observation wells. Two hundred and twenty-three test holes were drilled by consulting firms employed by CNC and USEC, and 58 wells and one boring were drilled as a part of this study. Some of the test hole locations are shown in figure 6. Test holes were drilled by auger, mud rotary, cable tool, or air rotary.

Core samples were collected in 52 of the 59 test holes drilled for the Geological Survey using 3-inch by 36-inch thin-walled tubes. A 2-foot-long split spoon was used to sample coarser sediments. Cores were obtained either by pushing a thin-walled tube 36 inches, withdrawing it, cleaning and reaming the 3-foot sampled interval with a drill bit or auger to 4-inches in diameter, and then pushing another tube; or by driving a split spoon 24 inches, removing the spoon and cleaning and reaming a 3-foot section before driving the next spoon. Thus, either 36 or 24 inches of sample was collected every 3 feet, depending on the type of material.

Wells 501 through 524 were augered in August and September 1976. After core samples had been collected to the maximum depth of the hole, each well bore was reamed to a 9-inch diameter to the base of the most permeable sediment or sediments as determined from the core samples. Five-inch diameter casing with a 4-foot length of stainless-steel screen attached to the bottom was set in the hole. Sand was packed around the screen and bentonite placed on top as a seal. The remainder of the annulus above the bentonite plug was filled with an expansion-compensating cement grout composed of chem-comp cement mixed with 2 percent by weight of bentonite, 20 percent by weight of fly ash, and 6 gallons of water per bag of cement. Twelve wells (wells 525-533, 535-537) were augered in May and June 1977, and seven wells (534, 540-542, 548, 549, 551) were augered in October 1978. Due to caving of sediments below the water table, problems had been experienced in setting screens in augered holes and in isolating the vertical section of the hole in which the screen is set. Consequently, the last group of 15 wells (538, 539, 543-547, 550, 552-557, and 559), drilled in the fall of 1979, were drilled using a mud-rotary rig. In the holes drilled by a mud-rotary rig, the casing was set as soon as drilling had reached a preselected depth or lithologic unit, and the annulus was grouted through a grout shoe. Sampling continued below the casing to bedrock, after which the open hole was backfilled with grout leaving a 2-foot open section below the casing in which a stainless-steel screen was installed.

Borehole Geophysical Logging

Geophysical logs, including natural gamma, gamma spectral, and neutron, were made of all USGS wells and a few USEC wells. Natural-gamma logs record the amount of gamma radiation emitted by geologic materials surrounding the well bore. Naturally occurring radioisotopes are generally contained in clay minerals, and thus the natural-gamma log is useful for identifying lithologic units. Anomalously high levels of gamma radiation adjacent to the borehole could indicate migration.

A gamma-spectral log provides a means of determining the specific radioisotopes present in the soil or water adjacent to a well bore. Gamma energies which are specific for each nuclide are converted by the down-hole sonde to electrical energy in megaelectron volts. The specific voltages are separated by a multichannel analyzer and recorded on magnetic tape as well as being displayed on a cathode-ray tube.

Three or four depths were selected from the natural-gamma log of each well for obtaining gamma-spectral data. The gamma-spectral data were obtained to determine if any radioisotopes other than naturally occurring were present in the soil or water. Laboratory analyses were made to determine concentrations of the naturally occurring isotopes uranium-238, potassium-40, and thorium-232 of soil cores taken at depths corresponding to the spectral data collection points. A computer program was used to subtract the natural-gamma spectra determined in the laboratory from the spectra obtained in the bore hole. The residual energies, if any, are the contaminant isotopes.

Gamma-spectral logs were made in wells 501 through 537. The only artificial radioisotope detected was cobalt-60 at a depth of 10.5 feet in well 507. It was later determined that the end of trench 11 had been incorrectly marked and that well 507 was actually located adjacent to a ramp on the northwest corner of the trench. The well is close enough to the buried waste that the spectral sonde was able to detect the presence of cobalt-60.

Neutron logs were made of USGS wells to determine the relative moisture content of the material in the unsaturated zone. The neutron logs, in conjunction with the natural-gamma logs and core samples, were particularly helpful in determining the contacts between the coarser grained sediments and finer grained sediments, because the latter generally had much higher moisture content.

Tunnel

As a means of obtaining data in the unsaturated zone and to evaluate the geologic and hydrologic elements related to migration, a horizontal tunnel was excavated beneath waste trenches 11, 3, 2, and 1 (fig. 3). The tunnel is 290 feet long and 6.5 feet in diameter with 8-gauge steel liner plates for wall support.

An area was excavated to the south of trench 11 to provide a working space for the tunnel construction operation. The excavation provided space to bring soil from the tunnel in a muck car, dump it in a pile, and then transport it by end loader and deposit it along the slope near the west end of trench 11 without having to carry soil outside of the 20-acre licensed waste site. The horizontal tunnel is alined north and south; its floor has an altitude of 740 feet.

There were no records of surveys establishing either the horizontal or vertical boundaries of the trenches. However, the floor of trench 11 was determined to be at an altitude of 752 feet based on seismic and earth resistivity surveys and a natural-gamma log made of the sump pipe on the east end of the trench. With the roof of the tunnel at an altitude of 746.5 feet, there was about 5.5 feet of soil to absorb radiation between the roof of the tunnel and the floor of trench 11. Trenches 3, 2, and 1 were higher on the hillside. Based on the reported depths of these trenches, there should be an even greater thickness of soil between the roof of the tunnel and the floor of these trenches.

Each evening soil samples were collected with an auger ahead of the next day's tunneling and analyzed for radionuclides to protect the crew from exposure to highly contaminated soil. Also, it was necessary to determine radiation levels to know if some soil would require special handling. Each 1-foot sample was split into two parts. Personnel from IDNS analyzed one part for gamma radiation on a gamma spectrophotometer in their mobile laboratory on site. Soil water was extracted from the other sample, and the tritium concentration in the water was determined. Tritium was the only radioisotope detected in soil or water during tunnel construction.

Tunneling was done with air spades. The hole was advanced by alternately excavating a 2-foot long by 6.5-foot diameter space and lining the hole by bolting a set of six full liner plates and one half plate together to form a ring. Each succeeding ring is bolted to the preceding ring.

The tunnel was excavated in a clay till for a distance of 178 feet from the entrance. At 178 feet, a pebbly sand was encountered in the roof of the tunnel. The till-sand contact dipped to the north in the direction of the excavation. At 192 feet, the till disappeared below the tunnel floor. From this point to the end of the tunnel at 290 feet, the excavation was in pebbly sand which, because of its caving nature, made construction difficult. Tunnel construction took from November 29, 1978, until March 8, 1979.

GEOLOGY

The Sheffield low-level radioactive-waste disposal site is in an area of rolling terrain. Pennsylvanian shale is overlain by unconsolidated Pleistocene glacial sediments. The shale is about 450 feet thick. Glacial sediments range from 10 to 90 feet thick and average about 55 feet (fig. 7).

The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey (ISGS) and does not necessarily follow the usage of the U.S. Geological Survey. The glacial sediments revealed by test well and tunnel sediment samples were correlated by texture and mineralogy with units in the rock-stratigraphic classification system of the ISGS (Willman and Frye, 1970, p. 12). Figure 8 shows the ISGS time-stratigraphic and rock-stratigraphic classifications. Each lithologic unit was characterized on the basis of the percentage composition of sand, silt, and clay by plotting grain-size percentages on the trilinear classification diagram developed by Shepard (1954) (fig. 9).

Pennsylvanian System

Immediately below the glacial deposits is a part of the Carbondale Formation of the Desmoinesian Series. Rock samples from test hole B-2 (fig. 6) drilled by California Nuclear Company show the Pennsylvanian rocks to be predominantly fossiliferous shales and mudstones (H. W. Smith, 1966, sample description well B-2, unpublished data on file in office of Illinois State Geological Survey). Samples of weathered shale ranged from a silty clay to a clayey silt. The bedrock topography (fig. 10) generally follows the present surface topography. Silurian and Ordovician limestones and dolomites and Cambrian sandstone underlie the Pennsylvanian rocks (Willman and others, 1975, p. 36, 47, 87, and 169).

Quaternary System

Pleistocene Deposits

Duncan Mills Member of the Glasford Formation

The oldest Pleistocene sediments at the Sheffield site are a thick sequence of lacustrine-rhythmite sediments of the Duncan Mills Member of the Glasford Formation. This deposit is found largely overlying the bedrock in the northern valley (fig. 10). The Duncan Mills Member is seen in several geologic sections (figs. 12, 13, 14, and 15; lines of section are on fig. 11). The Duncan Mills Member is found below the Hulick Till as seen in figures 12, 13, 14, and 15. The Duncan Mills Member consists of silty clay interbedded with silt, clayey silt, and a few pebbly, sandy silt layers. The lower part of the deposit consists of clayey silt beds from 1 to 18 inches thick, with interbedded coarse pebbly layers. The upper part consists of finely laminated silts and silty clays.

The Duncan Mills Member thickens toward the northeast, where the bedrock valley deepens, reaching a thickness of 55 feet in well 518. The top of the deposit is at an altitude of 731 feet on the hilltop near well 508.

Hulick Till Member of the Glasford Formation

The next oldest unit is the Hulick Till Member of the Glasford Formation (figs. 12-18). The grain-size distribution of the Hulick Till Member is predominantly a sand-silt-clay. Sand in the Hulick Till Member ranges from 16 to 33 percent, while the predominant clay mineral is illite (usually 56 to 65 percent).

Decreased illite and sand content within the Hulick Till Member, in some areas, have been attributed to the glacier incorporating the lacustrine sediments of the Duncan Mills Member into the till (W. H. Johnson, University of Illinois, written commun., 1979). Another compositional variation in the Hulick is seen in the higher illite content of samples from wells 509 (75 percent) and 510 (74 percent), probably representing a zone in the till containing a higher percentage of shale bedrock. Numerous silt, sand, and silty sand lenses in the Hulick Till Member were exposed during construction of the tunnel.

Most of the site is underlain by Hulick Till Member except for a few small isolated areas. The thickness in cores ranged from 0.25 to 16.5 feet and averaged 6.5 feet.

Toulon Member of the Glasford Formation

A channel-like outwash deposit of the Toulon Member of the Glasford Formation underlies 67 percent of the site. The outwash sediments grade from a well-sorted pebbly sand in the eastern half of the site into a moderately sorted pebbly-silty sand to the west. The pebbly-sand unit is a few feet to 20 feet in thickness (fig. 19), averaging 15 feet. The pebbly sand is apparently absent in the northwest and southeast areas of the site.

A structure contour map (fig. 20) of the pebbly-sand unit shows it dipping from near the southwest corner northeast across the site. The pebbly sand probably covered all or most of the site up to an altitude of at least 761 feet at one time. The present upper surface of the pebbly sand developed during an erosional period prior to the deposition of the younger glacial deposits overyling the unit.

The lacustrine deposit of the Duncan Mills Member was used as a marker bed to establish the base of pebbly sand on the west side of the site and in correlating the pebbly-sand unit across the site. The pebbly sand is overlain by a fossiliferous lacustrine deposit, Toulon Member, on the west side of the site and by Radnor Till Member on the east side (figs. 15-17). The absence of the Toulon Member (lacustrine deposit) and Radnor Till Member near the northeast corner makes it difficult to ascertain if the pebbly-sand outwash here was deposited contemporaneously with the outwash on the southern half of the site, although the deposits appear to be continuous.

The lacustrine deposit of the Toulon Member consists of silt, clayey silt, sand-silt-clay, sandy silt, and marl. The deposit covers most of the southwest quarter of the site and ranges in thickness from 2 to 6 feet. Highly fossiliferous material was encountered in wells 509, 511, 522, and 532 and nonfossiliferous material was encountered in wells 508, 529, and 531.

Radnor Till Member of the Glasford Formation

The Radnor Till Member of the Glasford Formation consists of clayey silt and sand-silt-clay, ranging in thickness from a few feet to almost 20 feet (fig. 18). It is distinguished from the Hulick Till Member by differences in sand content and clay mineralogy. Sand content of the Radnor ranges from 6 to 46 percent, while the clay minerals are 72 to 76 percent illite. It also contains a few sand and silt lenses. The till is present only in the southern half of the site (figs. 14-18) except for an isolated mound encountered in the excavation of trench 18. The Radnor was used as a key marker bed in correlating the pebbly-sand unit of the Toulon Member.

Berry Clay Member of the Glasford Formation

The Berry Clay Member of the Glasford Formation is an accretion-gley deposit, typical of the intrazonal soil profile of the Sangamon Soil (Willman and Frye, 1970, p. 85-86). A gley soil develops in an environment of poor drainage. The condition results in the presence of reduced iron and other elements and in gray colors and mottles in the soil. There was an extended erosional period after the retreat of the Illinoian glaciers during which time the Sangamon Soil was developed. The Sangamon Soil occurs as two distinct pedologic soil types in two upland areas of the site. One soil, developed by weathering of the Radnor Till Member, is present near the southeast corner (wells 503, 504, and 505) and the other, in the Berry Clay Member, is present in the west central and southwest corner of the site (wells 509, 510, 511, 522, and 532). In cores from test wells, the Sangamon Soil ranged in thickness from 1.3 to 11.8 feet.

Roxana Silt and Peoria Loess

During the Wisconsinan Stage, ice did not cover the Sheffield site, but aeolian silts and sands were deposited on the site. The silts originated from lake deposits along the Mississippi River (Willman and Frye, 1970, p. 36) and the sands from nearby outwash deposits.

Lower Wisconsinan aeolian silts are assigned to the Roxana Silt. The Roxana Silt is largely loess, but it contains layers of clayey silt and sand-silt-clay. Two deposits of Roxana Silt are present at the site. One deposit was penetrated by wells 503, 504, and 505, and the other penetrated by wells 510, 511, 530, and 532. The thickness of Roxana Silt in cores ranged from 1.3 to 7.2 feet.

Middle to upper Wisconsinan aeolian silts are assigned to the Peoria Loess. The Peoria Loess covers the entire site, ranging in thickness from 2 to 30 feet, with the thicker accumulations found near the north and west boundaries.

Cahokia Alluvium

Two feet of sandy silt of the Cahokia Alluvium was penetrated near the northeast corner of the site in well 518.

Modern Soil

The present soil cover is developed in the upper part of the Peoria Loess and assigned to the Modern Soil (Willman and Frye, 1970, p. 89). This soil is predominantly clayey silt and, where present, ranges in thickness from 2 to 9 feet. In many areas of the site, the soil has been either removed or covered by fill.

Fill

Fill is the youngest deposit on the site. It consists of clayey silt to silt and has been used to build trench caps and to raise the land surface in low areas. Fill encountered in cores from wells ranged in thickness from 2.0 to 23.3 feet.

HYDROGEOLOGIC SYSTEM

The drainage divides of three small drainage basins form natural hydrologic boundaries for the site (fig. 3). Ground-water divides correspond with the topographic drainage divides. The site hydrogeologic system includes the glacial sediments extending from land surface to the bedrock surface (fig. 21). The approximately 450 feet of shale underlying the glacial deposits form a relatively impermeable barrier, hydaulically isolating the shallow ground water from the deeper regional ground-water aquifers. Precipitation is the source of water for the system as there is no underflow of ground water from adjacent areas except for flow from the divide just west of the site.

Unsaturated Zone

The unsaturated zone extends from land surface to the top of capillary fringe. It includes those sediments with moisture filling less than 100 percent of the porosity. On site the thickness of the unsaturated zone ranges from 5 feet in the valleys to 55 feet on the hilltops and averages 40 feet.

Lithologic Units

All lithologic units present on site are either partly or completely unsaturated except for the silt and silty clay of the Duncan Mills Member and the Pennsylvanian shale, both of which are entirely saturated across the site. Moisture content and hydaulic conductivity in the unsaturated zone are functions of soil suction and soil texture. As soil suction increases (figs. 22 and 23), moisture content and hydraulic conductivity of a soil decrease. At suction values greater than about 24 inches, the silts and sand-silt-clay are more conductive than the sand. As the moisture content of the sand approaches saturation, the soil suction drops below 24 inches and the sand becomes more conductive than the finer grained sediments.

The glacial sediments represented in the unsaturated zone include a wide range in texture. The coarsest material, the pebbly sand, averages 79 percent sand, 14 percent silt, and 7 percent clay. The silt of the Peoria Loess averages 3 percent sand, 82 percent silt, and 15 percent clay. The grain-size distribution of the loess is intermediate between the pebbly sand and sand-silt-clay of the Hulick Till Member. Samples of sand-silt-clay average 24 percent sand, 45 percent silt, and 31 percent clay.

Water Movement

Water that moves through the soil into the underlying sediments will normally move vertically downward to the zone of saturation and then laterally in a permeable bed in the direction of ground-water flow. The Peoria Loess has fairly uniform texture so water would be expected to move vertically downward. However, at an interface between the silt and a coarser sediment (sand) or finer sediment (silty clay) water may move laterally.

Miller and Burger (1963) determined that at the interface between coarse grained and fine grained sediments soil suction is nearly the same in both units. Figure 22 shows that the moisture content of the sand is 0.18 cm^3/cm^3 less than that of Hulick Till at a soil suction of 25 inches. At this soil suction the hydraulic conductivity of the sand is much less than the adjacent finer grained sediments (fig. 23) so the sand would impede the downward flow of water, possibly making it easier for water to move around the sand than through it. The sloping interface between the sand and overlying silt (fig. 24) also favors the movement of water by unsaturated flow through the silt rather than the sand. Similar phenomena of coarse sediments impeding the vertical movement of water through layered soils have been reported by Miller (1963), Frind, Gillham, and Pickens (1976), Clothier, Scatter, and Kerr (1977), and Hillel and Talpaz (1977). Two types of field data support the contention that in some instances the sand unit acts as a barrier to water movement in the unsaturated zone. Neutron logs of wells 502 and 508 show the pebbly-sand unit to be much drier than the finer grained sediments (figs. 25 and 26). Pebbly sand encountered during construction of the tunnel was so dry that it would not stand up in the working face.

Tritium was found in soil moisture extracted from the pebbly sand during tunnel construction (IDNS, written commun., 1978-79) indicating that water does move through the sand. For moisture to enter the sand the overlying sediments must reach or approach saturation. Once moisture nearly saturates the sand, high hydraulic conductivity causes the moisture to move through the sand rather rapidly. At the interface with the underlying sand-silt-clay the water moves laterally above the interface to where the sand unit is saturated. Some moisture, however, enters the sand-silt-clay below the sand as shown by the presence of tritium in moisture extracted from sand-silt-clay samples collected during tunnel construction.

French drains are situated in the unsaturated zone in the bottom of trenches. The purpose of the drains is to transport any leachate accumulating in the trenches to the sumps where it can be removed through the sump pipes. The only records of sumps containing water are trench 18, constructed below the water table, and trenches in which runoff entered through collapse holes in the trench caps in March 1979. An explanation for the reason that water is not normally found in sumps can be explained on the basis of unsaturated flow hydraulics. The difference between the textures of soil (silt and silty clay) surrounding the drains and the coarse rock filling the drains is the reason that water does not enter the drains under unsaturated flow conditions; at low moisture contents, the hydraulic conductivity of the fine grained sediments surrounding the drains is greater than that of the coarse rock in the drains. Hence, under unsaturated conditions the French drains would not be expected to accumulate leachate from the trenches.

Saturated Zone

The saturated zone, which includes glacial sediments lying between the water surface and bedrock, ranges in thickness from 5 feet in the valleys to 35 feet on the hills, and averages 20 feet. Sediments in the saturated zone include a wide range of compositions based on percentages of sand, silt, and clay. Most units are low permeability sediments with the exception of the pebbly-sand unit.

The saturated zone extends across the following lithologic units: silt (Duncan Mills Member); sand-silt-clay (Hulick Till Member); pebbly sand (Toulon Member); pebbly silt (Toulon Member); silt (Toulon Member); and silt (Peoria Loess). The horizontal hydraulic conductivity of these sediments ranges from 1.8×10^{-3} to 1.2×10^{-9} ft/s, and the vertical hydraulic conductivity ranges from 2.4×10^{-5} to 2.7×10^{-9} ft/s (table 3). Figure 27 shows the glacial deposits that intersected the water table on February 28, 1978. The change in both vertical and horizontal hydraulic conductivity from unit to unit makes it difficult to map the distribution of recharge and lateral flow.

The pebbly-sand unit of the Toulon Member underlies 14 acres of the 20-acre site. Under the hydraulic conditions of February 28, 1978 (fig. 28), 10 acres were partially to completely saturated and the remaining 4 acres were

Table 3.--Hydraulic conductivities of the glacial sediments at the Sheffield site as determined by laboratory and field tests computed by various methods

[All values are in feet per second]

Lithology (stratigraphic unit)	Laboratory Constant head method (average values)		Bailer tests on selected wells Methods described by Skibitzki, 1958, and Bouwer and Rice, 1976			Aquifer test on well 516 Computed by various methods from data collected at wells 516 and 556	
	Vertical	Horizontal	Well	Skibitzki	Bouwer and Rice	Well 516 (pumped well)	Well 556 (observation well)
Silt (Peoria Loess)	$3.6X10^{-7}$	$2.9X10^{-7}$	520	$7.4X10^{-7}$	4.5X10-7	--	--
Clayey silt (Modern Soil)	$2.7X10^{-9}$	$6.2X10^{-8}$	--	--	--	--	--
Pebbly clayey silt (Hulick Till[1])	$4.8X10^{-8}$	$1.8X10^{-8}$	--	--	--	--	--
Clayey silt with silt and clay (Duncan Mills Member, lacustrine rhythmites)	$2.2X10^{-8}$	--	--	--	--	--	--
Clay (weathered shale)	$2.1X10^{-9}$	$1.2X10^{-9}$	--	--	--	--	--
Pebbly sand (Toulon Member[1])	--	--	502	$7.3X10^{-6}$	$2.8X10^{-6}$	--	--
Silty sand (Toulon Member[1])	--	--	511	$7.9X10^{-6}$	$1.1X10^{-5}$	--	--
			530	$1.1X10^{-5}$	$1.0X10^{-5}$	--	--
Sand (Toulon Member[1])	repacked	$8.2X10^{-5}$	--	--	--	--	--
Pebbly sand (Toulon Member[1])	--	--	--	--	--	$9.8X10^{-5}$	$4.4X10^{-4}$
						$2.2X10^{-4}$	$1.8X10^{-3}$
						$6.7X10^{-5}$	--
						$4.0X10^{-5}$	--
Pebbly silty sand (Toulon Member[1])	repacked	$5.7X10^{-5}$	522	$1.8X10^{-6}$	$7.5X10^{-7}$	--	--

[1] of the Glasford Formation

unsaturated. Where the pebbly sand is fully saturated, water is confined under artesian pressure by either Peoria Loess, Toulon marl, or Toulon clayey silt. A water table is present where the pebbly sand is not fully saturated.

The hydraulic conductivity of the pebbly-sand unit varies across the site, ranging from 1.8×10^{-3} to 7.5×10^{-7} ft/s. The range in hydraulic conductivity is associated with the changes from a clean well-sorted sand on the east side of the site to a moderately sorted silty sand on the west. Table 3 gives the results of bailer tests, pumping tests, and laboratory tests from which hydraulic conductivities were computed. The highest value for hydraulic conductivity was obtained from an aquifer test on well 516. The screen in well 516 is 4 feet long and, therefore, only partially penetrates the 6.4 feet of pebbly sand found in this well. Hence, the hydraulic conductivity of 1.8×10^{-3} ft/s may be low due to the anisotropy of the pebbly sand. Observation well 556 used in this test had 2 feet of screen open in the sand and was 11 feet from the pumped well.

Silt of the Peoria Loess is unsaturated over most of the site. However, in some places it extends into the saturated zone as much as 12 feet. The horizontal hydraulic conductivity of the silt averages 2.9×10^{-7} ft/s, and the vertical hydraulic conductivity averages 3.6×10^{-7} ft/s.

Silt and silty clay (Duncan Mills Member) overlie the bedrock in the northern valley and are fully saturated. The vertical hydraulic conductivity of the unit is 2.2×10^{-8} ft/s.

Sand-silt-clay of the Hulick Till Member act as semi-impermeable beds that restrict the flow of water in the saturated zone. The sand-silt-clay overlies the shale bedrock beneath 65 percent of the site; in the northern valley it overlies the lacustrine silt and silty clay. The sand-silt-clay is overlain by the pebbly sand over much of the site. Water does move down through the sand-silt-clay as evidenced by the tritium concentrations in moisture extracted from core samples during construction of the tunnel. From observations in the tunnel, soil water reaches field capacity at the interface between the pebbly sand and sand-silt-clay and flows laterally through the sand along the interface.

Hydrology

Water Surface

Water-level measurements at 113 wells located on and in areas adjacent to the site were obtained four times over periods of a few days each from 1977 to 1980. The shape of the water surface generally corresponds to the land surface configuration. The water is confined in some areas and unconfined in others; thus, the water surface maps portray combined artesian and water-table conditions. Figure 28 shows the water surface for February 1978, a period of slightly below average water levels, and figure 29, a period of high water levels in June 1979.

Direction of Flow

Ground water generally flows perpendicular to the equipotential lines (fig. 30) that represent the altitude of the water surface. Ground water moves from beneath the hill areas toward the valleys to the north and south as depicted by the arrows. As the ground water approaches the axis of the valley the direction of flow changes to the east. Flow lines W-W', X-X', Y-Y', and Z-Z' (fig. 30) represent lines of convergence of ground-water flow into the valleys from adjacent hills. Ground-water flow from beneath the waste trenches is generally to the east. Ground water that flows northward from beneath the two hills within the site approaches flow line W-W' where it turns to the east and flows along or parallel to the line. Line Z-Z' forms a similar flow line on the south side of the site. Any leachate migration in ground water could be intercepted by monitor wells located along the east side of the site between these two flow lines.

Recharge--Discharge

Precipitation that falls on and immediately west of the site is the source of recharge to the saturated zone. Moisture that infiltrates the surficial materials and underflow from the area adjacent to the west edge of the site provide all of the water moving through the shallow ground-water system. Recharge is estimated to be between 1 and 2 inches per year. The amount of recharge varies across the site depending upon vegetative cover, texture of surficial materials, and surface slope. Time variations in recharge may be affected by the season of year that precipitation occurs and other factors, such as intensity and duration of rainfall as well as total precipitation.

Lateral movement of water in the unsaturated zone along the contact between the pebbly sand and sand-silt-clay results in reduced recharge to the saturated zone beneath the hills which is reflected in unusually low water levels. The depth to water beneath the hills is greater than in glacial terrain with similar topographic relief in other areas of the State (Keros Cartwright, oral commun., 1979).

Discharge of ground water on site is through transpiration by trees and bushes located in the north and south valleys. Surface discharge from the saturated zone is to the strip-mine lake 700 feet northeast of the site and to the tributary to Lawson Creek where ground water intercepts the streambed 2,400 feet east of the site near the east end of the lake.

Water-Level Fluctuations

Periodic water-level measurements for 30 wells and continuous water-level record for 10 wells were obtained during the study. The depth to water ranges from 5 to 55 feet, with depths in the trench areas ranging from 30 to 55 feet.

Water levels were measured from October 1976 to January 1980, a period when the net total precipitation was below normal. However, water levels in wells either showed little change or had a net increase. Water levels generally rise during the spring after the ground thaws and decline in the summer and early fall (fig. 31).

The fluctuation of water levels in all wells ranged from 0.97 foot in well 501 to 10.97 feet in well 524 (fig. 32). The difference between the lowest and highest water-level measurements for a well depends in part on the lithology of the screened section of the well. The smallest and greatest fluctuation in water levels in wells screened in different lithologic units and under different hydraulic conditions are as follows: (1) fine grained sediments, 4.41 and 10.97 feet; (2) fine to coarse grained sediments, 2.10 and 3.57 feet; (3) coarse grained sediments with a free-water surface, 1.34 and 3.16 feet; and (4) coarse grained sediments with a confined water surface, 3.32 and 4.73 feet (table 4). The pebbly-sand unit provides an underdrain to move water from beneath the hills to the northern valley and to the east. In areas where the pebbly sand is present beneath the hills the fluctuation in the water level in wells is dampened.

Figure 33 shows water level fluctuations for three wells and rainfall for a 3-month period, illustrating the time required for water to reach the saturated zone. During the 3-day period from August 18-20, 1979, there was 9.38 inches of rain.

The water level in well 512 responded in less than 1 hour following a 5.4-inch rain on August 18, 1979. The net water-level rise in well 512 was 1.85 feet over a 4-day period. Well 512 is located in a valley, and the depth to water below land surface is 18 feet.

Well 531 is located on a hillside where the depth to water is 30 feet. The water level in well 531 responded in 76 hours with a net change of 0.41 foot over a 13-day period. The smallest response occurred in hilltop well 511, taking 50 hours to respond with a net change of 0.24 foot in 9 days. Depth to water in well 511 is 36 feet.

The trenches are located on the higher ground in areas where water levels fluctuate least. On the basis of water-level records, water levels would not rise much above highs recorded to date even during a period of several years of above normal precipitation. Water levels probably will not rise into the trenches, particularly where they are underlain by the pebbly sand. An exception is trench 18 which intersects the saturated zone.

Flow Paths

In complex hydrogeologic environments, such as the study site, lithologic units with higher hydraulic conductivities act as ground-water flow paths so that water moves faster relative to movement in other lithologic units. A flow path may be composed of all or part of a sedimentary unit or a combination of units. Once leachate has migrated from a trench into a flow path, the rate of flow along the flow path becomes the controlling factor in determining the rate of migration.

Table 4.--Lithology of screened section of wells and the range in water-level fluctuation for the period of record

Well No.	Lithology of screened section	Water-level range (feet)
	FINE GRAINED SEDIMENTS	
501	Sand-silt-clay	0.97
512	Silt, clayey silt and silty clay	9.09
513	Silt and clayey silt	6.21
515	Silty sand	4.81
520	Silt	6.94
524	Sandy silt to silty sand	10.97
527	Silt to silty sand	6.92
531	Silt to clayey silt	3.01
533	Pebbly silty sand	6.63
536	Clayey silt to silty clay	1.34
	FINE TO COARSE GRAINED SEDIMENTS	
502	Sand to sand-silt-clay	3.38
507	Clayey silt to sand-silt-clay	2.10
525	Pebbly sand	5.76
528	Pebbly silty sand	4.41
532	Clayey silt to pebbly silty sand	3.57
535	Pebbly silty sand to silt	3.30
	COARSE GRAINED SEDIMENTS (UNCONFINED)	
509	Pebbly silty sand	1.42
510	Silty sand	1.34
522	Silty sand	1.86
529	Pebbly silty sand	3.16
530	Pebbly silty sand	2.56
	COARSE GRAINED SEDIMENTS (CONFINED)	
511	Silty sand to sand	3.32
516	Pebbly sand	4.66
517	Pebbly silty sand	4.73
518	Pebbly sand	4.28

The primary flow path is along line X-X' (fig. 30) through the saturated part of the pebbly-sand unit. A flow path of lower hydraulic conductivity is along line Y-Y' through the silt of the Peoria Loess.

The primary flow path (X-X') extends from offsite on the west across the middle of the site to some distance northeast of the site. The pebbly sand ranges from 1 to 16 feet thick and averages 8 feet. It ranges from 100 to 750 feet wide. As ground-water levels change, the saturated thickness of the pebbly sand changes. The amount of change can be seen by comparing the thickness of saturation during the period of low water levels in February 1978 (fig. 28) with the period of higher water levels in June 1979 (fig. 29).

The water-table gradient along line X-X' ranges from 0.01 foot per foot (ft/ft) in the area near the southwest corner of the site to approximately 0.10 ft/ft in the middle of the site. The changes in gradient are a reflection of changes in the hydraulic conductivity and in the cross-sectional area of the pebbly sand through which water is flowing.

Flow velocities along path X-X' were found to range from 6.68×10^{-1} feet per year (ft/yr) in the western part of the site to 1.6×10^{3} ft/yr in the eastern part. Using hydraulic conductivities from table 3, gradients scaled from figure 30, and an assumed porosity of 0.35 for the sand, velocities were calculated by the formula:

$$v = \frac{K}{n}\frac{dh}{dl}$$

where v = ground-water velocity,
K = hydraulic conductivity,
n = effective porosity,
$\frac{dh}{dl}$ = head gradient or difference in head, $h_2 - h_1$, divided by flow length l.

The secondary flow path (Y-Y') extending from the south side of trench 11 near well 523 into the south valley, is through the silt of the Peoria Loess (fig. 30). The gradient of the water table along this flow path is 0.07 ft/ft. The hydraulic conductivity is 2.9×10^{-7} ft/s, and the porosity 0.20. Using these values the flow velocity along the flow path was calculated to be 3.2 ft/yr. The rate of migration of tritium from trench 11 to well 523 and then to well 527 was estimated to be 25 ft/yr, moving a distance of 75 feet in 3 years. There is a discrepancy in the calculated flow rate of 3.2 ft/yr through the silt in relation to the estimated migration rate of tritium of 25 ft/yr. Tritiated water has probably been short circuited through the unsaturated zone where it has moved along the contact between the pebbly sand and the sand-silt-clay. Lateral movement of water through the unsaturated zone would shorten the time of travel from trench 11 to well 523. Another explanation is that tritium may have moved laterally as vapor in soil gas and then been carried to the saturated zone with infiltrating water. Although tritium has been found along flow path Y-Y', the potential for a significant amount of migration is less because of the smaller velocities and smaller volume of flow than along X-X'.

Digital Modeling of Ground-Water Flow

A two-dimensional digital computer model was used to simulate ground-water flow through the glacial sediments and to help understand the flow system. The model was useful in assessing the validity of hydrogeologic data.

Several modeling problems related to the complexity of the hydrogeologic system were recognized early in the study: (1) the irregular shape of the base of the pebbly-sand unit allows changing water levels to saturate or dewater parts of the unit which significantly alters the rate of flow in these areas; (2) it is difficult to determine the distribution of recharge rates because of the likelihood of lateral movement of water within the unsaturated zone, at contacts between sedimentary units; and (3) the model covered an area of 0.75 mi^2, including not only the entire site, but also adjacent areas within the basin of the Lawson Creek tributary where subsurface data were not available.

It was assumed that all ground water flowed northeast from the site to the strip-mine lake or east to the Lawson Creek tributary. The relatively high hydraulic conductivity of the pebbly-sand unit made it the dominant unit controlling ground-water flow. The hydraulic conductivity of the pebbly sand was so much higher than other materials that the model was insensitive to the relatively small differences in hydraulic conductivity between other units.

The model area is within the following boundaries: (1) a bedrock high and ground-water divide to the west; (2) a ground-water divide passing through the south half of the site; (3) a ground-water divide to the north; and (4) the strip-mine lake and Lawson Creek tributary on the northeast and east (fig. 34). There was no lateral inflow to the system, consequently, the only inflow was infiltration from precipitation. Constant head boundaries were assumed at the strip-mine lake and at the tributary to Lawson Creek. No-flow boundaries were assumed to exist at the north, west, and south ground-water divides.

Theory

The partial differential equation describing ground-water flow in two dimensions (Pinder and Bredehoeft, 1968) is:

$$(1) \quad \frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) + W(x,y,t) = S\frac{\partial h}{\partial t}$$

where T_{xx} and T_{yy} are x and y principal components of the transmissivity tensor (L^2/T, length squared over time);
h is the mean hydraulic head in the vertical (L);
W is the recharge rate (negative for discharge) (L/T);
S is the storage coefficient (dimensionless);
t is time.

See Pinder and Bredehoeft (1968) for development and discussion of equation 1.

In this study the system was assumed to be isotropic and at steady state. Hence,

$$T_{xx} = T_{yy} = T = bK$$

where b = saturated thickness (L);
K = hydraulic conductivity (L/T);

and $\frac{\partial h}{\partial t} = 0$;

so that (1) reduces to

$$(2) \quad \frac{\partial}{\partial x} T \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} T \frac{\partial h}{\partial y} + W(x,y,t) = 0.$$

Equation 2 was solved by finite element techniques (R. L. Cooley, U.S. Geological Survey, written commun., 1977) on a grid of 130 nodes and 117 elements.

Calibration Techniques

Hydraulic conductivity and recharge are the only unknown parameters in the model (except for hydraulic heads). Different values for these parameters were used in the model to generate heads that most closely matched the water levels of February 28, 1978. The water levels on that date were assumed to represent steady state conditions. As values of parameters were changed in the model to improve the agreement between model output and actual water levels, the degree of fit was determined by computing a value for an error function (E):

$$E = \sum_{i=1}^{N} (\hat{h}_i - h_i)^2/N$$

where h_i is the computed head at node i; $\hat{h}_i$ is the observed head (from Feb. 28, 1978) at node i; and N is the number of nodes where heads were measured (N = 32 in this case). Model output was concluded to be a best fit when realistic values for input parameters resulted in a minimum value for the error function. The water levels of February 28, 1978, are slightly below average for the period of record. No long-term records are available so it is not known how close these values would be to the long-term average.

As a part of the calibration, all grid elements were grouped into one of three zones (fig. 34). Zone I represented the area where the pebbly-sand unit is present beneath the site. Zone II represented the area beneath and adjacent to the site where the sand unit is absent. For simplicity, in the following discussion this area will be termed the till unit, although it is actually comprised of several different units. Zone III represented the area between the site and the strip-mine lake in which the lithology of the glacial deposits is largely unknown. Zone III was treated alternately as being underlain by the sand unit or the till. An initial saturated thickness was specified for each element within a zone. One value of hydraulic conductivity and one value for recharge were assigned to each zone and were held constant during a computer-model simulation. Values for these parameters were changed on a zone by zone basis for subsequent computer simulations until a best fit between the model and the water surface of February 28, 1978, was obtained. There are no unique values of hydraulic conductivity and recharge that produce a best fit. A best fit is determined by a unique ratio of hydraulic conductivity to recharge. This ratio will be called a KR ratio. The best fit KR ratio can be used to help evaluate independently determined values of recharge and hydraulic conductivity.

A smaller model error could have been achieved if parameter values had been changed element by element instead of zone by zone. However, data coverage was not sufficient to permit this. In addition, changing element by element would have increased the number of KR ratios that produced a best fit. In the till zone, KR ratios ranging from 10 to 60 were found to cause no appreciable change in the error function value. A KR ratio of 47.3 computed from constant values of hydraulic conductivity (1×10^{-7} ft/s) and recharge (0.8 in/yr) was used for the till.

Two possible hydrogeological settings were evaluated to determine the possible hydraulic connection between the pebbly-sand unit and the strip-mine lake. One setting assumed that the pebbly-sand unit extended to the lake (zone III was a sand zone). In the second setting, the pebbly sand ended just outside the site boundary (zone III was a till zone). In the first setting the best model fit produced an error function value of 4.5 feet. The KR ratio for the sand zones was 1.24×10^4. If it is assumed that recharge to the pebbly-sand unit is in the range of 1-3 in/yr, then the best fit hydraulic conductivity of the sand will be in the range of 3.28×10^{-5} to 9.83×10^{-5} ft/s. These values are within the ranges given in table 3 for field and laboratory tests.

The range of water levels computed by the model (highest water level minus lowest) is 60 feet. The 4.5 feet best fit error function is quite high when compared to 60 feet (4.5 is 7.5 percent of 60). For this reason the model is not considered to be a good fit. When contoured, the output water levels had the same basic shape as the water-surface map of February 28, 1978. However, details of the more irregular contour shapes were not reproduced by the model.

For the second setting the best fit error function value was 6.2 feet. The KR ratio for the sand zone was 2.40×10^4. In the till zones the same values were used for hydraulic conductivity and recharge that were used in the first setting. Again, assuming a recharge rate to the sand of 1-3 in/yr, this model indicates the hydraulic conductivity of the sand would be between 6.34×10^{-5} and 1.90×10^{-4} ft/s. A contoured map of model generated water levels showed both a much steeper head gradient in zone III and a flatter gradient in zone II than was present in setting one. On the basis of error function values, the second setting was a poorer fit than the first.

Sensitivity tests were performed on the models. The models were not sensitive to changes in the KR ratio values in the till zones. KR ratios for the pebbly-sand zones were increased by 50 percent and then decreased by 50 percent. Results were identical for the two settings. A 50 percent increase in the KR ratio resulted in a 6-fold increase in the error function. A 50 percent decrease resulted in a 12-fold increase in the error function. The models are very sensitive to parameter changes in the pebbly-sand zones, another indication of a lack of good fit. Changes in head between best fit computer simulations and sensitivity simulations were examined in an effort to distinguish areas in which corresponding heads changed. However, the changes occurred randomly, preventing any successful attempt to contour them.

Because of the lack of a good model fit, model results should be viewed with caution. The ground-water system was doubtlessly oversimplified by the model. Still, modeling was useful in several respects. It verified the expected importance of the pebbly sand as the unit controlling ground-water movement beneath site. The sand unit is so much more permeable than other units that it is not necessary to distinguish between the other units within a model. The best fit KR ratio is a useful tool in evaluating rate of recharge to hydraulic conductivity of the pebbly-sand unit. Additional data collection would be most advantageous in the area between the site and the strip-mine lake, concentrating on delineating the extent of the pebbly-sand unit. Best results were obtained when the sand was considered to extend to the lake. Whether or not this condition actually exists can only be obtained from further drilling in that area.

Water Quality

Water samples were collected from wells, streams, and sumps in waste trenches. The samples were analyzed for radionuclides, common inorganic constituents, and several organic constituents. The purpose of obtaining the data was to determine if any radionuclides were migrating from trenches, to define the source of any migrating leachate, to use migrating leachate as a tracer to determine the pathways and rates of ground-water movement, to describe the natural water chemistry, and to study changes in ground-water chemistry associated with waste migration.

Inorganic and Organic Chemistry

Trench-Water Quality

Water is present in the sump of trench 18 which is partially below the water table, and was found in the sumps of trenches 7, 14A, 23, 24, and 25C following the collapse of soil into voids beneath the trench caps.

In April 1979, personnel from Brookhaven National Laboratory (BNL) collected water samples for inorganic, organic, and radiometric analyses from trenches 14A and 18. Results of these analyses show that the composition of the leachate from trench 14A is significantly different from that of trench 18. The water from trench 18 is higher in alkalinity, hardness, sulfate, calcium, magnesium, potassium, iron, pH, specific conductance, and temperature than water from trench 14A (table 5). Composition of trench water can, in part, be attributed to differences in trench contents and in sources of water. Water in trench 18 was mostly ground water that flowed into the trench from the west, whereas, water in trench 14A was water from melting snow. Concentrations of constituents in water from trench 14A indicated that the melt water that entered the collapse hole mobilized the leachate generated by infiltration moisture during the life of the trench (about 1.5 years).

Dissolved organic carbon (DOC) concentations in trenches 14A and 18 were 100 and 50 mg/L, respectively. The difference in concentration is probably due to the difference in composition of the waste and the types of containers. Trench 14A contains special nuclear material, source material, and byproduct material in an assortment of containers including 55 gallon steel drums, plywood crates, steel bins, and concrete casks. Water from melting snow entered the trench through collapse holes, picking up leachate as it percolated down through the waste. Whereas, waste in trench 18 is largely contaminated soil that was cleaned up following a spill of radioactive material. The soil is contained in both steel bins and concrete casks that cover the floor of the trench. Water in the trench is ground water that rose up into the waste after the trench was filled and covered. Consequently, the water has been in contact largely with steel bins and concrete casks.

Ground-Water Quality

Four sets of water samples, totaling 140, were collected from 35 wells between May 1978 and January 1980 to compare the chemistry of naturally occurring water with that of water from wells located adjacent or downgradient from waste trenches (U.S. Geological Survey, 1980). Samples were analyzed for major inorganic constituents. Specific conductance, pH, and temperature were measured in the field.

The trilinear diagram (fig. 35) shows that the water is a calcium-magnesium bicarbonate type which results from the solution of carbonate minerals contained in the sediments. Because ground water in the glacial sediments comes from precipitation that falls on or adjacent to the site, the water chemistry results predominantly from solution of minerals contained in these sediments. Inorganic compounds are also present in trench waste. The presence of anions and cations in ground water in concentrations above those naturally occurring might be an indication of leachate migration from the burial trenches.

Wells sampled were screened in one or more of seven distinct lithologic units. The character of water from different lithologic units varied as shown in figure 36. The plots include only wells whose water has not been affected by leachate from trenches.

Table 5.--Representative well, creek, and trench water analysis values for the Sheffield site

[Values are in milligrams per liter, except as indicated. Micromhos per centimeter at 25°C (µmho/cm at 25°C), degree Celsius (°C), and microgram per liter (µg/L)]

Property of constituent	Creek	Well water sample without tritium	Well water sample with tritium	Trench[1] 14A	Trench[1] 18
pH (units)	7.1	6.7	7.0	5.0	6.8
Specific conductance (µmho/cm at 25°C)	543	539	1750	600	1600
Temperature (°C)	19.4	10.5	9.0	8.5	10.0
Total alkalinity (as $CaCO_3$)	344	380	1020	200	850
Hardness (as $CaCO_3$)	300	400	990	200	870
Bicarbonate (as HCO_3)	310	340	540	--	--
Carbonate (as CO_3)	0	0	1	--	--
Chloride, dissolved (Cl)	4.8	3.3	22	20	28
Nitrite + Nitrate (as N)	.19	.05	.07	.04	.38
Phosphate, ortho, dissolved (as P)	.02	.01	.01	<.50	<.50
Silica, dissolved (SiO_2)	13	9.3	23	7.4	7.0
Sulfate, dissolved (SO_4)	39	53	71	78	190
Calcium, dissolved (Ca)	65	86	150	52	190
Iron, dissolved (Fe) (µg/L)	0	60	1900	10.9	.4
Magnesium, dissolved (Mg)	34	45	150	17	94
Manganese, dissolved (Mn) (µg/L)	80	410	970	1600	1100
Potassium, dissolved (K)	1.8	2.0	3.5	13	72
Sodium, dissolved (Na)	7.2	9.0	28	50	67

[1] Analyses by Brookhaven National Laboratory.

Several sets of water samples collected from wells located near the northwest corner of the rad site and downgradient from the chemical waste facility were analyzed for dissolved organic carbon (DOC). The results of these analyses indicate that chemical waste has not migrated in ground water into the area of rad waste trenches. A clay core perimeter wall extending from land surface into the top of the shale bedrock was constructed around the chemical waste trenches. The relatively impermeable wall has reduced the flow of ground water from the chem site into the northwest side of the rad site.

Surface-Water Quality

Water samples from the Lawson Creek tributary south of the site were collected in June and September 1978. Flow was estimated to be near base flow at the time of sampling. The inorganic content in water from the creek is similar to the ground water except for lower concentrations of sulfate, iron, and sodium in the creek water. The similarity in the composition of creek water and ground water indicates that most of the water in the creek was derived from ground water.

Water samples have been collected quarterly by IDNS since 1967 for radionuclide analysis from the Lawson Creek tributary and from the strip-mine pond northeast of the site. Radionuclide contamination was not detected in these samples.

Radiochemistry

The radionuclide content of water from waste-burial trenches is dependent on the composition and quantity of wastes, length of time waste is in contact, pH of the solution, and geochemical reactions between the solution and soil in voids, trench bottom, and sides. The extent to which radionuclides contact water depends, in part, on the integrity of the waste containers. The radionuclide content of water from trenches 14A and 25C are higher than that of trench 18 (table 6) indicating that the waste in trenches 14A and 25C probably has a higher concentration of radioactive materials and/or is more susceptible to leaching than the waste in trench 18. Only two radionuclides, tritium and cobalt-60, were detected in water from trench 18, whereas, trench 14A water contained tritium, cobalt-60, sodium-22, cesium-137 and 134, strontium-89 and 90, and manganese-54 (table 6). Water from trench 25C contained tritium, cobalt-60, strontium-90, and manganese-54, and the concentrations of these radionuclides were higher than in water from trenches 18 or 14A.

Tritium was the most abundant radionuclide detected, ranging from 157 nCi/L in trench 18 to 620 nCi/L in water from trench 14A. These tritium concentrations are much less than the maximum permissible concentration (MPC) of 3,000 nCi/L established by the USNRC for release to unrestricted areas (10 Code of Federal Regulations 20, B, II).

Table 6.--Concentrations of dissolved radionuclides and their percentage of maximum permissible concentration (MPC) in water samples from trenches 14A, 18, and 25C in picocuries per liter (pCi/L) as indicated

[Values in picocuries per liter, except tritium values are in nanocuries per liter (nCi/L); N.D. - not detected.]

Nuclide	Trench 14A			Trench 18			Trench 25C	
	Sampled on 3/23/79[a]	Sampled on 4/3/79[b]	Percentage MPC	Sampled on 2/26/79[a]	Sampled on 4/3/79[b]	Percentage MPC	Sampled on 3/23/79[a]	Percentage MPC
^{3}H nCi/L	450	620	21	156	200	6	590	20
^{60}Co	1,500	23,000	45	560	410	1	61,500	123
^{22}Na	1,100	1,100	3	--	N.D.	--	--	--
^{137}Cs	700	30,000	150	--	N.D.	--	--	--
^{89}Sr	450	--	--	--	--	--	--	--
^{90}Sr	--	--	--	--	--	--	8,400	2,800
^{54}Mn	210	2,300	2	--	N.D.	--	1,400	1
^{134}Cs	200	14,000	156	--	N.D.	--	--	--
^{40}K	--	N.D.	--	--	N.D.	--	--	--

[a] Analysis by Illinois Department of Public Health.
[b] Analysis by Brookhaven National Laboratory.

A few radionuclides exceeded their MPC's (table 6). Radionuclide concentrations in water from trench 14A increased from March to April 1979. The increased concentrations resulted from the longer contact time between the waste and water.

Water derived from melting snow that flooded the trench through collapse holes in early March 1979 required over 2 months to drain out of the waste into a sump where the accumulation of water was removed daily by pumping. Also as the bulk of the water drained out of the waste and was removed from the trench, the proportion of leachate to water would increase resulting in the higher concentrations of radionuclides.

RADIONUCLIDE MIGRATION

The IDNS has collected well-water samples for radionuclide analysis on a regular basis since waste burial began in August 1967. The addition of 58 wells for this study considerably increased the number and expanded the distribution of ground-water sampling points for monitoring radionuclide migration. Tritium was the first radionuclide detected in ground water in concentrations above background. Water samples from wells 523 (October 1976) and 507 (November 1977) contained 30.6 nCi/L and 7.0 nCi/L, respectively. Tritium was later detected in concentrations above a background level of 0.85 nCi/L in water samples from wells 505, 527, 528, 531, 540, and V (table 7). Tritium is the only radionuclide that has been found in water from wells.

Table 7.--Record of tritium concentrations in water samples from wells in nanocuries per liter

[Analyses made by Illinois Department of Public Health]

Well	Number of analyses showing tritium	Maximum	Minimum	Mean
505	2	57.3	13.0	35.2
507	23	7.8	1.2	4.9
523	21	94.3	20.4	49.0
527	13	8.9	1.2	3.8
528	11	54.9	1.2	11.0
531	10	3.8	1.0	2.4
540	3	4.4	3.5	4.0
V	2	22.8	2.7	12.8

Areas in which tritium has been found in ground water in relation to trench locations are shown in figure 37. Tritiated water that has moved from a trench to the saturated zone will move in the direction of ground-water flow. Tritium in ground water in the southeast corner of the site has probably migrated from trench 11. Tritium concentrations in soil moisture obtained from the tunnel during construction reached the highest level beneath the center of trench 11 (fig. 38).

Tritium concentrations in water from wells 507 and 523 have increased fairly uniformly over the period of record (fig. 39) indicating a more continuous release of tritium. Whereas tritium concentrations in water from well 528 have fluctuated over a range from 1.2 to 55 nCi/L (fig. 40). The tritium concentration peaks in water from well 528 tend to follow rises in the water level suggesting that the peaks may represent slugs of tritium moving through the system after a recharge event.

The highest rate of tritium migration of any area on site is in excess of 25 ft/yr as determined from the travel time from trench 11 to well 527. Tritium detected in water from wells in other areas of the site has traveled much shorter distances over comparable time periods.

The tritium concentration in well V is not as high as in some other wells on site. However, the presence of tritium in the more permeable pebbly-sand unit within the primary flow path represents a greater potential for movement off site. The radionuclide contamination in well V probably came from infiltration of leachate from trench 14A in the spring of 1979.

Tritium was found in soil moisture extracted from soil samples collected beneath trenches 1, 2, 3, and 11 during construction of the tunnel (fig. 38). Tritium concentrations in the soil moisture were generally higher than concentrations in water samples from wells. Concentrations of tritium reached a high of 2,639 nCi/L in moisture samples from beneath trench 11. Soil moisture in pebbly sand, sampled from immediately beneath the French drain under trench 11, contained 460 nCi/L of tritium. The concentration of tritium in soil moisture decreased with depth in the sand-silt-clay below trench 11 (fig. 41).

Water with tritium also contained certain anions and cations in concentrations above background for local ground water. The relation between the concentration of inorganic constituents and tritium is indicated by the water quality of wells 523, 527, and 524, located along a line of ground-water flow. Tritium concentration in water from these wells decreases with distance away from trench 11 (fig. 42). There is a corresponding decrease in specific conductance, alkalinity, chloride (figs. 43, 44, and 45), silica, hardness, calcium, magnesium, sodium, and sulfate. A statistical correlation test was used to verify the relation between tritium and the inorganic constituents. Correlation coefficients (ρ) were calculated by the Pearson product-moment method. Computer program (Corr Procedure) developed by the Statistical Analysis System (SAS) was used to perform the calculations (Helwig and Council, 1979). The statistical analysis showed a high correlation coefficient (ρ) between tritium and alkalinity, $\rho = 0.84$; tritium and chloride, $\rho = 0.86$; and tritium and silica, $\rho = 0.73$. Figures 46, 47, and 48 show plots of tritium versus alkalinity, chloride, and silica, respectively. The statistical analysis showed a moderate correlation between tritium and calcium, $\rho = 0.66$; tritium and specific conductance, $\rho = 0.61$; and tritium and hardness, $\rho = 0.60$.

Concentrations of these ions above normal background can indicate possible leachate migration even in the absence of tritium. Water in well 535 contains inorganic constituents above background, even though tritium concentrations are not above background. Well 535, which taps the pebbly-sand unit, is adjacent to and down the water surface gradient from trench 23. Chloride concentration in water from well 535 is 7.7 mg/L as compared to a mean chloride concentration of 2.8 mg/L, computed from concentrations of chloride in uncontaminated water from all wells tapping the pebbly-sand unit. Calcium content is 120 mg/L for water in well 535 compared to a mean of 21.2 mg/L, silica 25 mg/L compared to a mean of 3.1 mg/L, and alkalinity 510 mg/L compared to mean of 202 mg/L.

SUMMARY AND CONCLUSIONS

The study has shown that moisture is moving through the glacial sediments in which the low-level radioactive-waste trenches were constructed. If radionuclides, other than tritium, have been leached from the waste trenches, the nuclides apparently are being sorbed by the clay particles in the sediments below the trenches. The only radionuclide that has been found in soil moisture and in ground water is tritium.

Average annual precipitation in the Sheffield area is 35 inches. Infiltration to the water table is 2 inches per year, evapotranspiration 24 inches per year, and runoff 9 inches per year.

Holes have periodically developed in trench caps permitting water to flow into the trenches. Holes probably will continue to form until the void spaces within the waste have been filled through settling and compaction.

The site is in the headwater tributaries of Lawson Creek. There are three east-flowing intermittent streams which drain the site.

Pennsylvanian shale bedrock underlies the glacial deposits in which the waste site was developed. The shale bedrock, which is 450 feet thick, forms a relatively impermeable barrier that isolates the glacial deposits from the regional ground-water aquifers below the shale.

The glacial deposits in which waste trenches were constructed are composed of a number of distinct lithologic units. The deposits range in thickness from 10 to 90 feet and average 54 feet.

The variable lithology of the glacial deposits provides a complex hydrogeologic system. The pebbly-sand unit which underlies 67 percent of the site is the controlling unit with respect to conveying water into, across, and from the site. The hydraulic conductivity of the pebbly sand ranges from 1.8 x 10^{-3} ft/s to 7.5 x 10^{-7} ft/s. The silt of the Peoria Loess is also an important hydrogeologic unit because of its areal extent. However, the silt has a low hydraulic conductivity of 2.9 x 10^{-7} ft/s. All wastes were buried in the unsaturated zone with the exception of trench 18 which is partly below the water table. The unsaturated zone, which ranges in thickness from 5 to 55 feet, and averages 40 feet, is important in the containment of radionuclides by sorption. Tritium has been measured in water samples from wells adjacent to and downgradient from trenches.

Water apparently is moving laterally in the unsaturated zone at contacts between the pebbly sand and the overlying silt and at the basal contact between the pebbly sand and sand-silt-clay. The lateral movement of water in the unsaturated zone may have been responsible for the more rapid movement of tritium in ground water on the southeast side of the site.

The saturated zone ranges in thickness from 10 to 90 feet and averages 50 feet. Recharge to the ground water is from precipitation.

The configuration of the water surface generally corresponds to the land-surface topography. Ground water flows into the site from the west and out of the site to the east. The primary flow path is through a section of the pebbly sand which is important because it is hydraulically connected to most saturated and unsaturated sediments on site. The flow path in the pebbly sand averages 8 feet in thickness, ranging from less than 1 foot to 16 feet. Measured thicknesses of saturation have ranged from 0.1 foot to 13.5 feet.

A secondary flow path extends from the south side of trench 11 near well 523 to well 524 and into the valley to the south. The migration of tritium along this flow path was used to compute a flow rate of 25 ft/yr.

A digital computer model was used to gain a better understanding of the ground-water flow system. The range of values for hydraulic parameters for various lithologic units made it difficult to calibrate the model and thus verify its validity. Preliminary modeling of the site did point to three important conditions: (1) recharge to the system varies widely over the site area; (2) the pebbly sand dominates the ground-water flow in the system to the extent that changing parameter values for other units did not significantly change the model; and (3) the model was quite sensitive to small changes in areal extent of the sand. Modeling the ground-water flow system of the site was useful in describing some hydrogeologic conditions, including a range of flow rates. Further modeling might well be successful in analyzing smaller parts of the pebbly-sand unit.

The ground water is characteristically a calcium-magnesium bicarbonate water. Above background concentrations of chloride, silica, alkalinity, and calcium were found in water samples from wells in which tritium had also been detected. The relatively high concentration of these inorganic ions was attributed to their having migrated with the tritium as leachate from waste trenches. Inorganic ions in relatively high concentrations have been found in water from one well in the absence of tritium suggesting that the ions may migrate ahead of the tritium. A statistical test demonstrated a correlation between the relatively high concentration of these ions and tritium.

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Figures 1 to 48

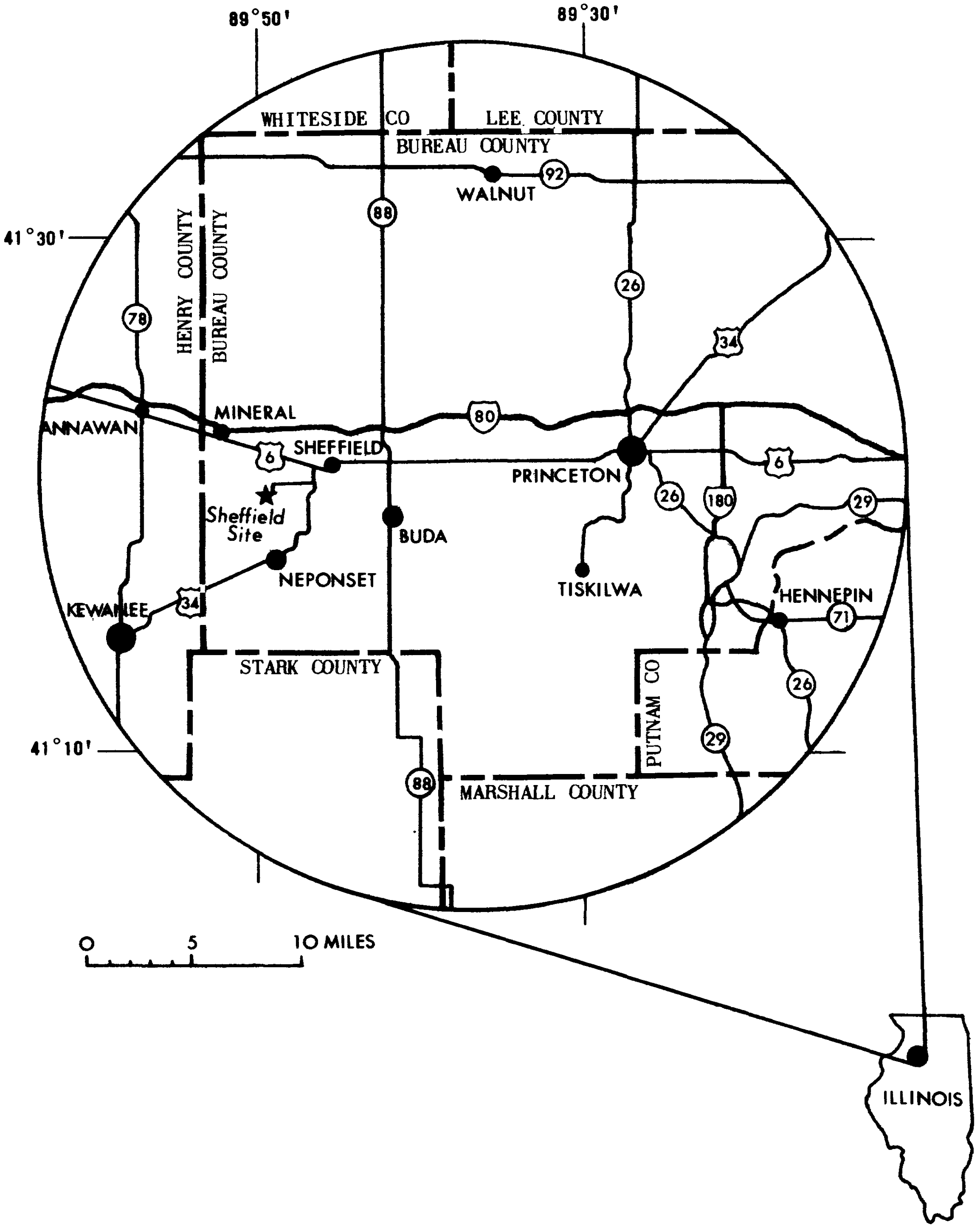


Figure 1.-- Location of Sheffield low-level radioactive-waste disposal site.

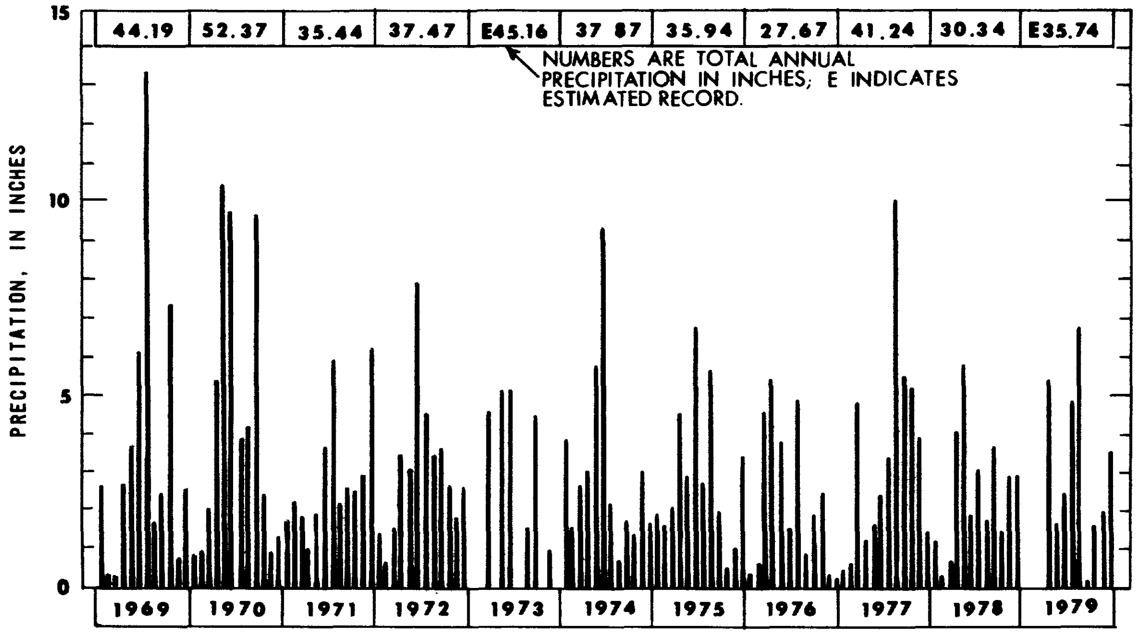


Figure 2.-- Monthly and total annual precipitation for the period 1969-79 at Kewanee, Illinois.

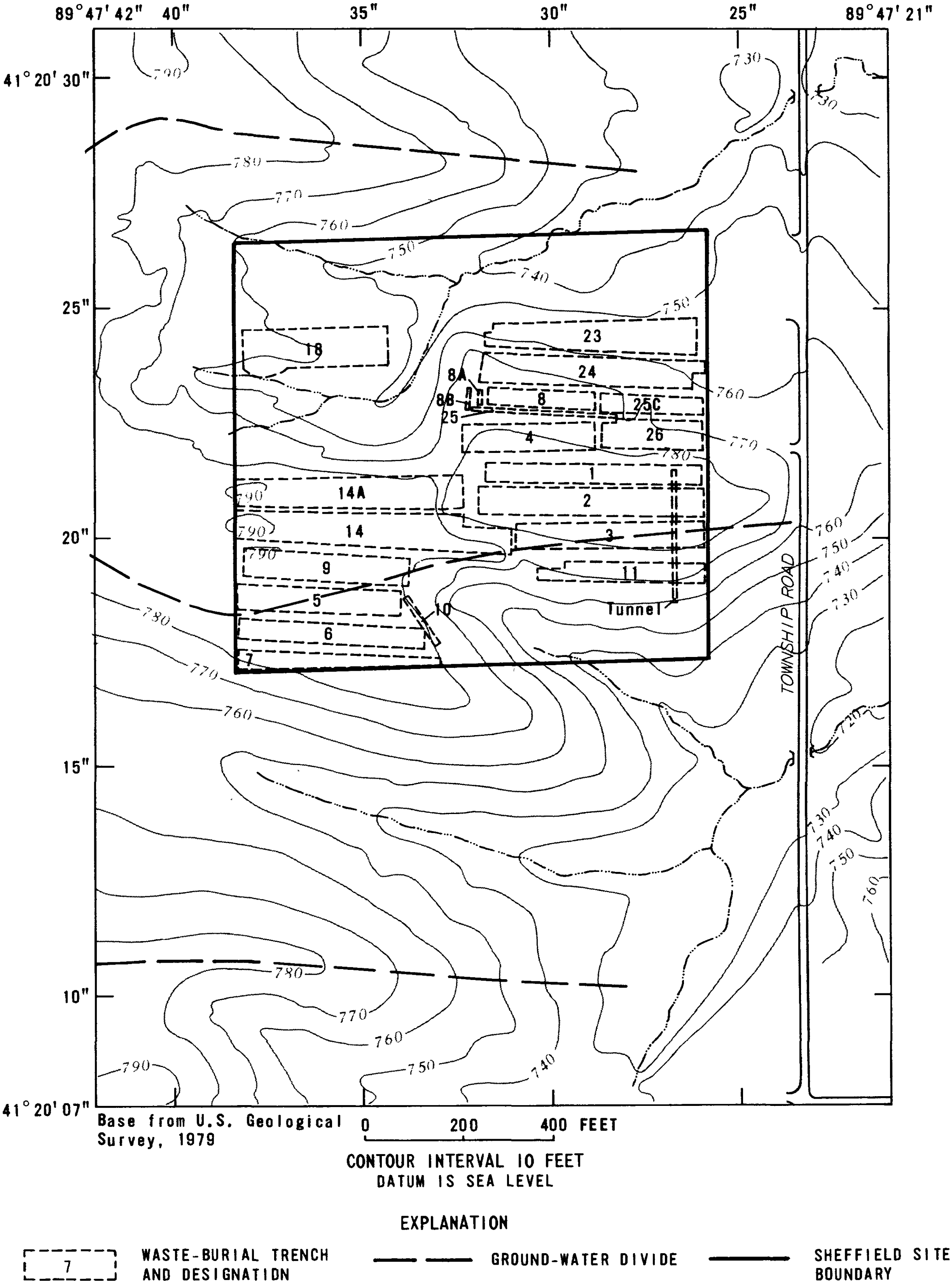


Figure 3.-- Waste-burial trenches, intermittent streams, ground-water divides, and topography at Sheffield site.

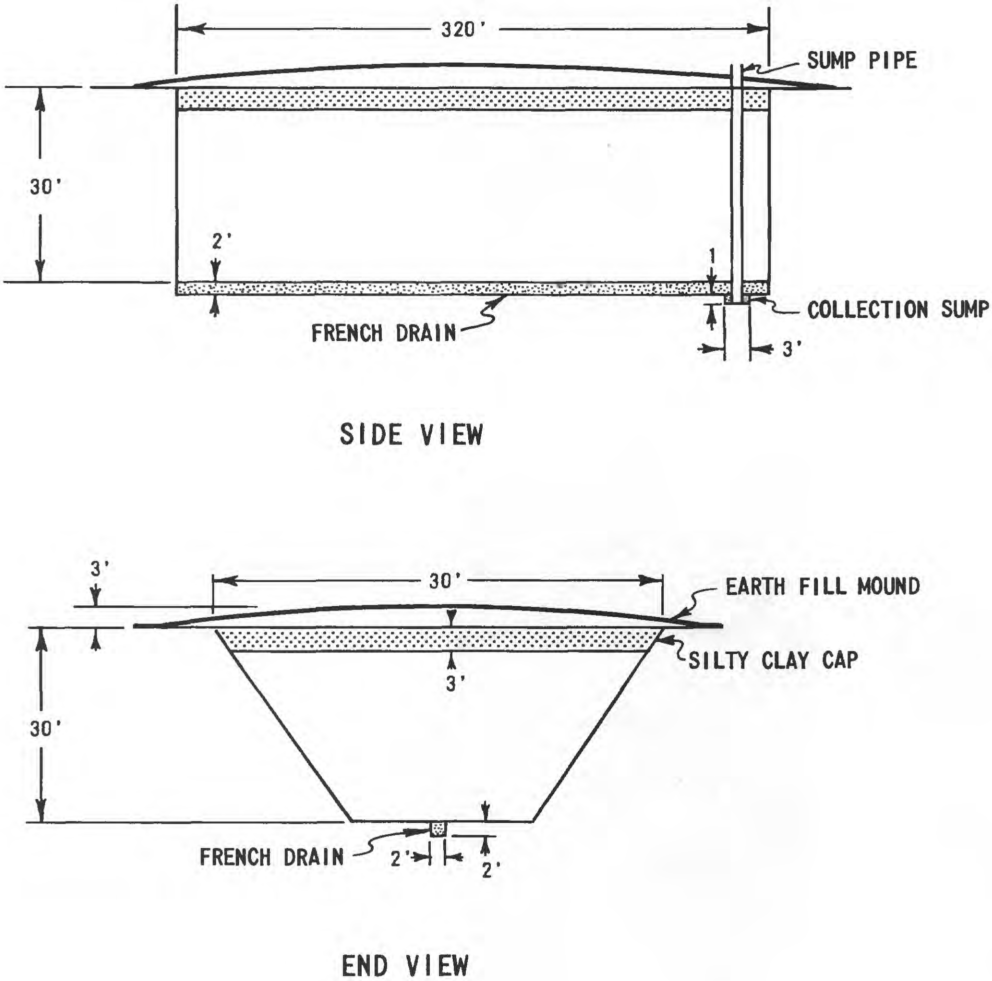


Figure 4.-- Side and end views of a typical trench.

Figure 5.-- Collapse holes exposed in trench surfaces after the snow melted in March 1979.

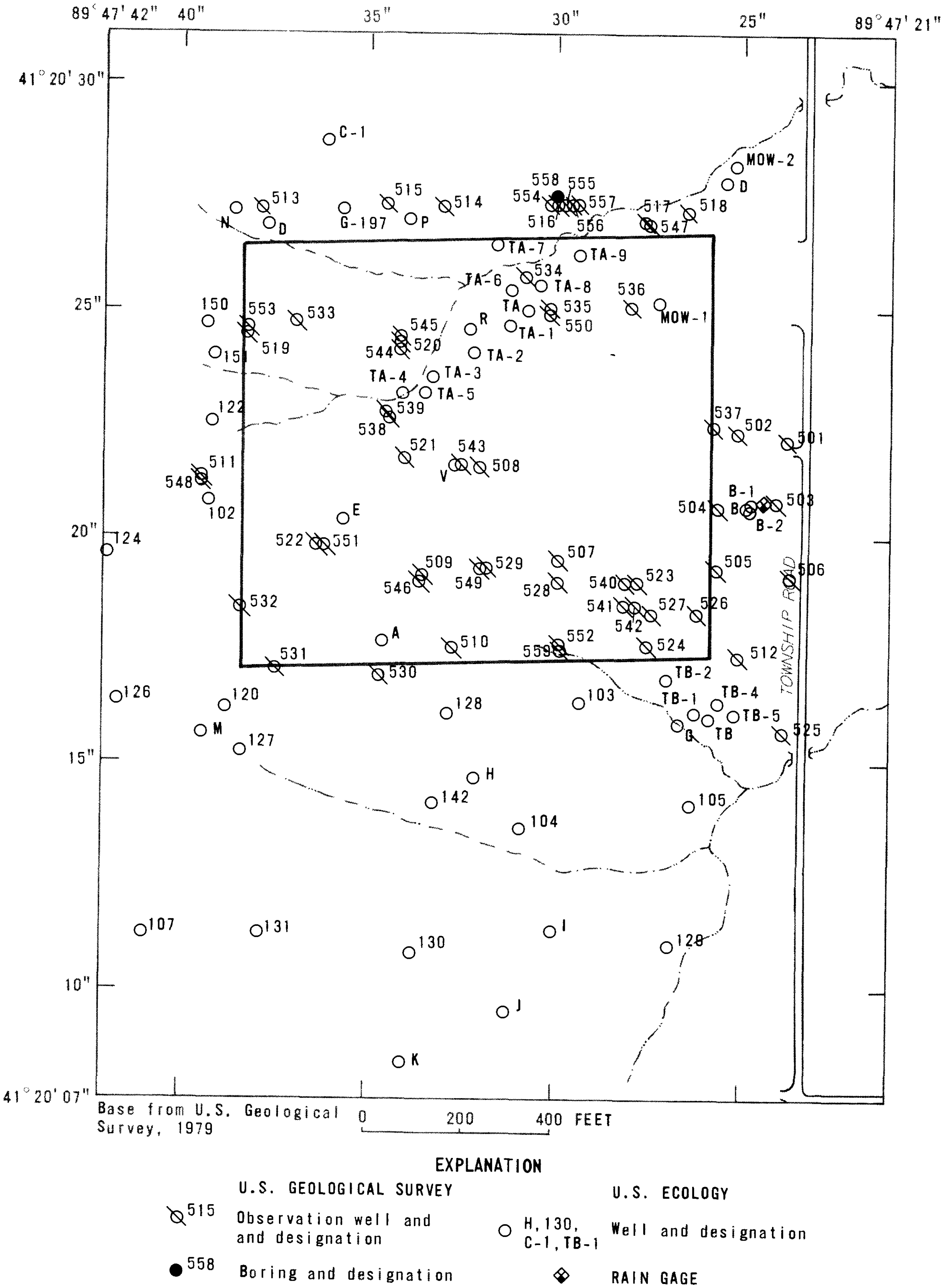
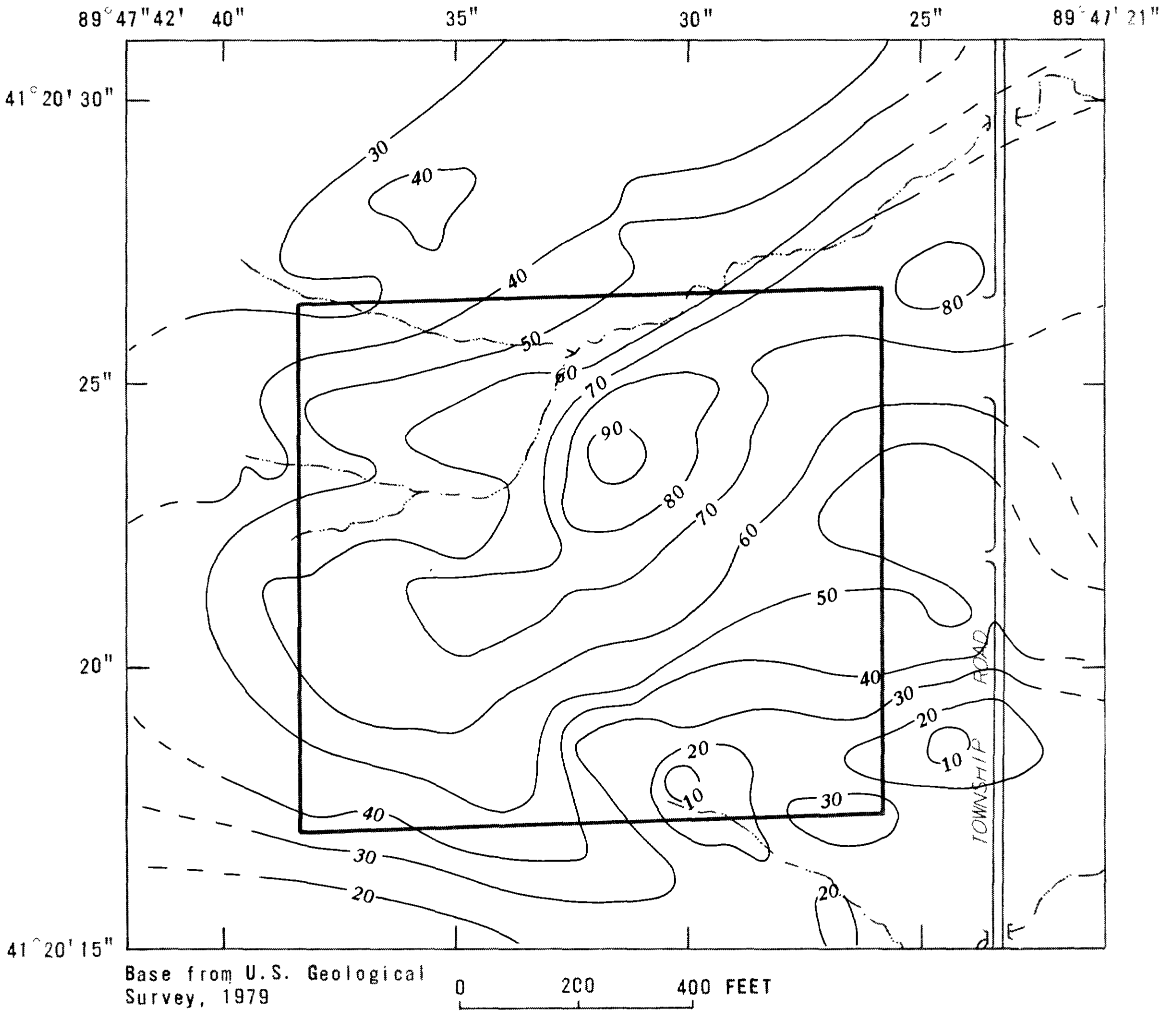


Figure 6.-- Wells and borings.



EXPLANATION

—— 20— — LINE OF EQUAL THICKNESS OF UNCONSOLIDATED SEDIMENTS -- Dashed where approximately located. Interval 10 feet

Figure 7.-- Thickness of unconsolidated sediments at the Sheffield site.

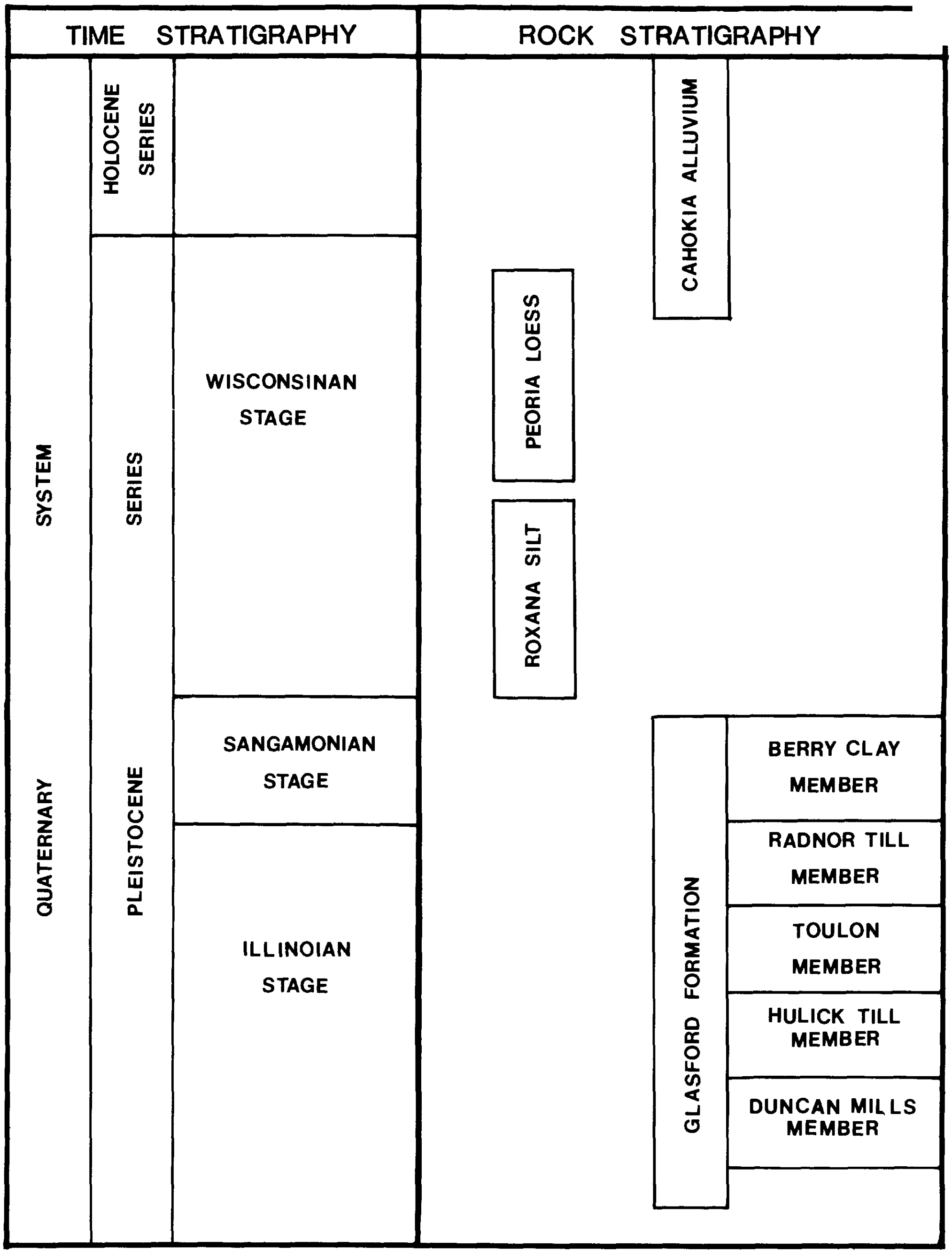


Figure 8.-- Illinois State Geological Survey time-stratigraphic classification and rock-stratigraphic classification (modified from Willman and Frye, 1970).

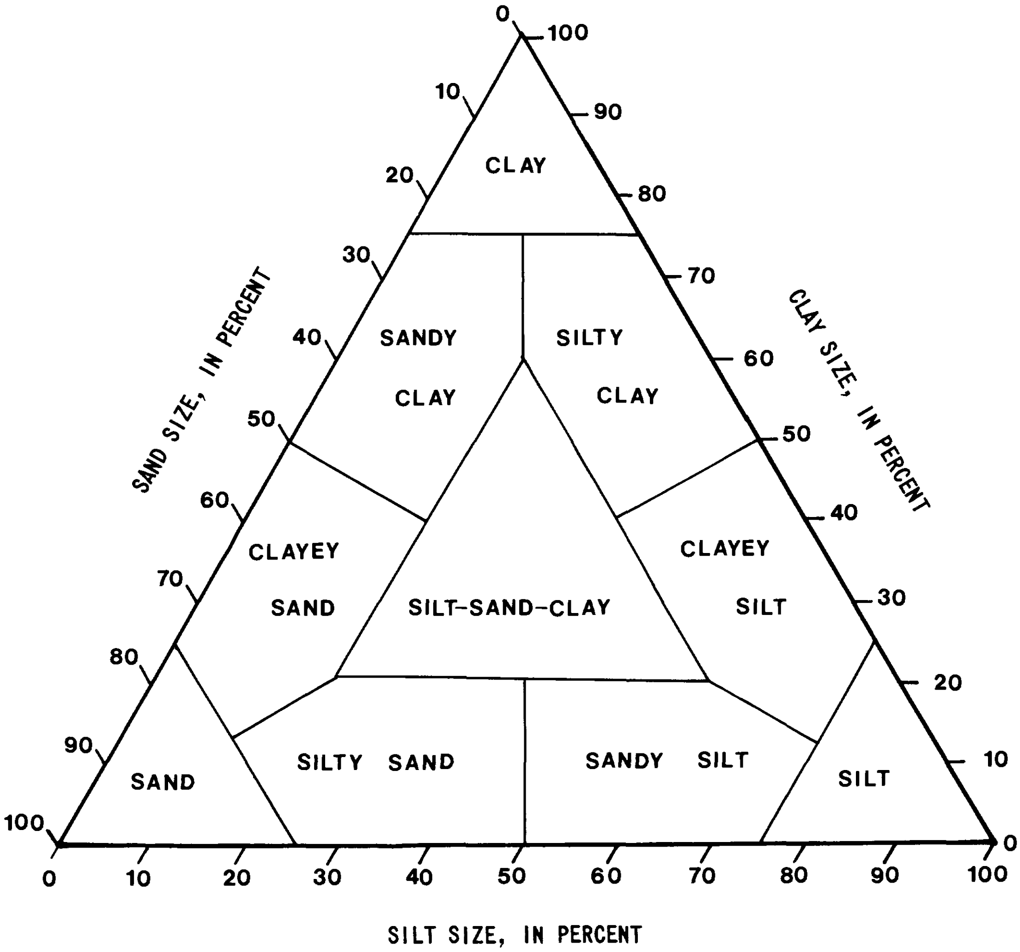
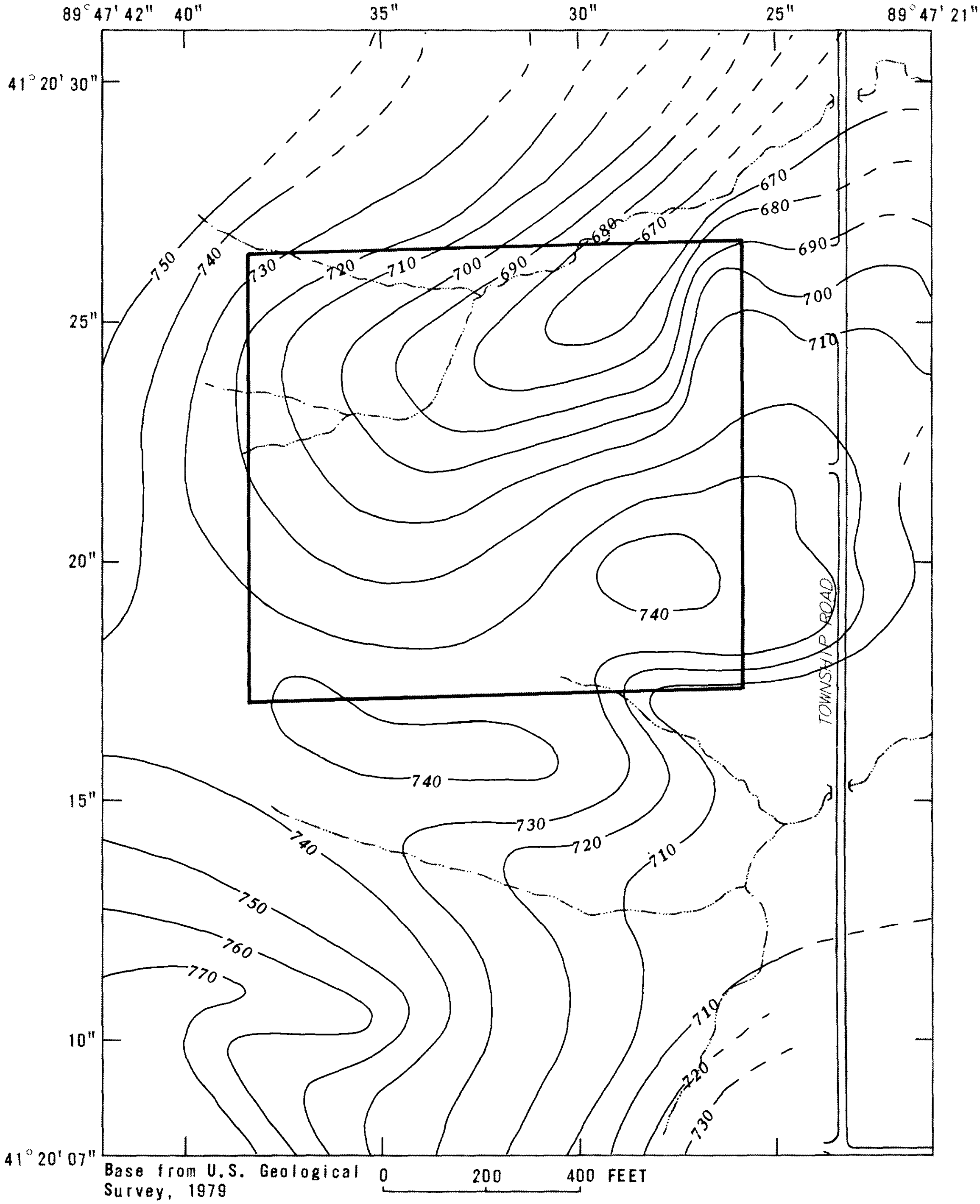


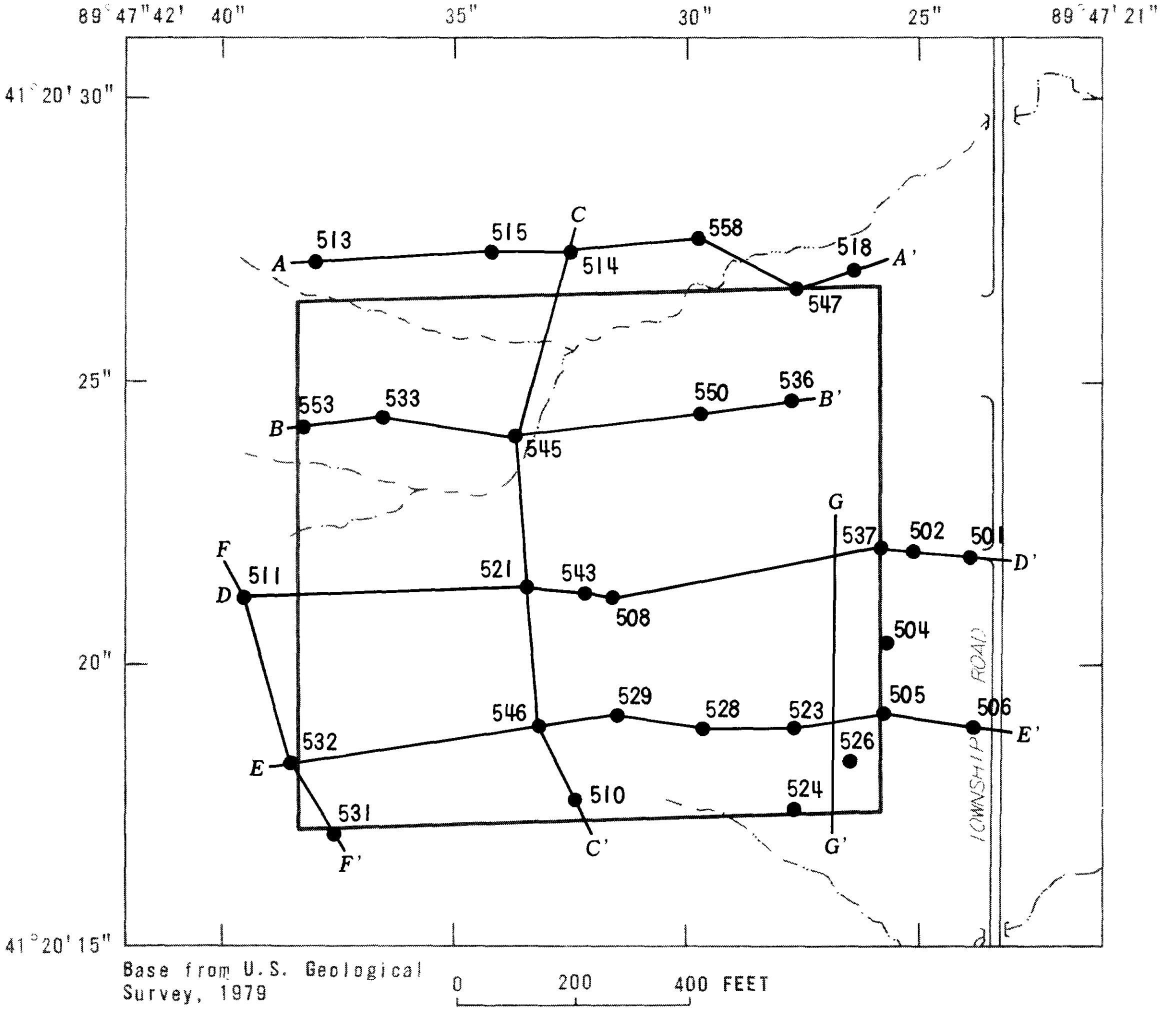
Figure 9.-- Sediment classification triangle (Shepard, 1954).



EXPLANATION

720 — — BEDROCK CONTOUR -- Shows altitude of top of Pennsylvanian shale. Dashed where inferred. Contour interval 10 feet. Datum is sea level

Figure 10.-- Bedrock topography of Sheffield site.



EXPLANATION

●510 OBSERVATION WELL AND DESIGNATION

A———A' LINE OF SECTION

Figure 11.-- Geologic cross sections.

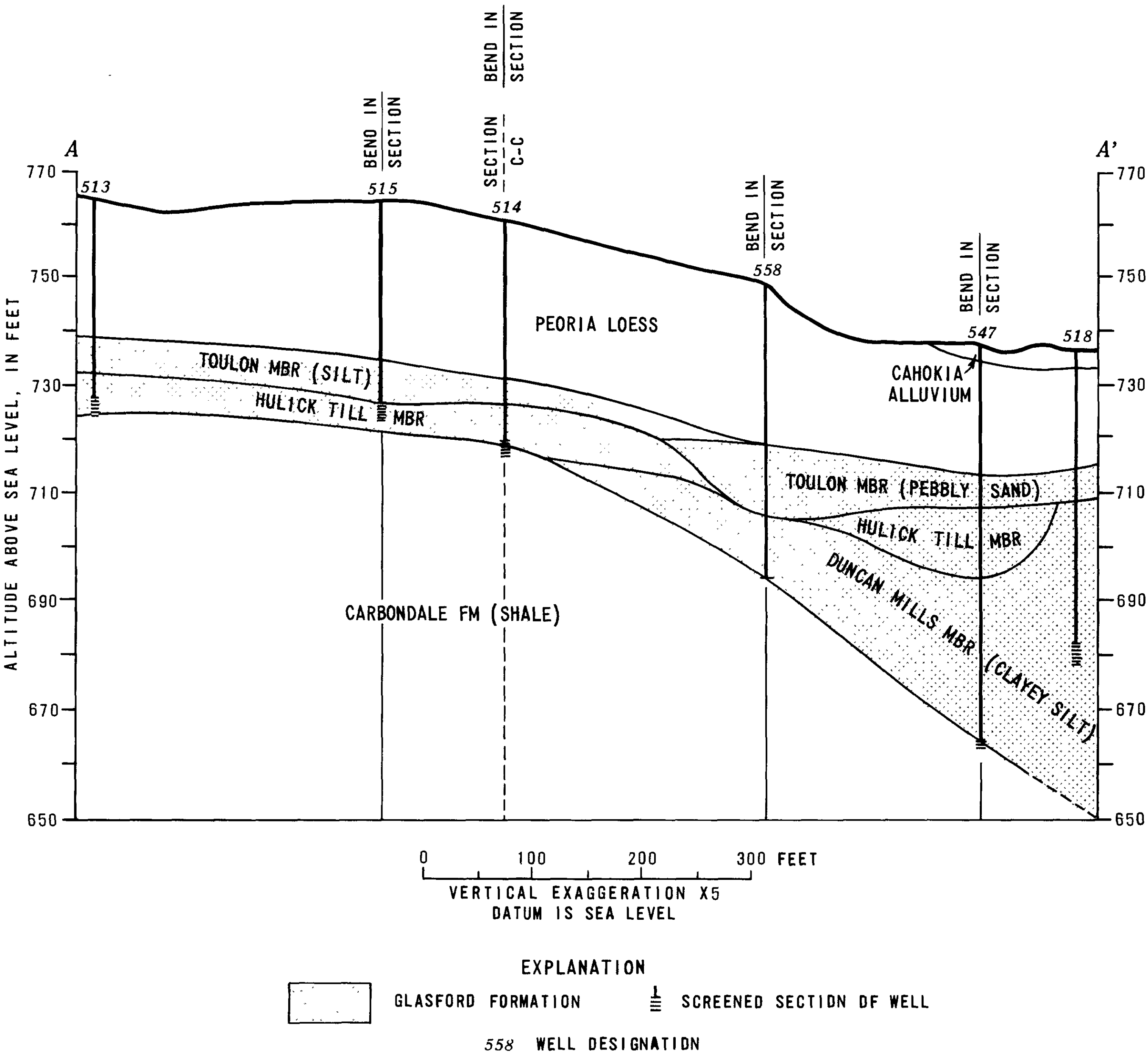


Figure 12.-- Geologic section A-A' of Sheffield site.

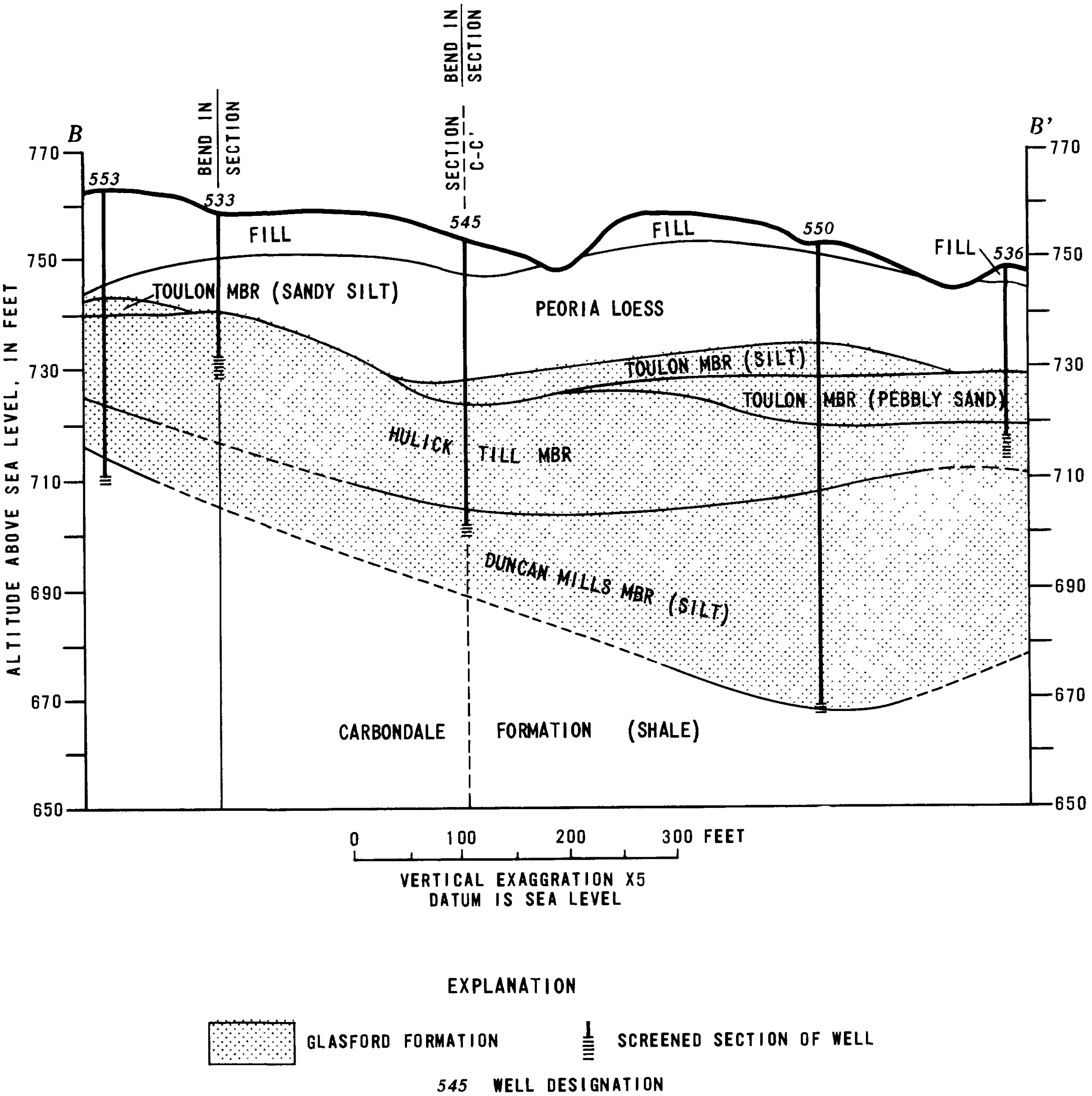


Figure 13.-- Geologic section B-B' of Sheffield site.

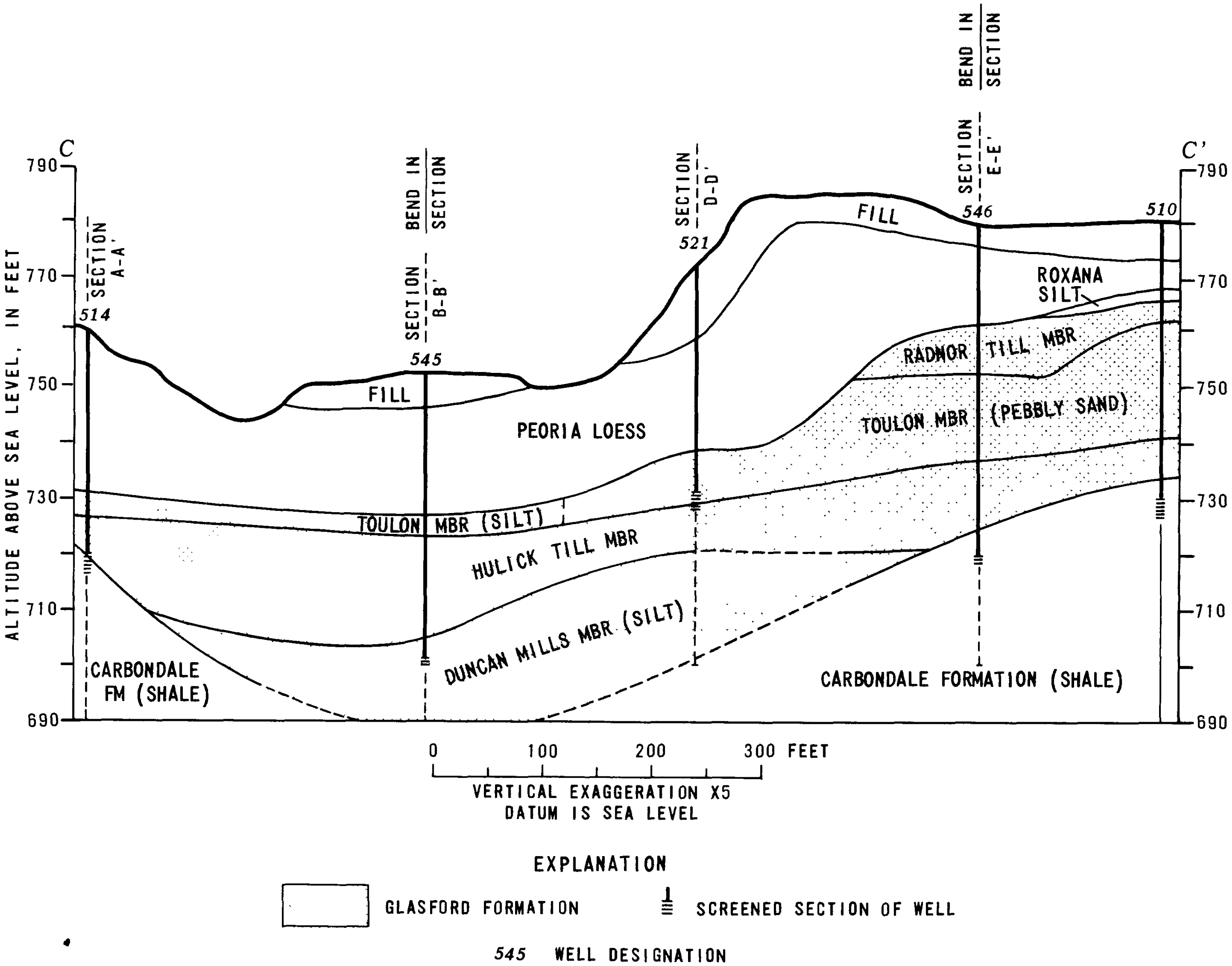


Figure 14.-- Geologic section C-C' of Sheffield site.

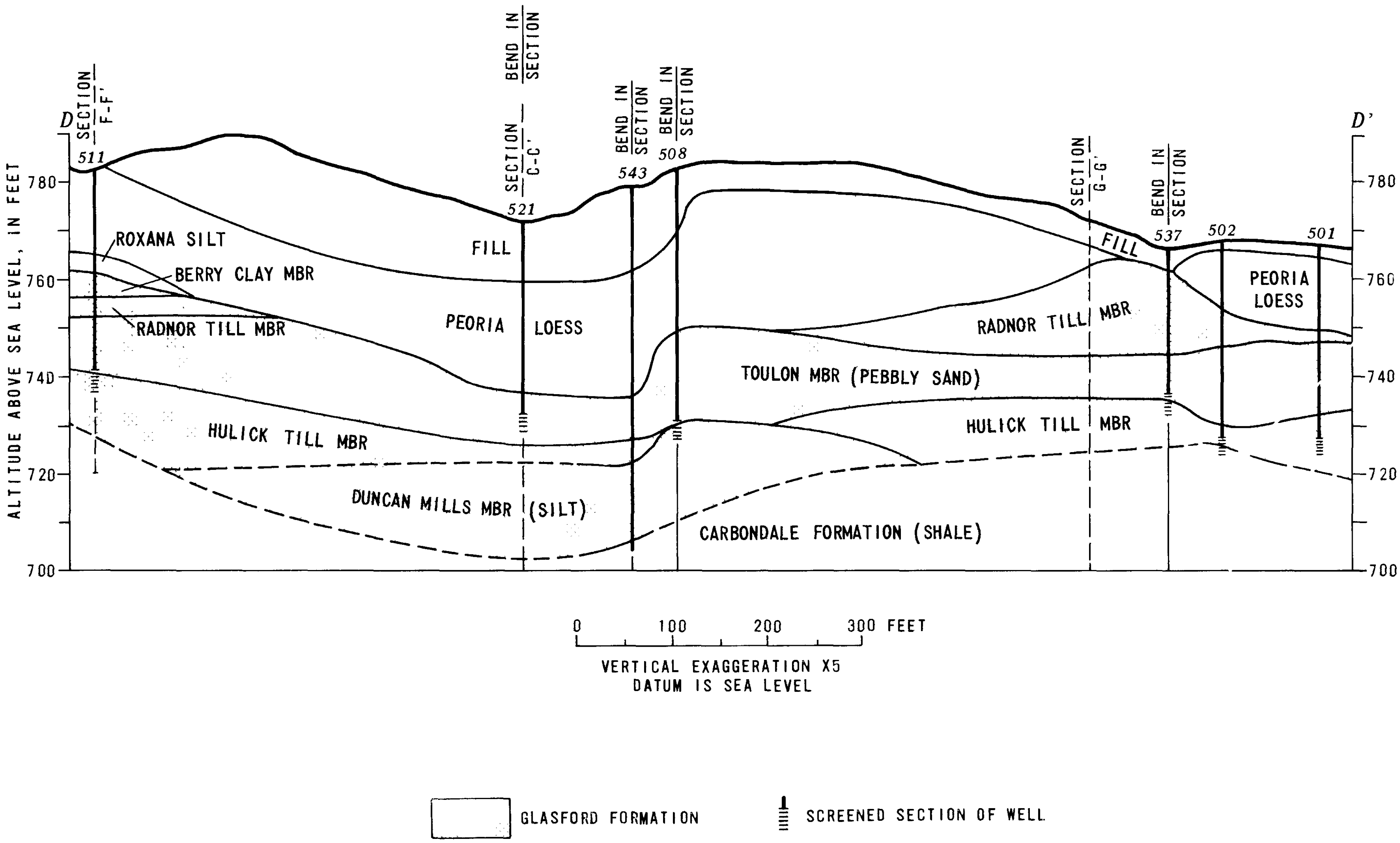


Figure 15.-- Geologic section D-D' of Sheffield site.

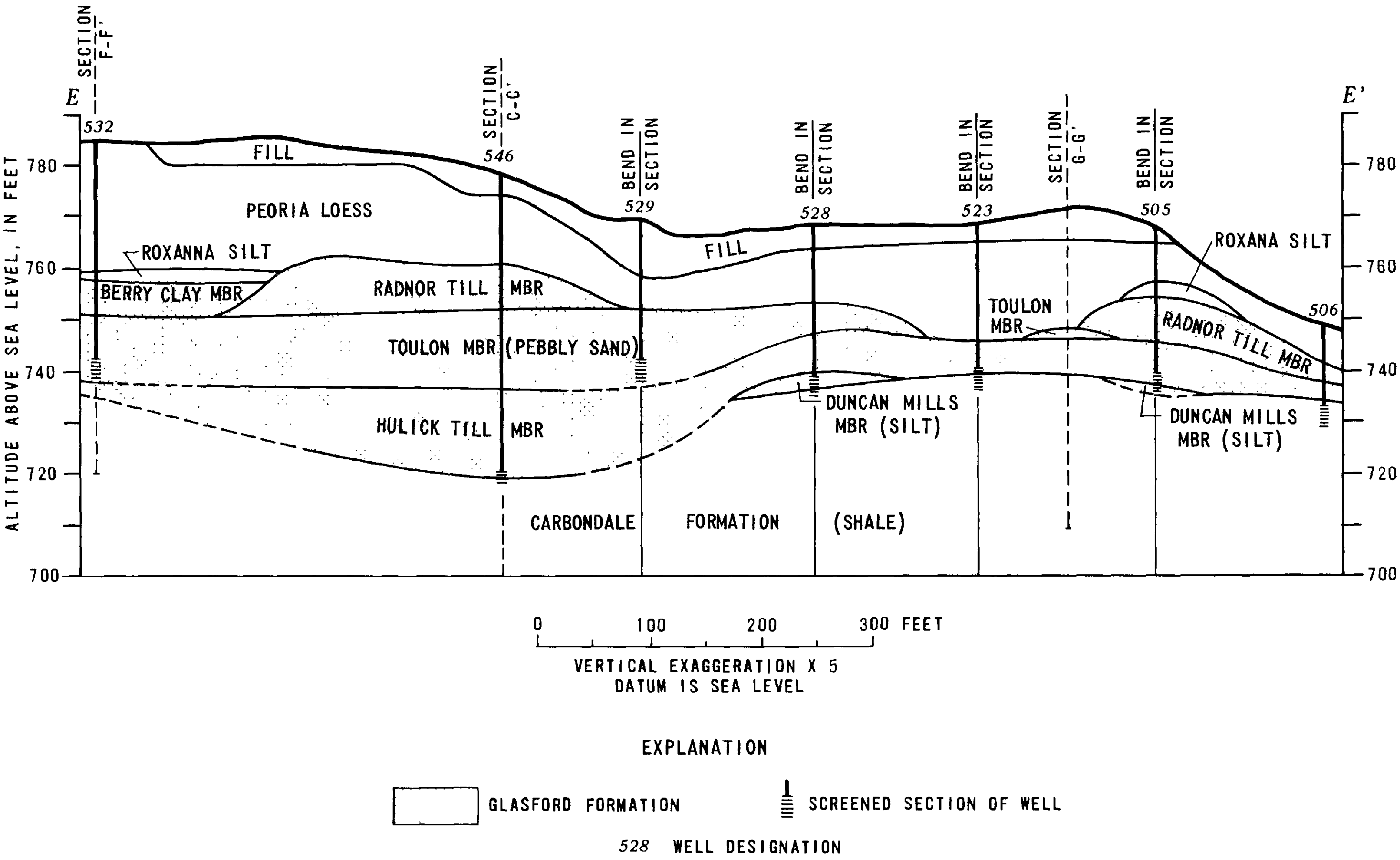


Figure 16.-- Geologic section E-E' of Sheffield site.

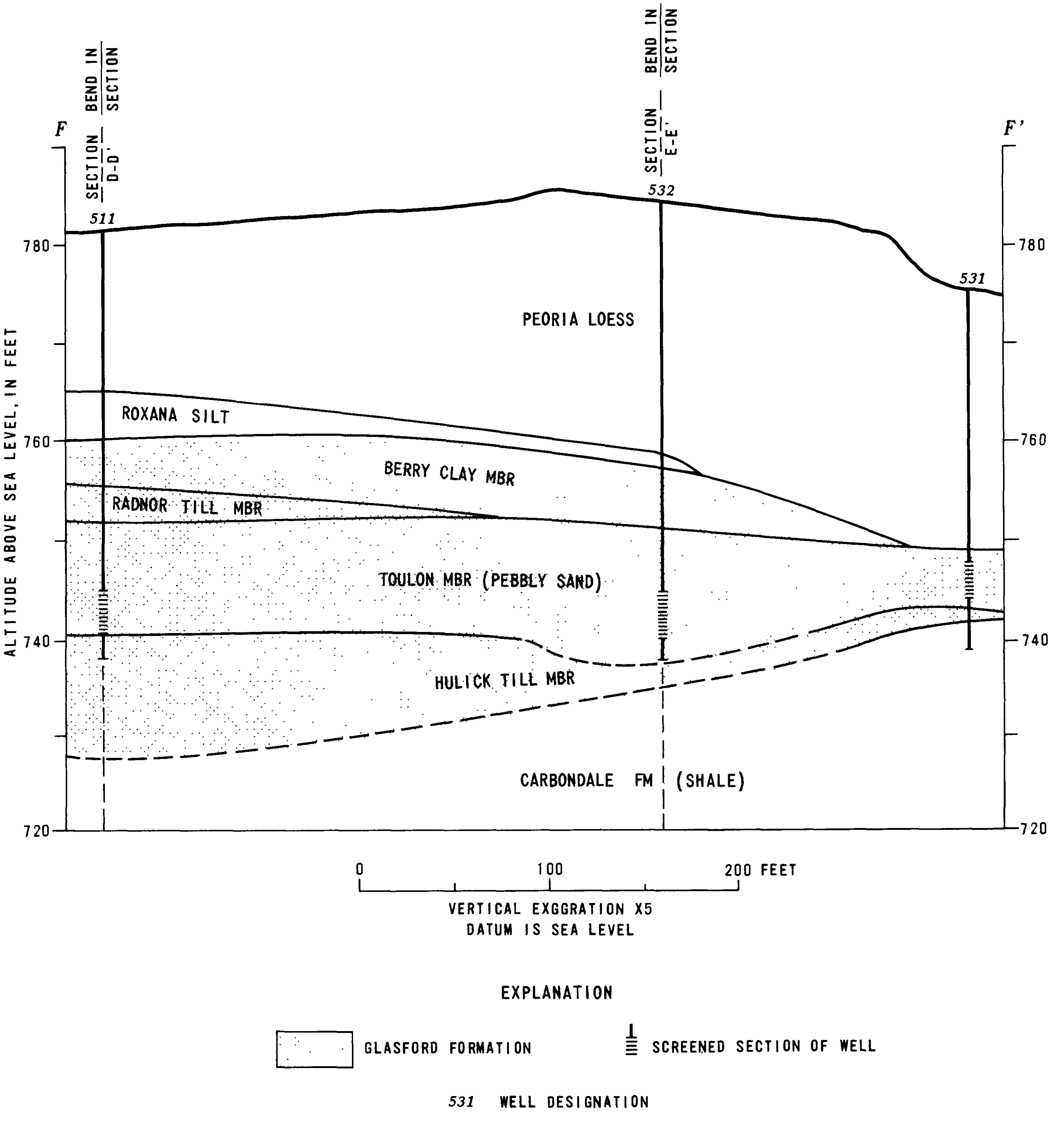
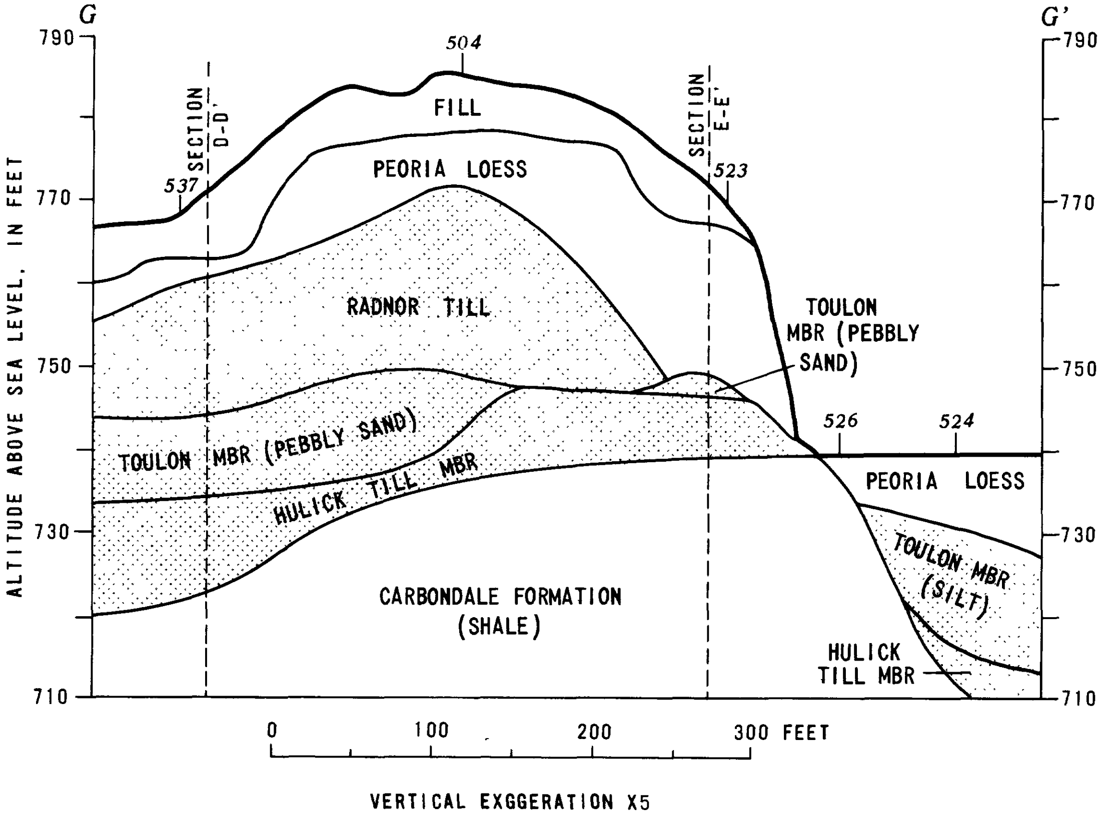


Figure 17.-- Geologic section F-F' of Sheffield site.

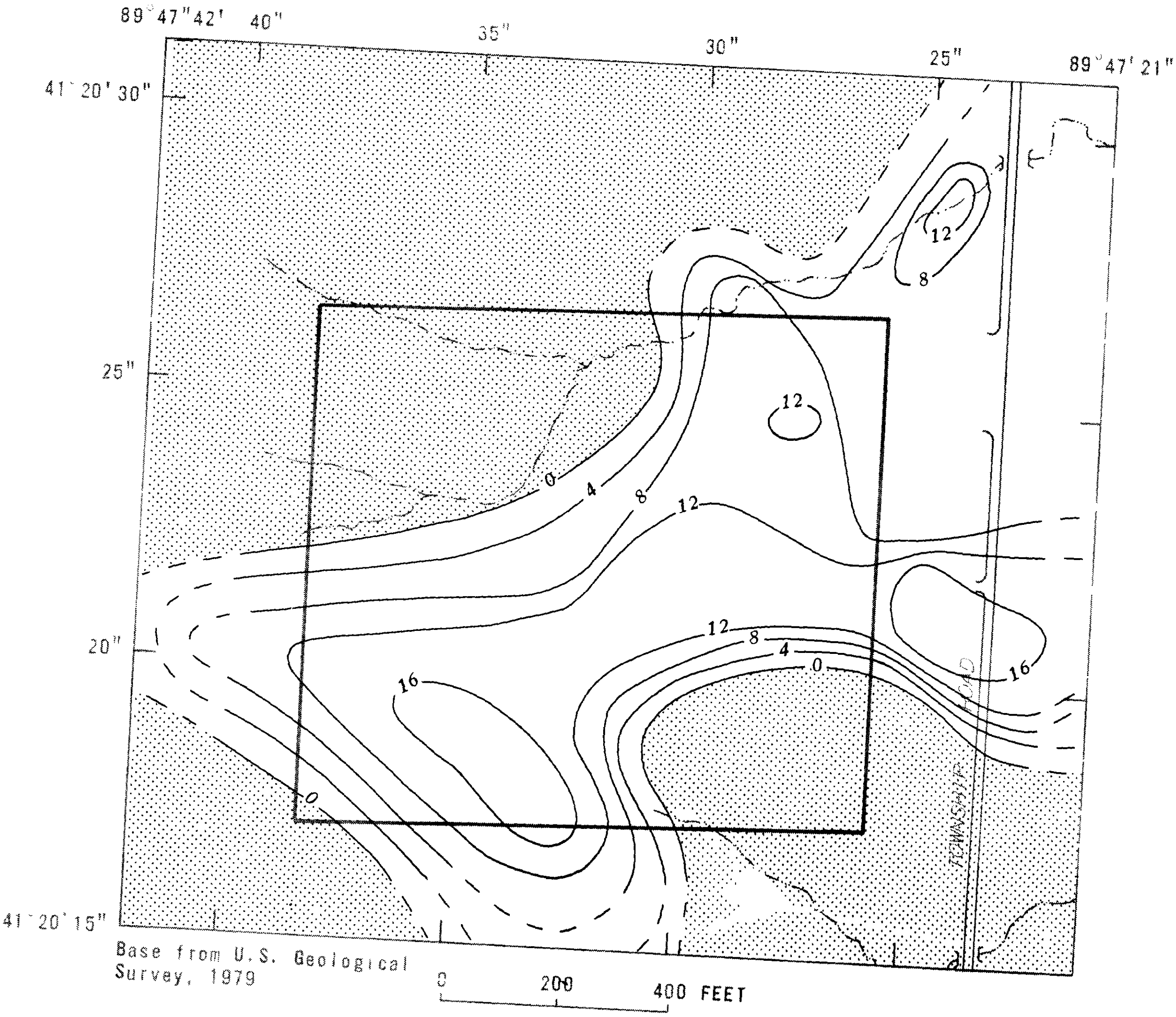


EXPLANATION

GLASFORD FORMATION

526 USGS WELL -- Projected to line of section

Figure 18.-- Geologic section G-G' of Sheffield site.

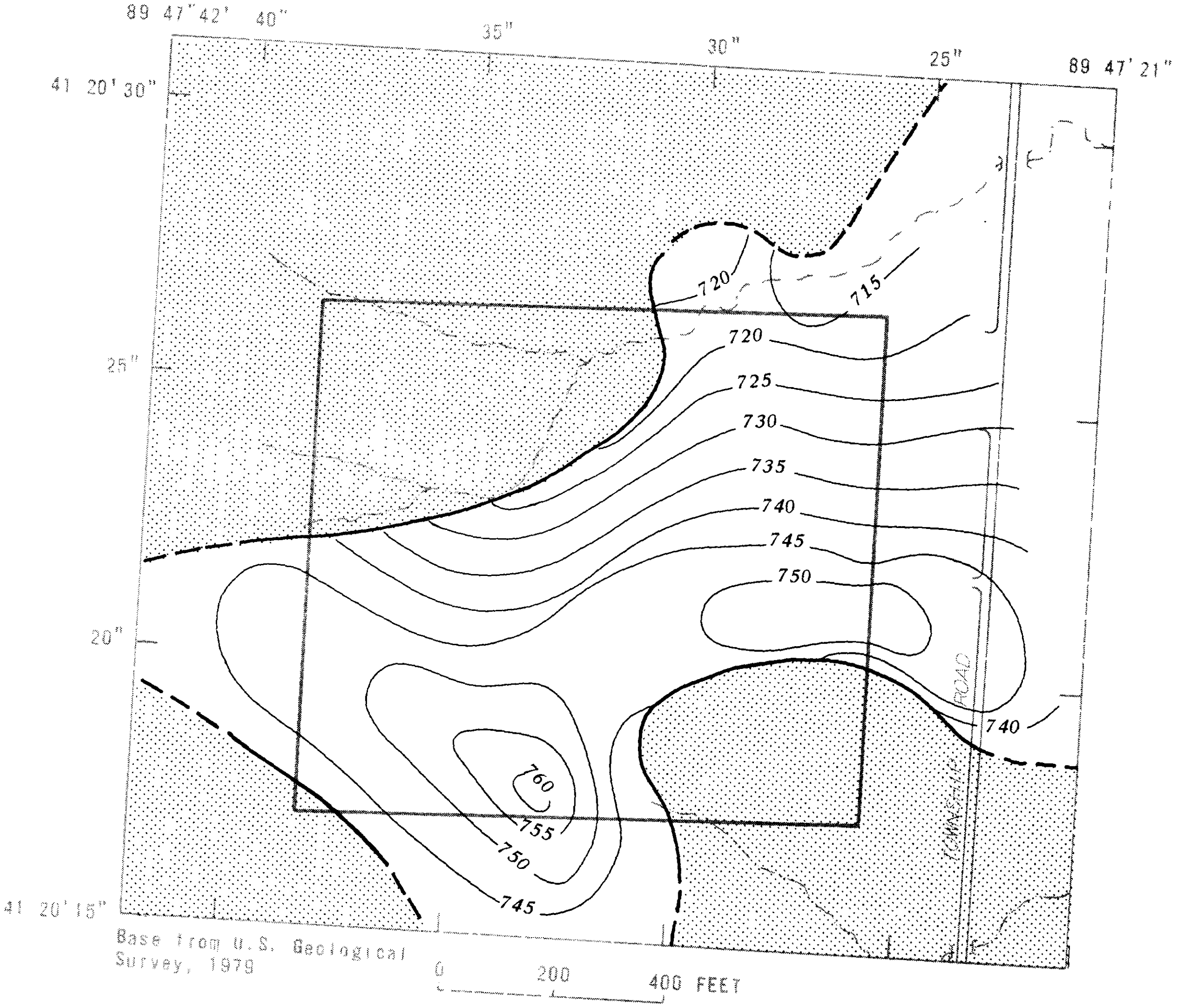


EXPLANATION

AREAL EXTENT OF PEBBLY-SAND UNIT

—— 4 — — LINE OF EQUAL THICKNESS OF PEBBLY-SAND UNIT -- Toulon Member of Glasford Formation. Dashed where inferred. Interval 4 feet

Figure 19.-- Thickness of pebbly-sand unit of Toulon Member of Glasford Formation.



EXPLANATION

AREAL EXTENT OF PEBBLY-SAND UNIT

740 STRUCTURE CONTOUR -- Shows altitude of top of pebbly-sand unit of Toulon Member of Glasford Formation. Contour interval 5 feet. Datum is sea level

EXTENT OF PEBBLY-SAND UNIT. DASHED WHERE INFERRED

Figure 20.-- Structure contours of upper surface of pebbly-sand unit of Toulon Member of Glasford Formation.

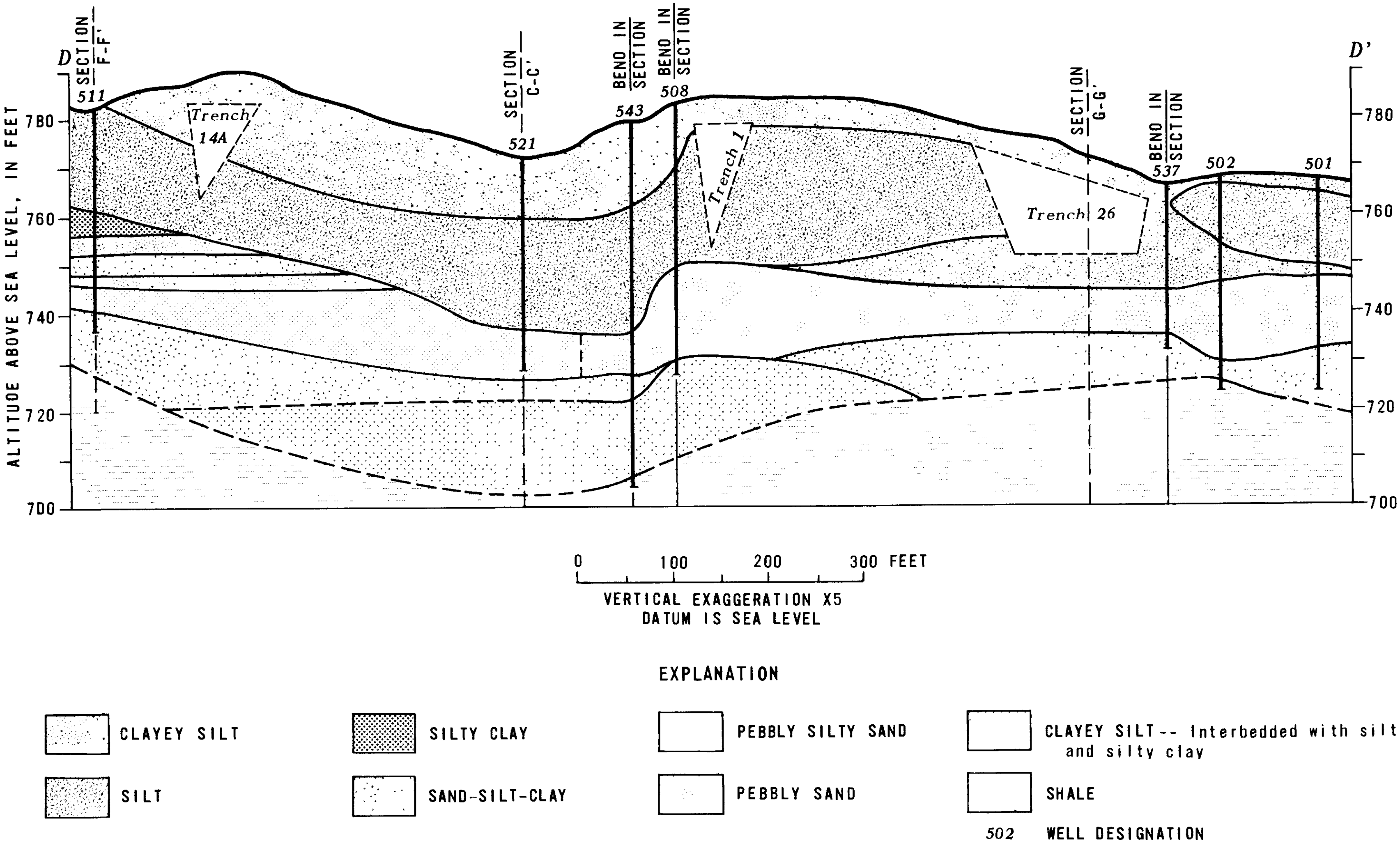


Figure 21.-- Lithologic section D-D' of Sheffield site.

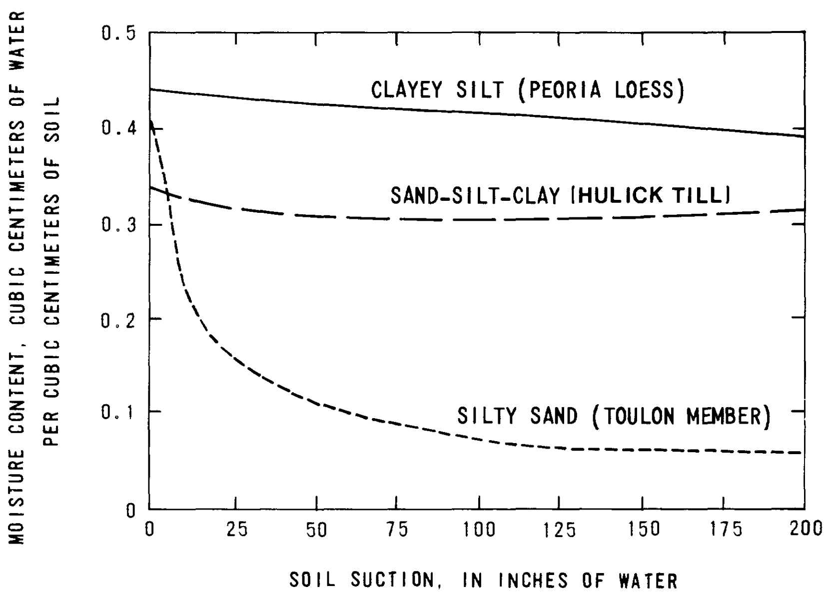


Figure 22.-- Soil moisture-tension curves for soil samples from Sheffield site.

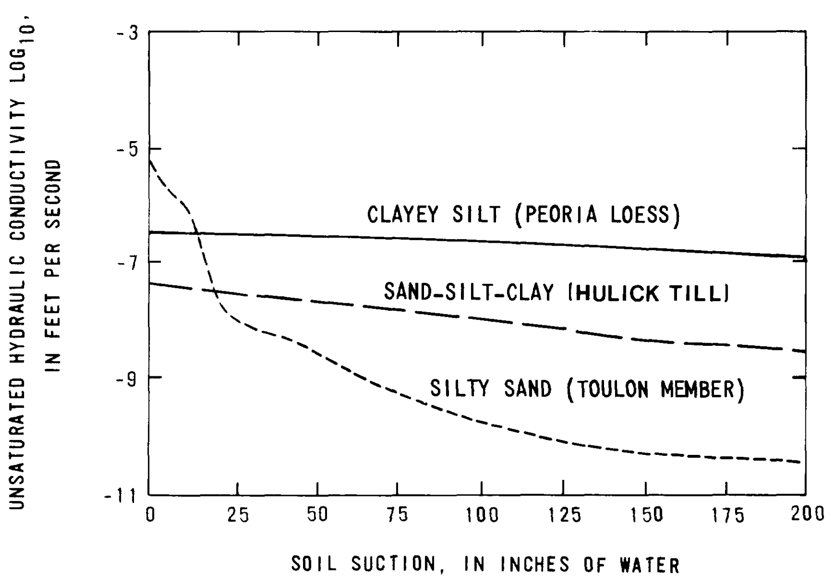


Figure 23.-- Unsaturated hydraulic conductivity-tension curves.

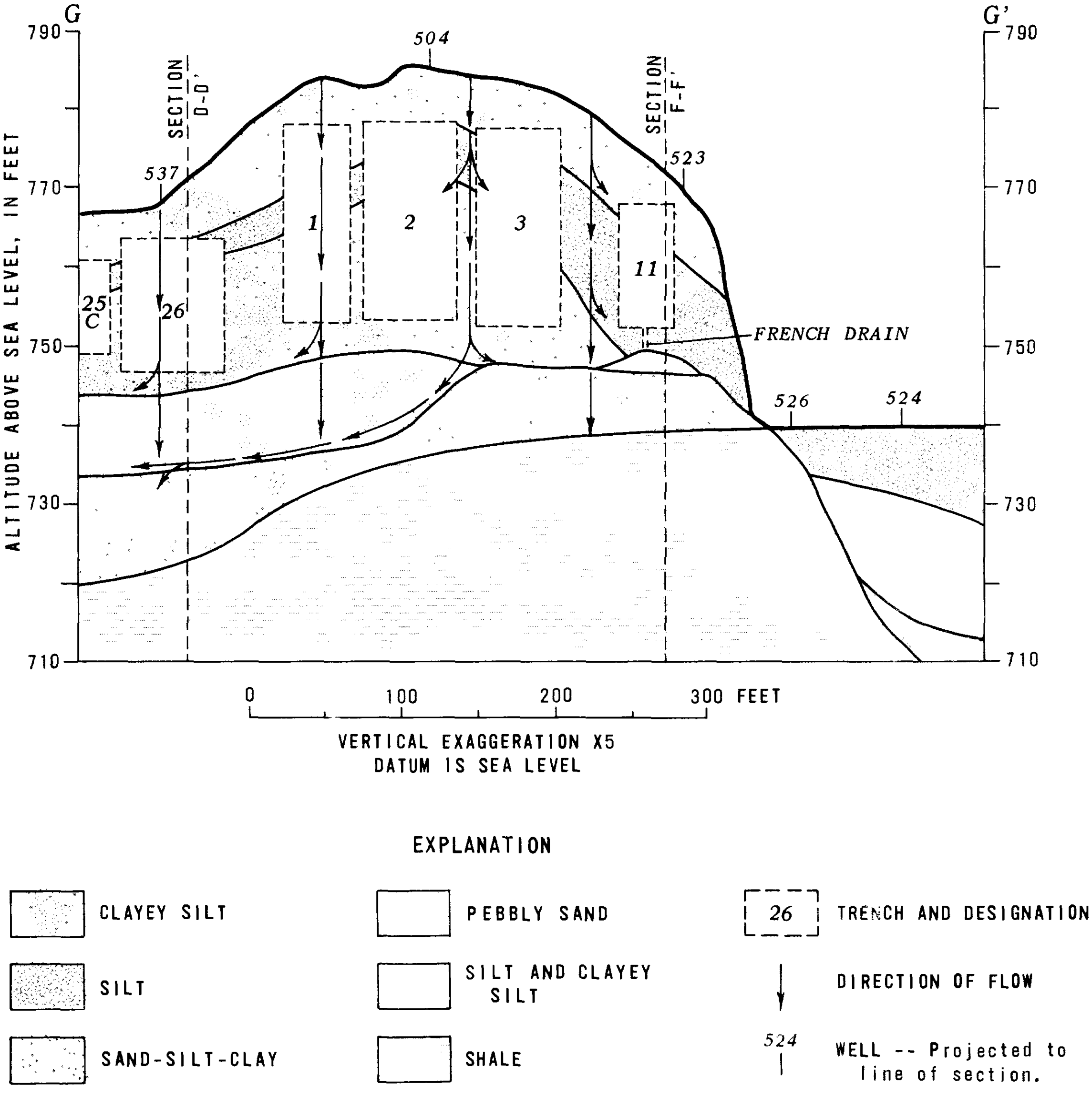


Figure 24.-- Lithologic section G-G' of Sheffield site showing possible flow paths through the unsaturated zone.

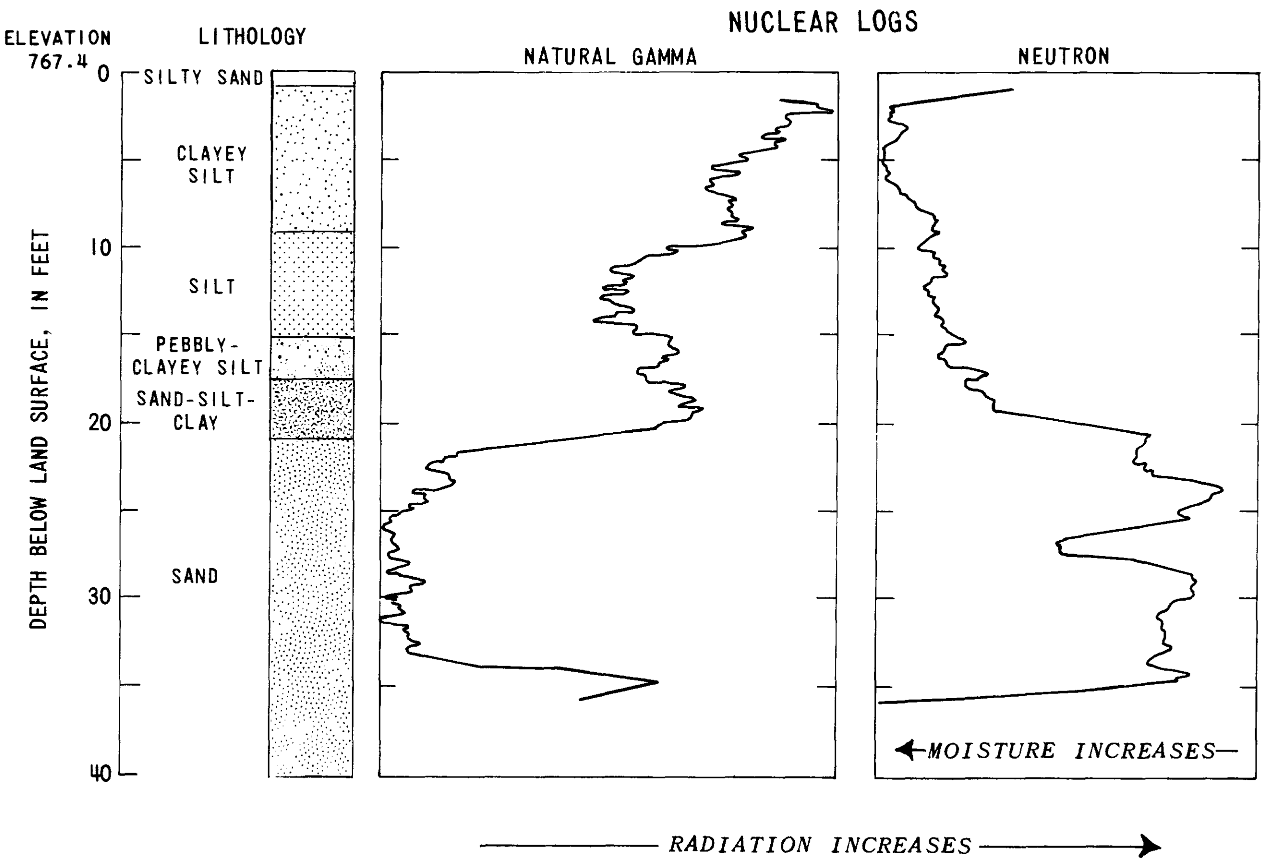


Figure 25.-- Relation between lithology and nuclear logs for well 502.

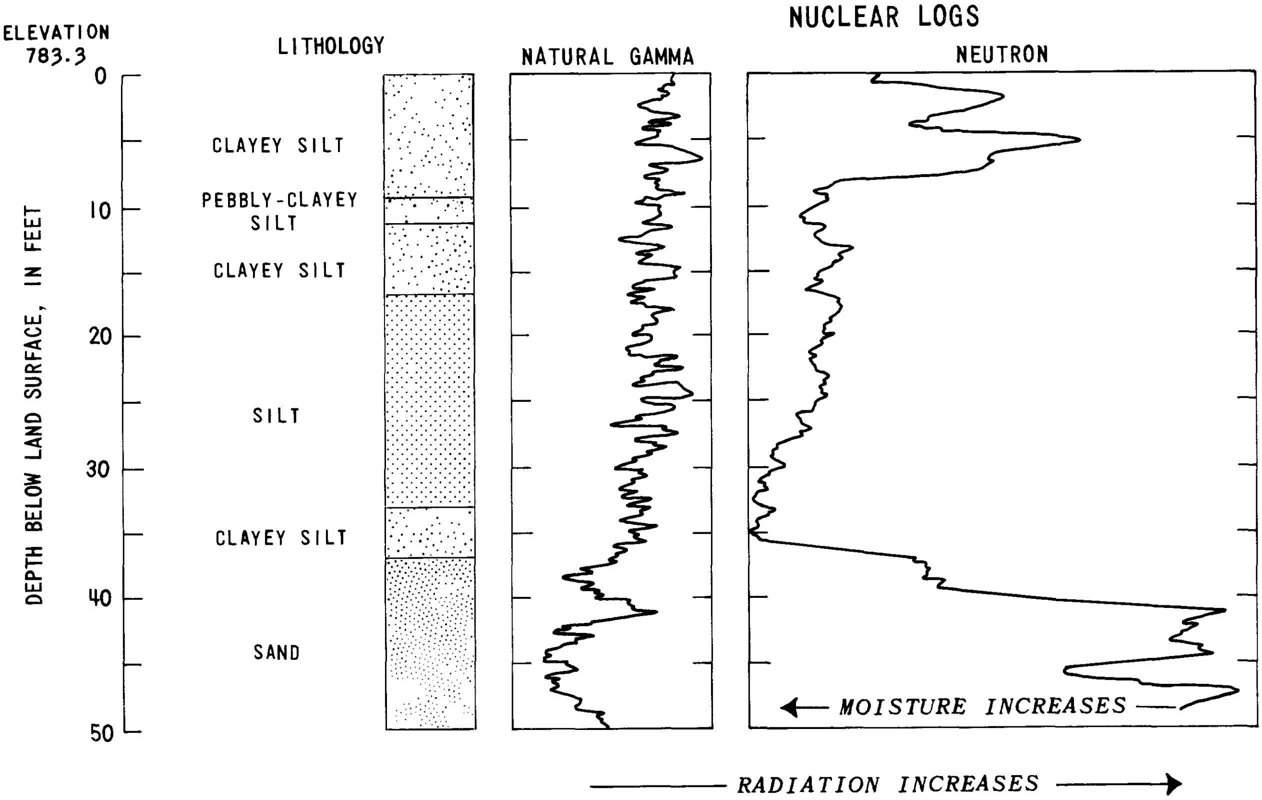


Figure 26.-- Relation between lithology and nuclear logs for well 508.

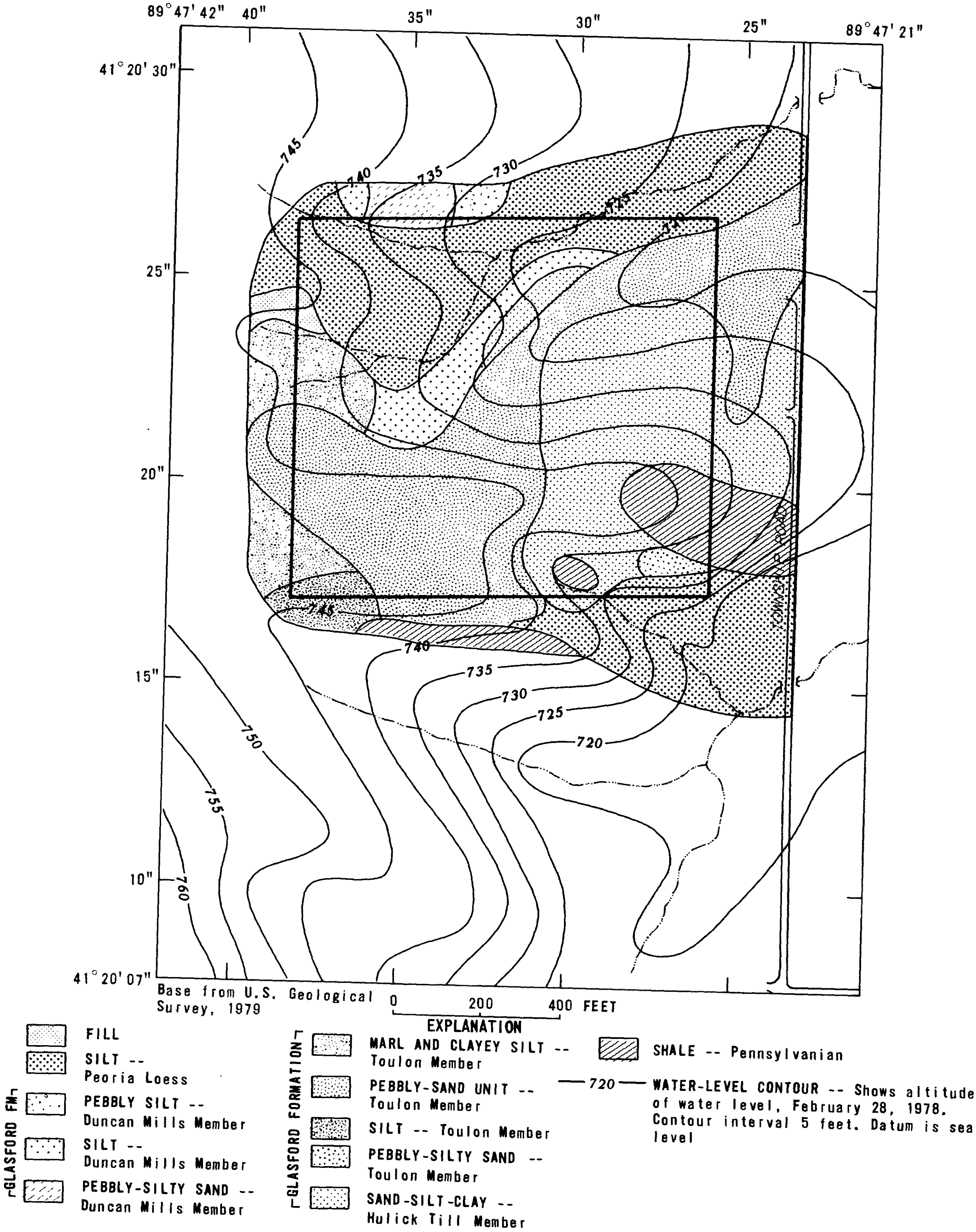
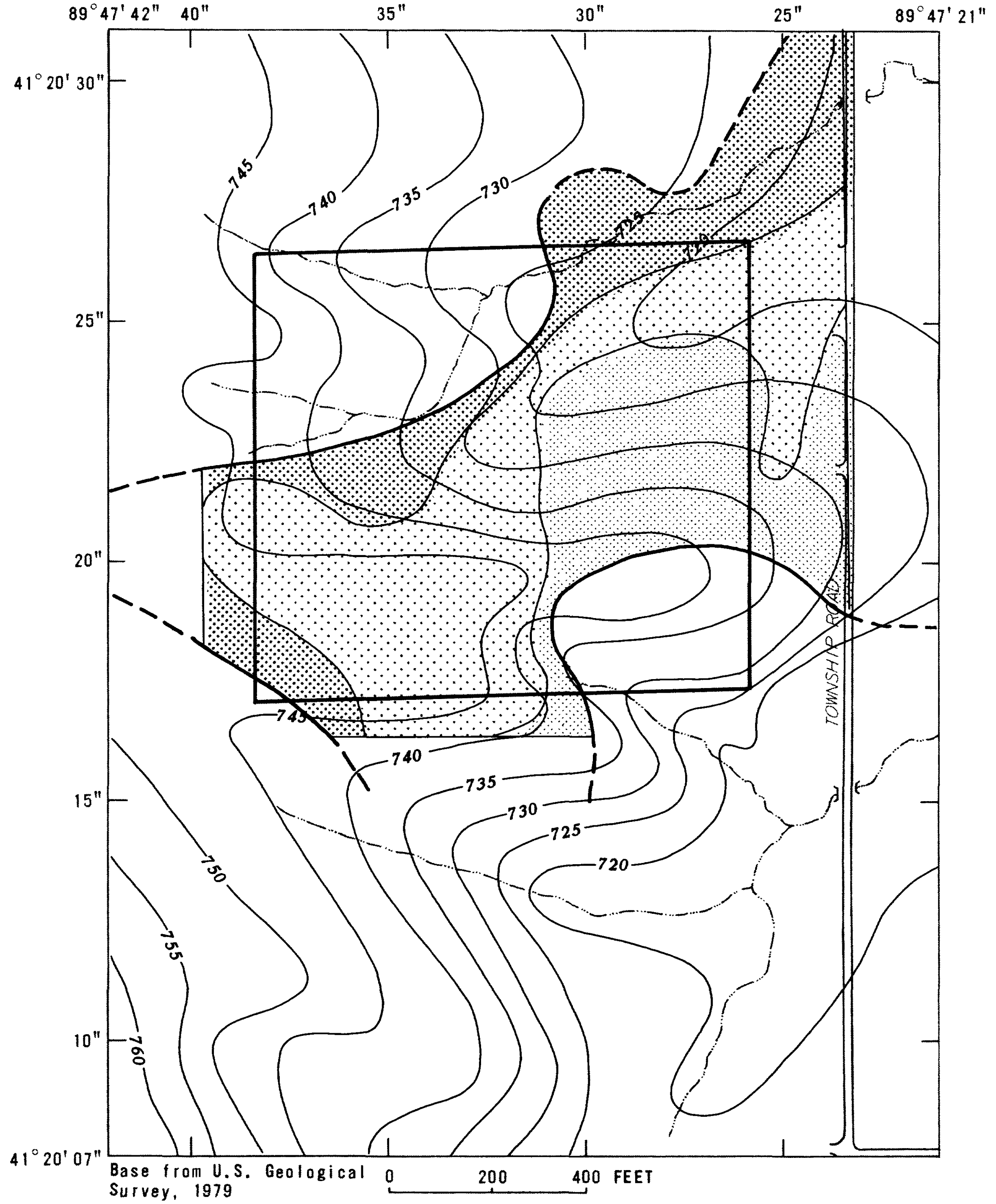


Figure 27.-- Lithology of upper surface of zone of saturation.



EXPLANATION

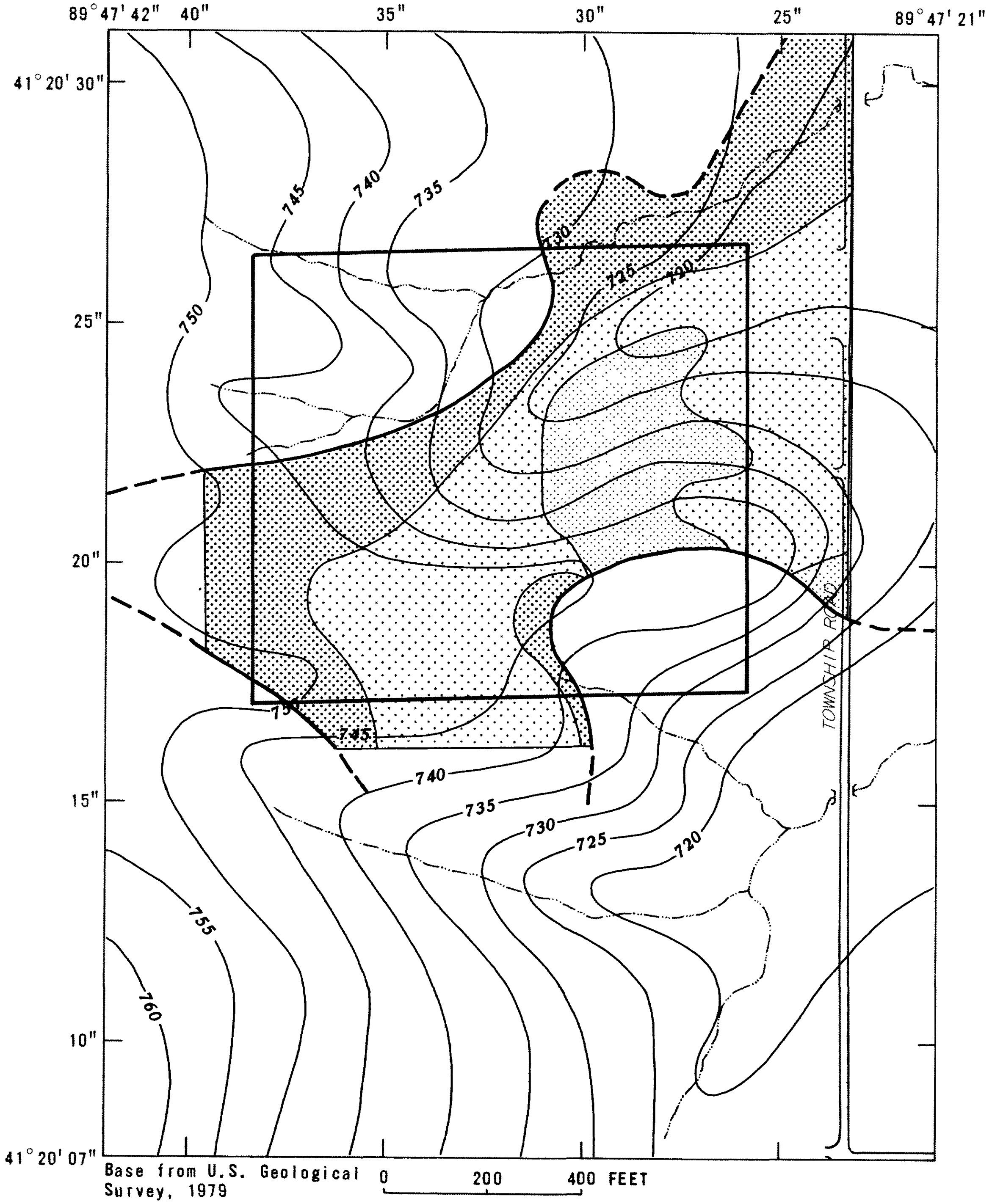
DISTRIBUTION OF PEBBLY-SAND UNIT

- Completely saturated
- Partially saturated
- Dry

—720— WATER-LEVEL CONTOUR -- Shows altitude of water level, February 28, 1978. Contour interval 5 feet. Datum is sea level

— — — EXTENT OF PEBBLY-SAND UNIT. DASHED WHERE INFERRED

Figure 28.-- Water-surface contours and degree of saturation of pebbly-sand unit on February 28, 1978.



EXPLANATION

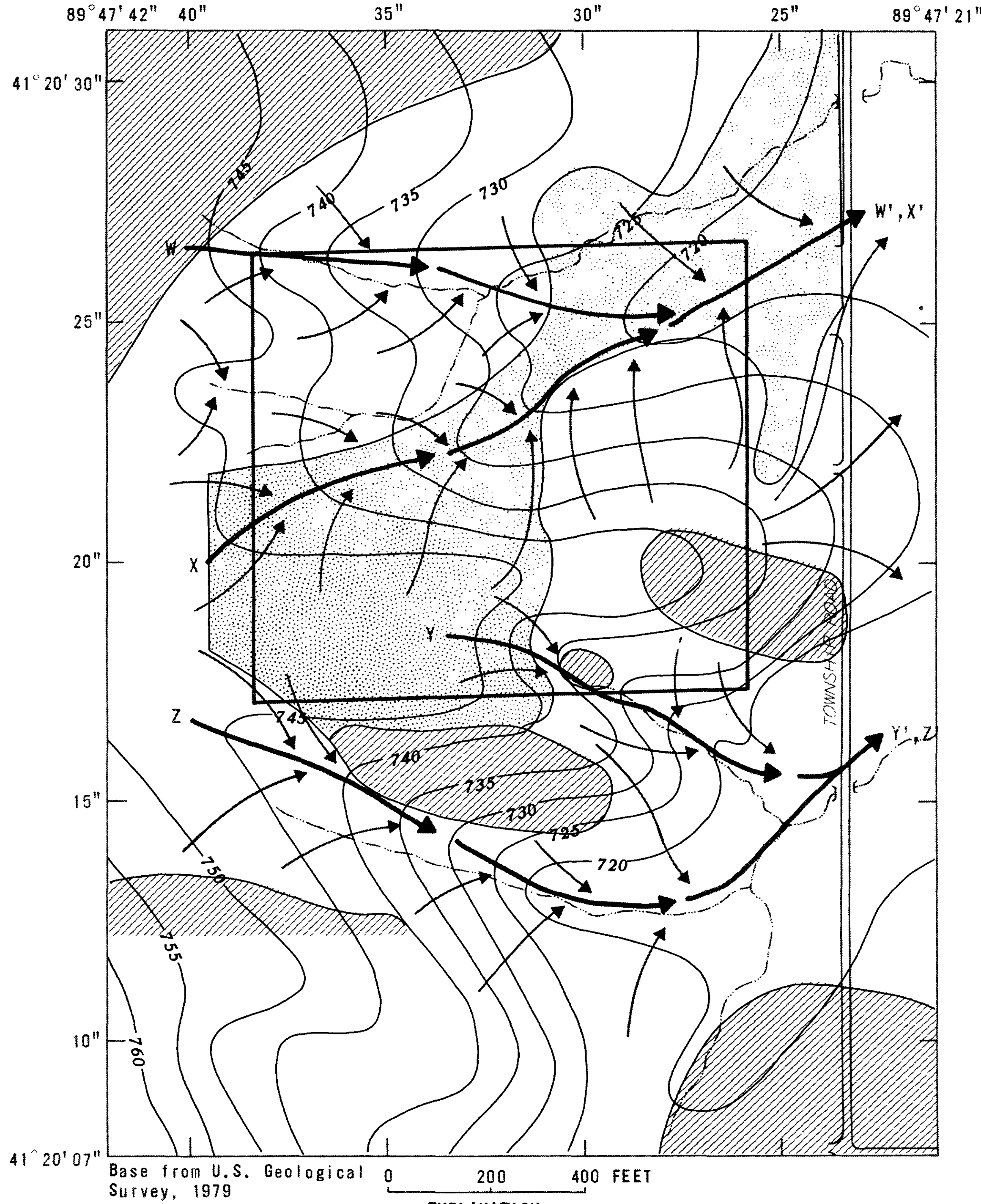
DISTRIBUTION OF PEBBLY-SAND UNIT

- Completely saturated
- Partially saturated
- Dry

—730— **WATER-LEVEL CONTOUR** -- Shows altitude of water level, June, 1979. Contour interval 5 feet. Datum is sea level

EXTENT OF PEBBLY-SAND UNIT. DASHED WHERE INFERRED

Figure 29.-- Water-surface contours and degree of saturation of pebbly-sand unit in June, 1979.



EXPLANATION

BEDROCK -- Area where bedrock elevation is at or above the water table

PEBBLY-SAND UNIT -- Partially or completely saturated

—720— WATER-LEVEL CONTOUR -- Shows altitude of water level, February 28, 1978. Contour interval 5 feet. Datum is sea level

FLOW PATHS

W - W' Northern boundary of flow
X - X' Primary flow path
Y - Y' Secondary flow path
Z - Z' Southern boundary of flow

DIRECTION OF GROUND-WATER FLOW

Figure 30.-- Flow boundaries, direction of flow, and principal flow paths for site.

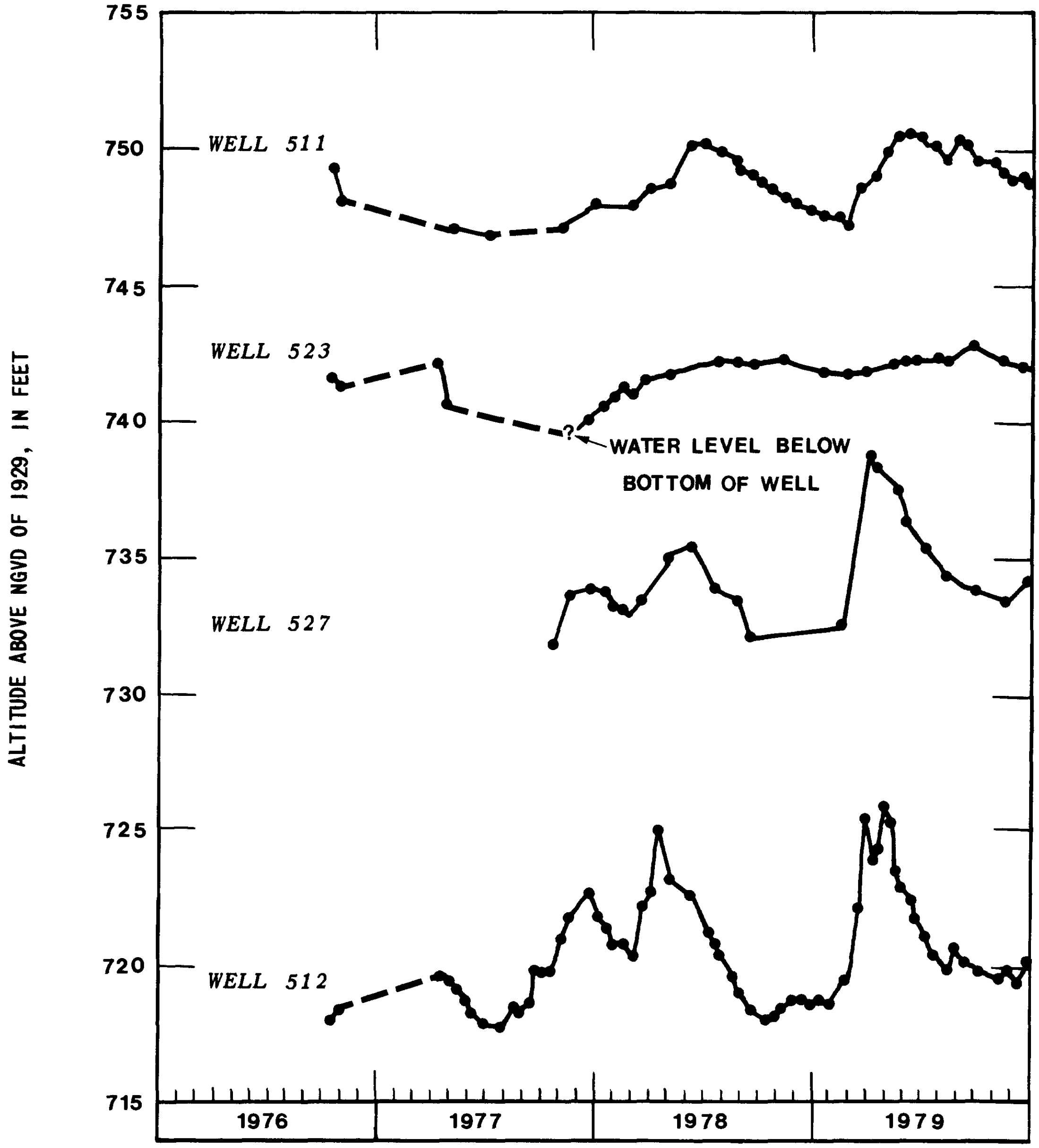
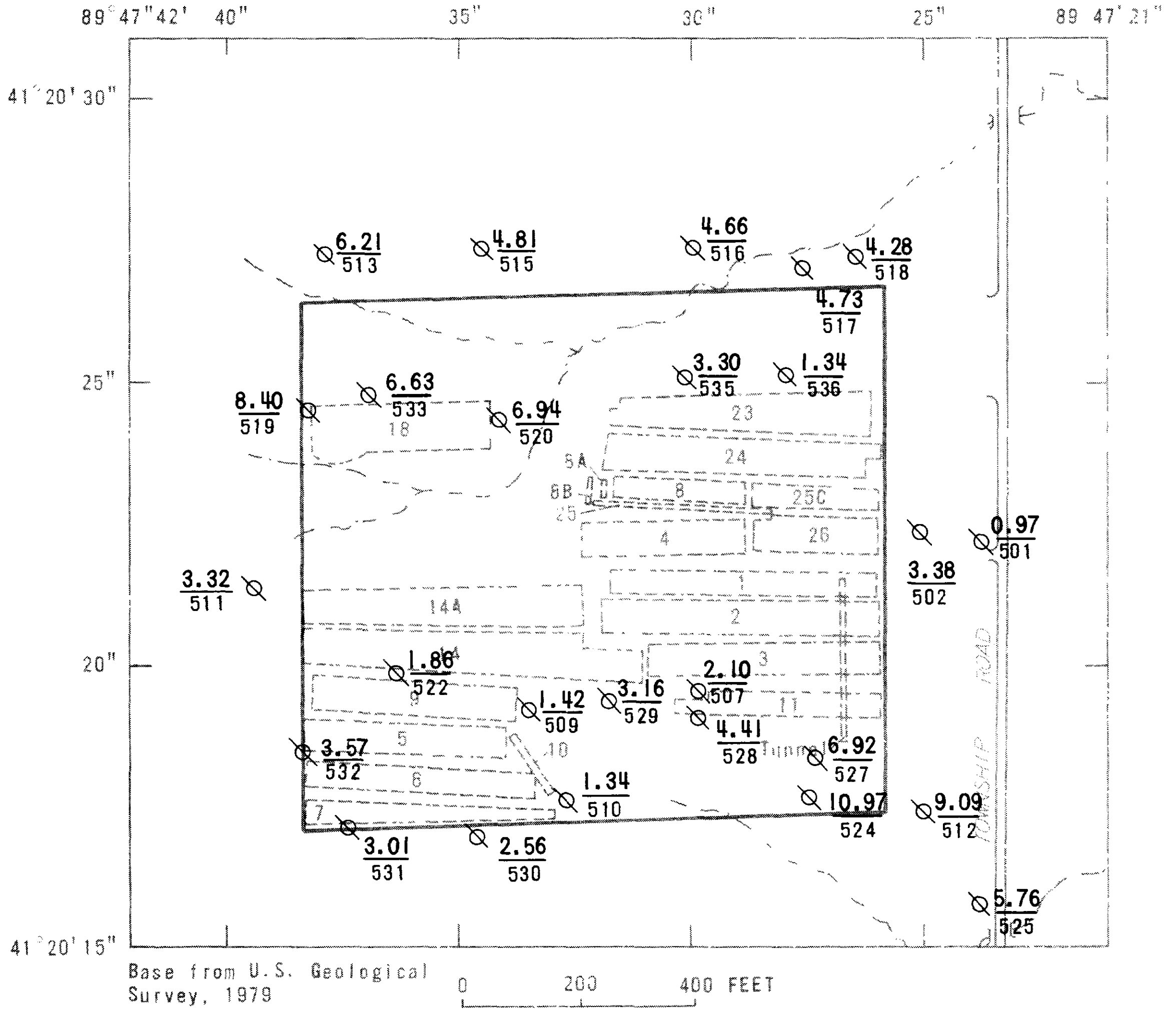


Figure 31.-- Seasonal and annual water-level fluctuations in wells.



EXPLANATION

3.01 / 531 — **OBSERVATION WELL** -- Upper number is range of water-level fluctuation in feet for period of record; October, 1976 to January, 1980. Lower number is well designation

7 — **TRENCH AND DESIGNATION**

Figure 32.-- Range of water-level fluctuations in wells from October 1976 to January 1980.

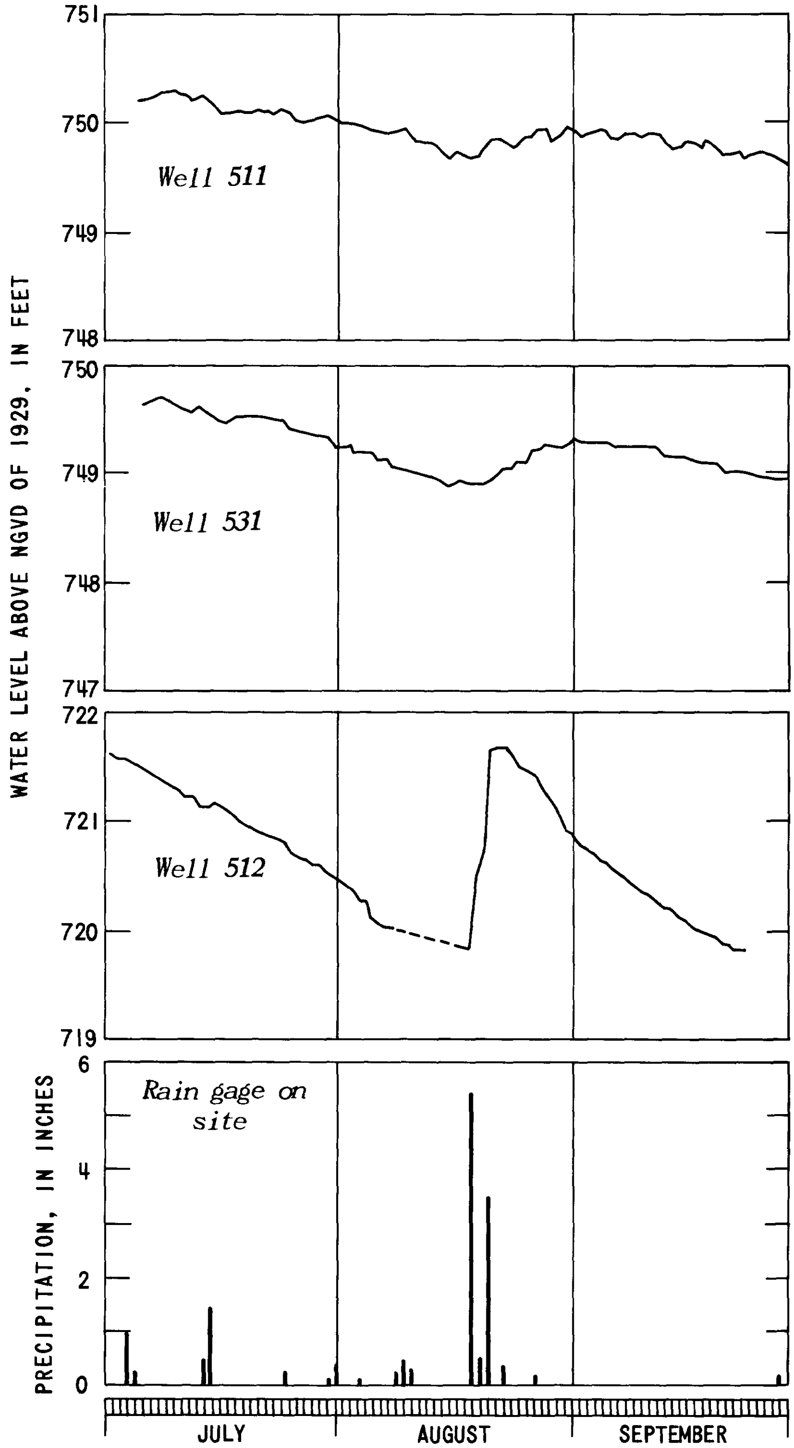


Figure 33.-- Water levels in wells compared to precipitation during July-September 1979.

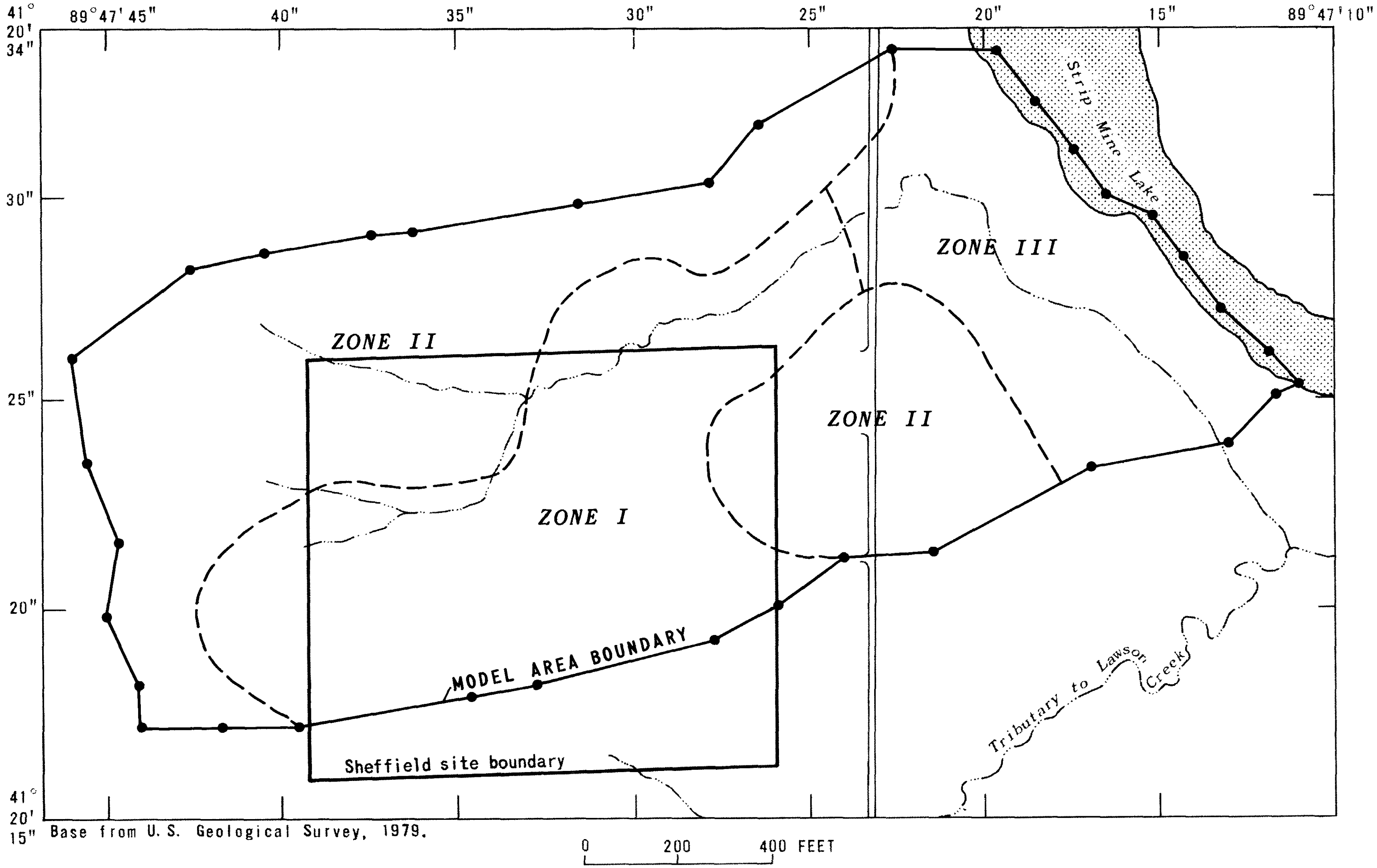


Figure 34.-- Model area boundaries.

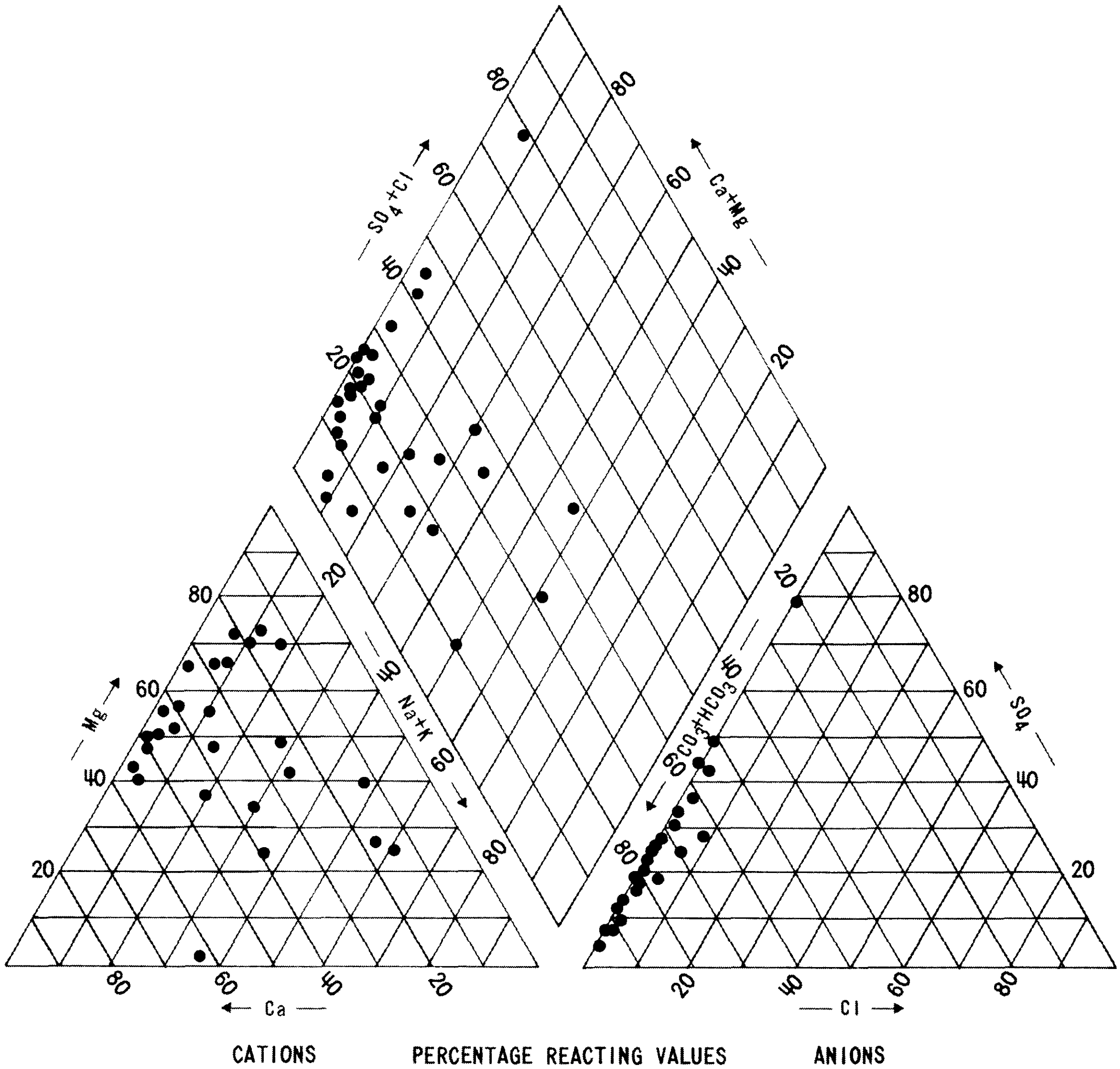


Figure 35.-- Trilinear diagram of ground water from Sheffield site.

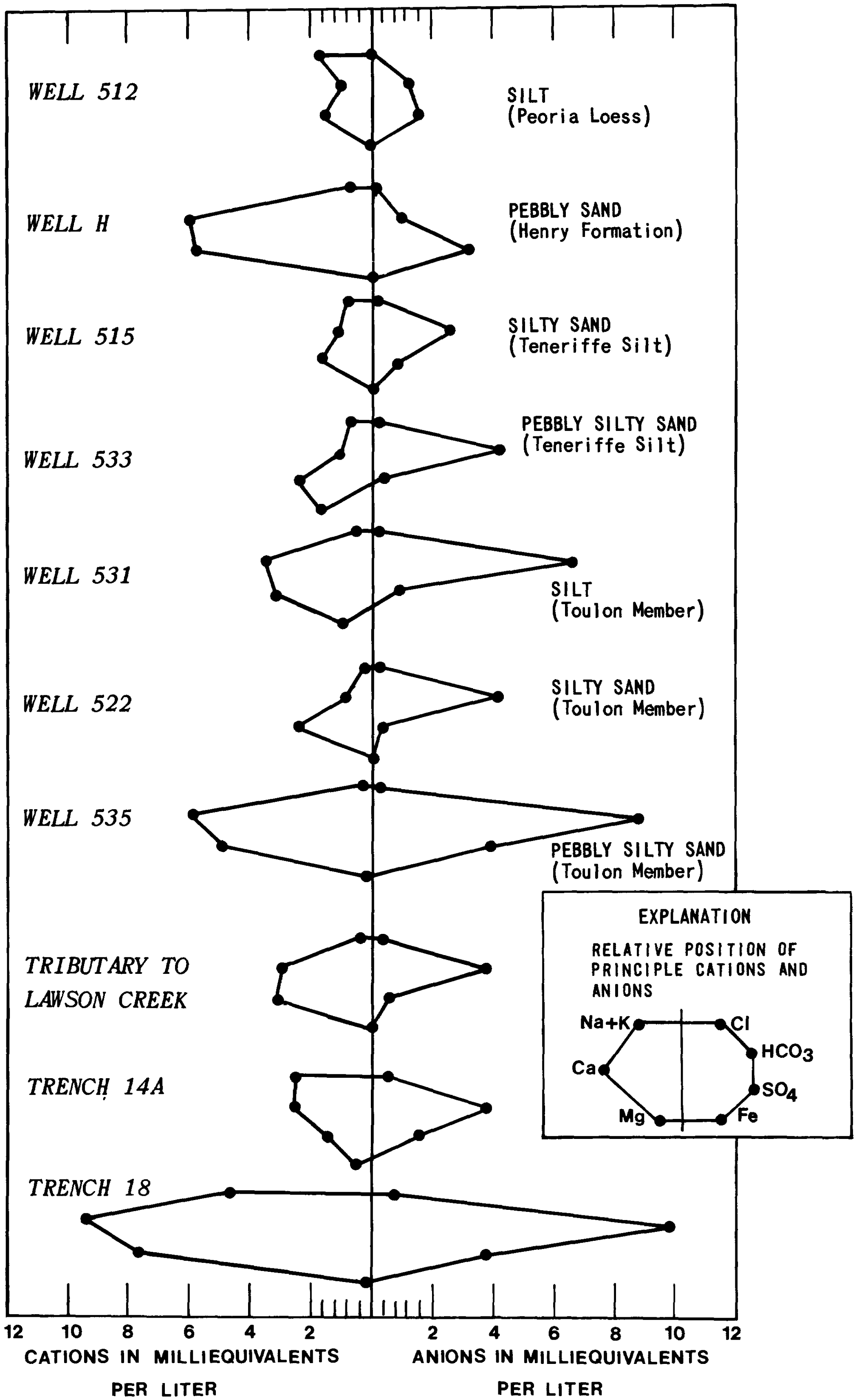
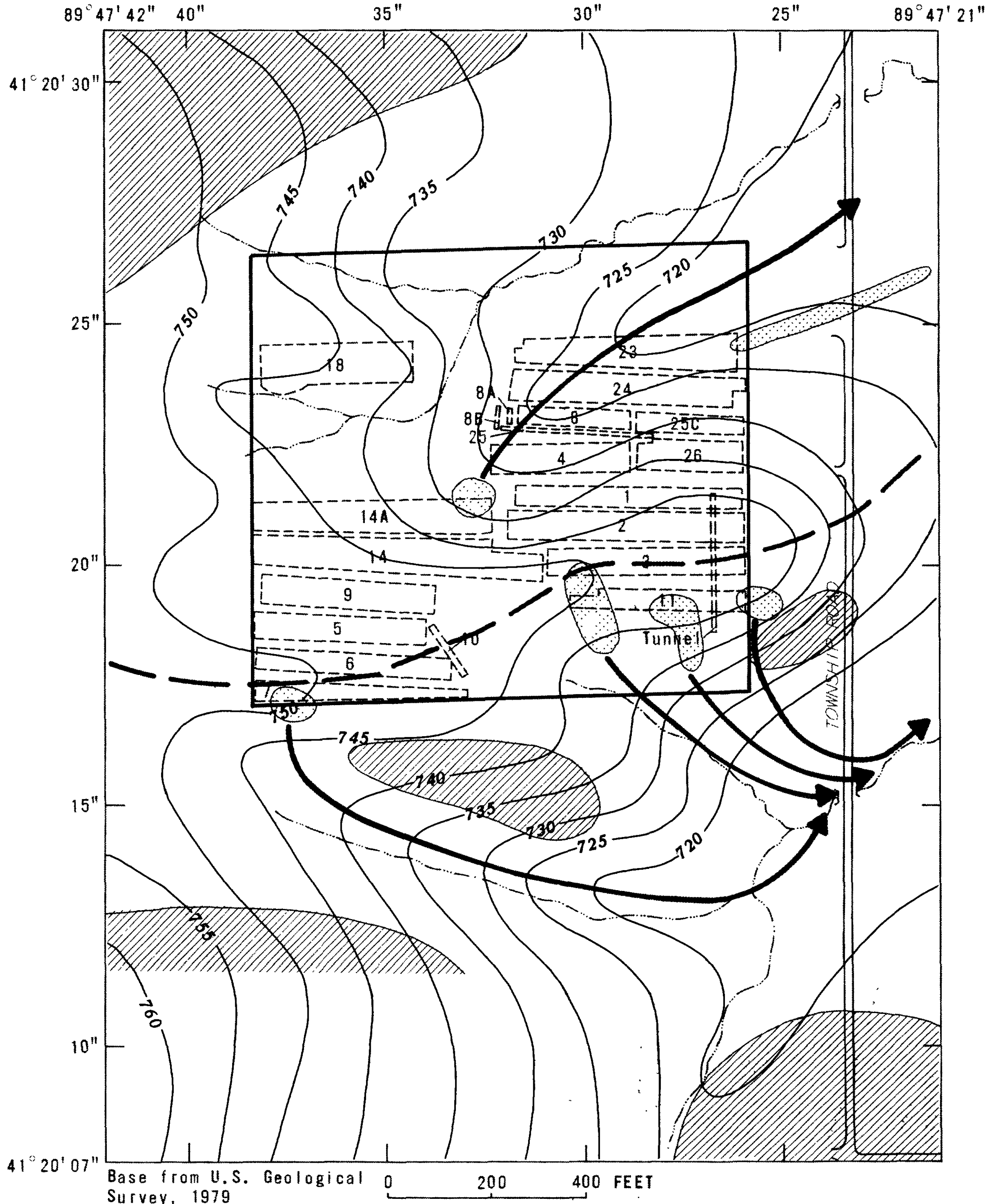


Figure 36.-- Stiff diagrams showing concentrations of principal cations and anions in water.



EXPLANATION

BEDROCK -- Area where bedrock elevation is at or above the water table

AREAS OF TRITIUM MIGRATION

7 TRENCH AND DESIGNATION

—730— WATER-LEVEL CONTOUR -- Shows altitude of water level, June, 1979. Contour interval 5 feet. Datum is sea level

FLOW PATHS OF TRITIUM

GROUND-WATER DIVIDE

Figure 37.-- Projected flow paths of tritium migration in ground water in relation to trenches.

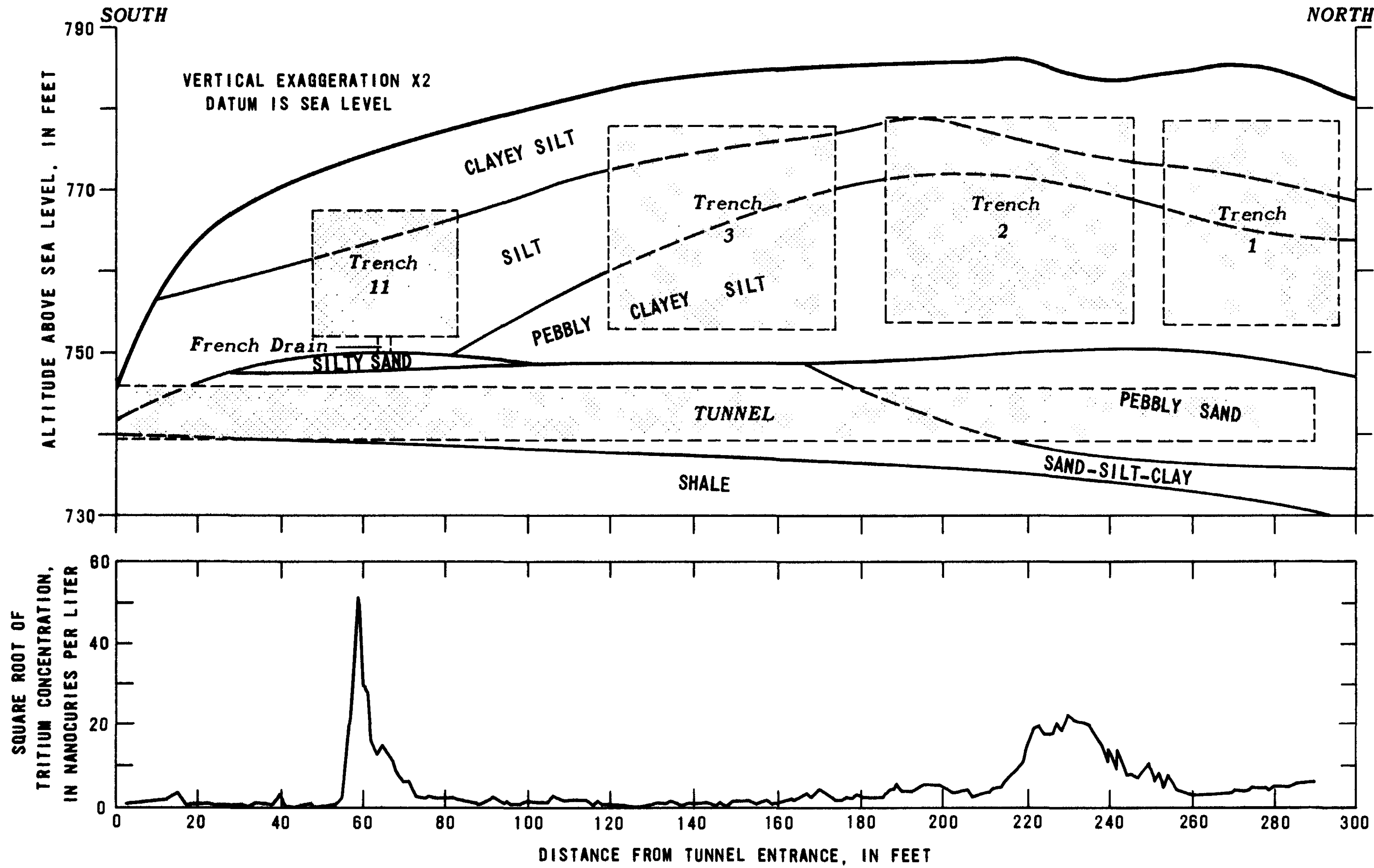


Figure 38.-- Tritium concentration in soil moisture along the tunnel in relation to the overlying trenches.

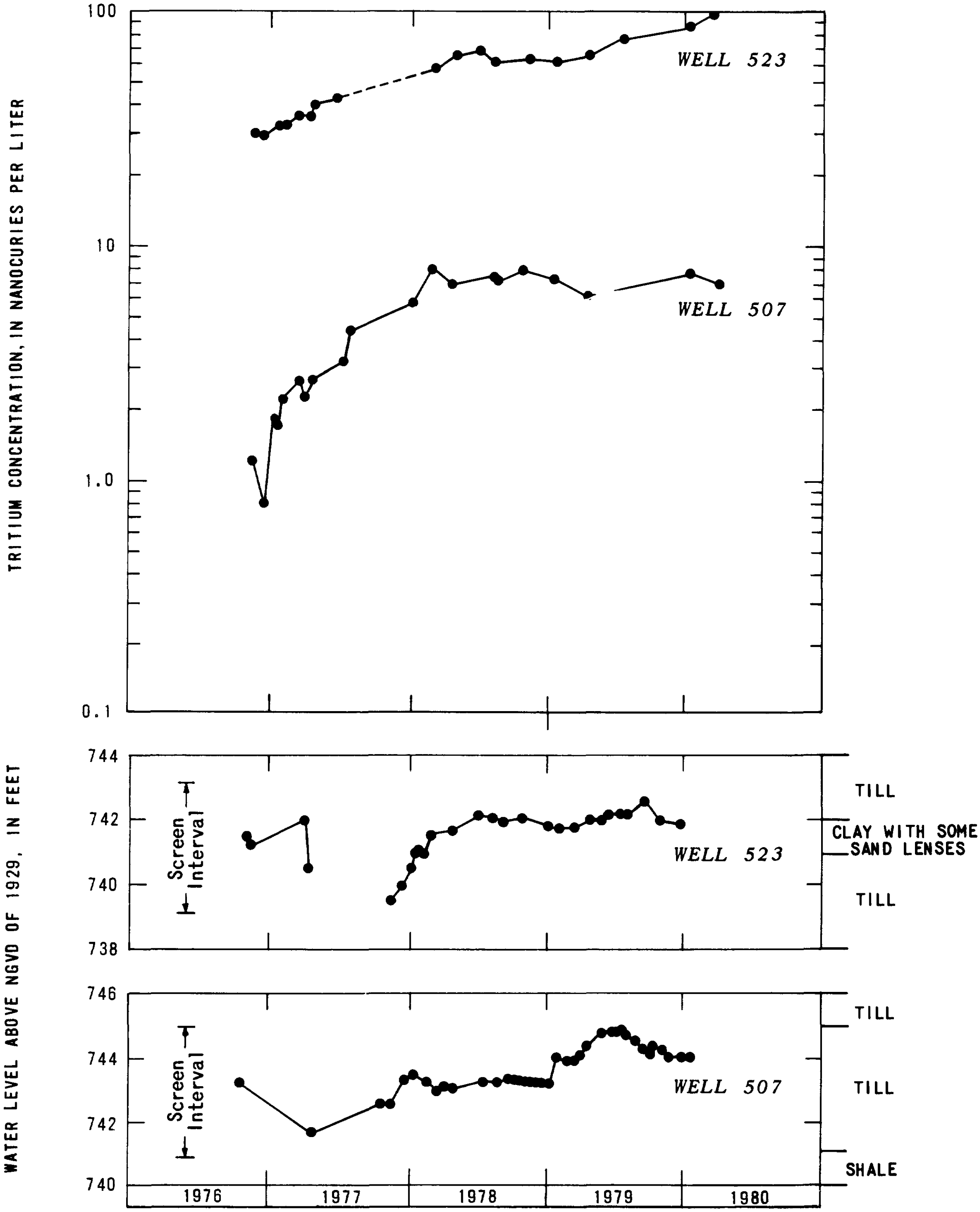


Figure 39.-- Tritium concentration in water in relation to water levels.

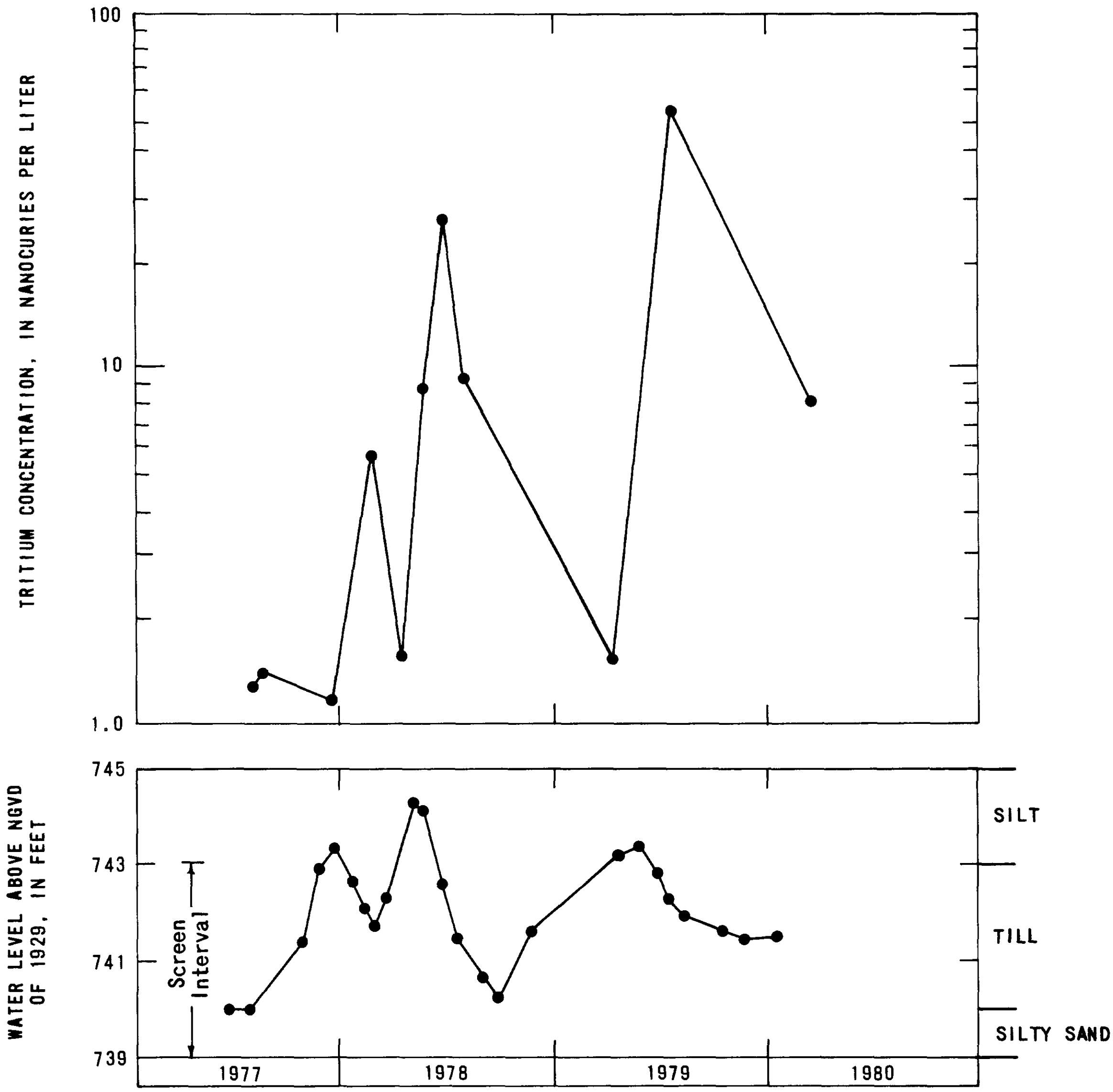


Figure 40.-- Tritium concentration in water from well 528 in relation to its water level.

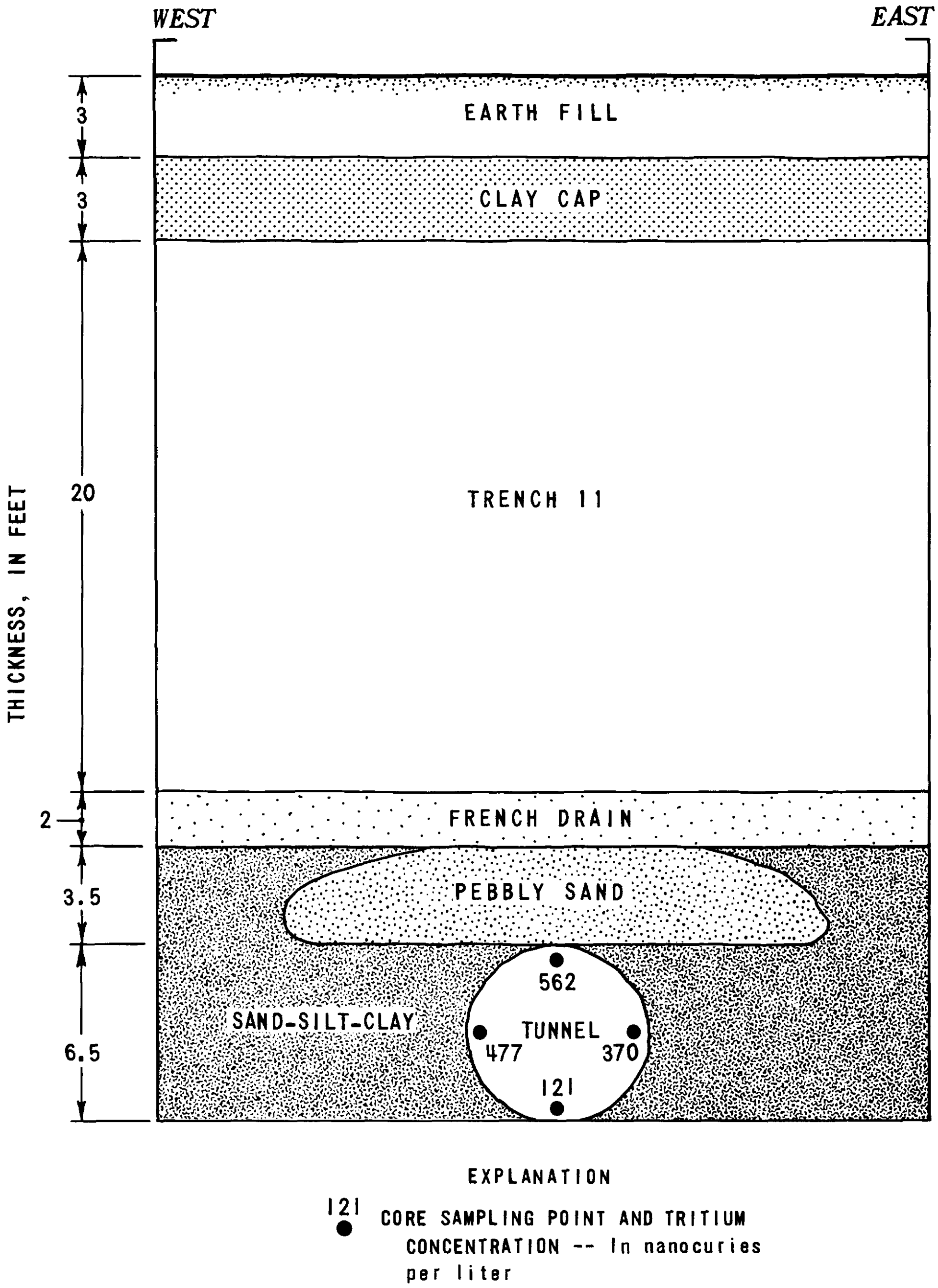


Figure 41.-- East-west section through tunnel and trench 11 showing the vertical change in tritium concentration.

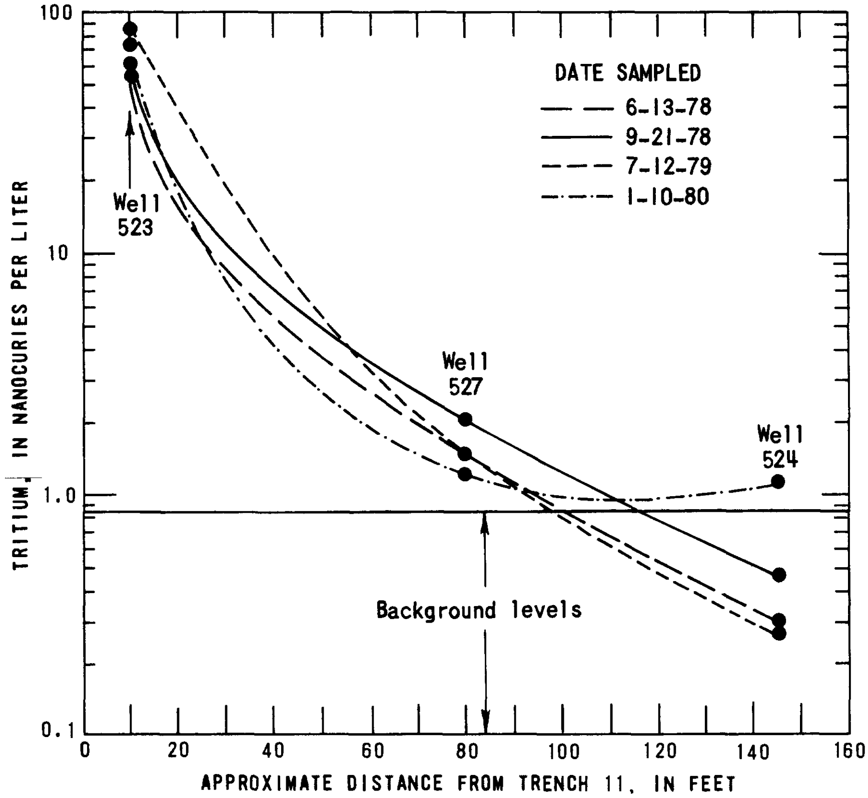


Figure 42.-- Tritium concentrations in water from selected wells versus distance from trench 11.

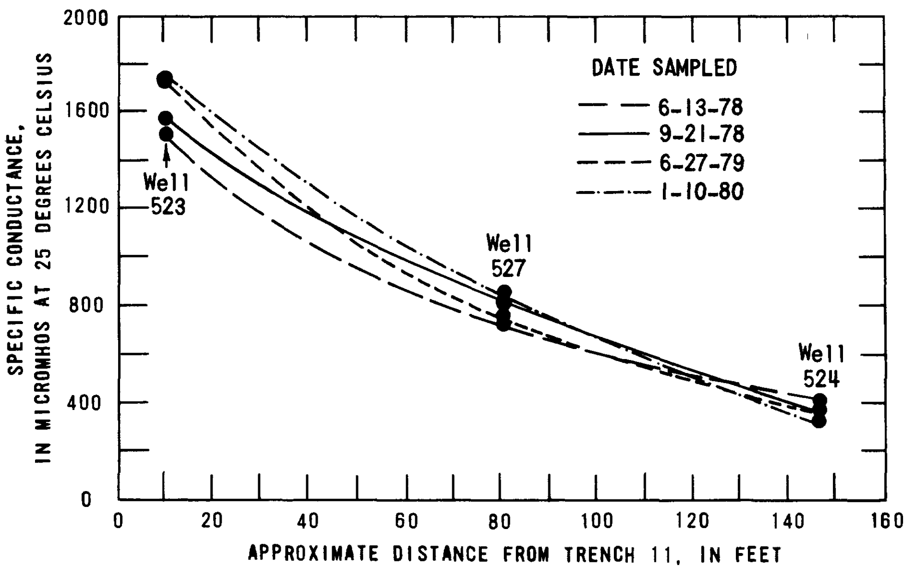


Figure 43.-- Specific conductance of water from selected wells versus distance from trench 11.

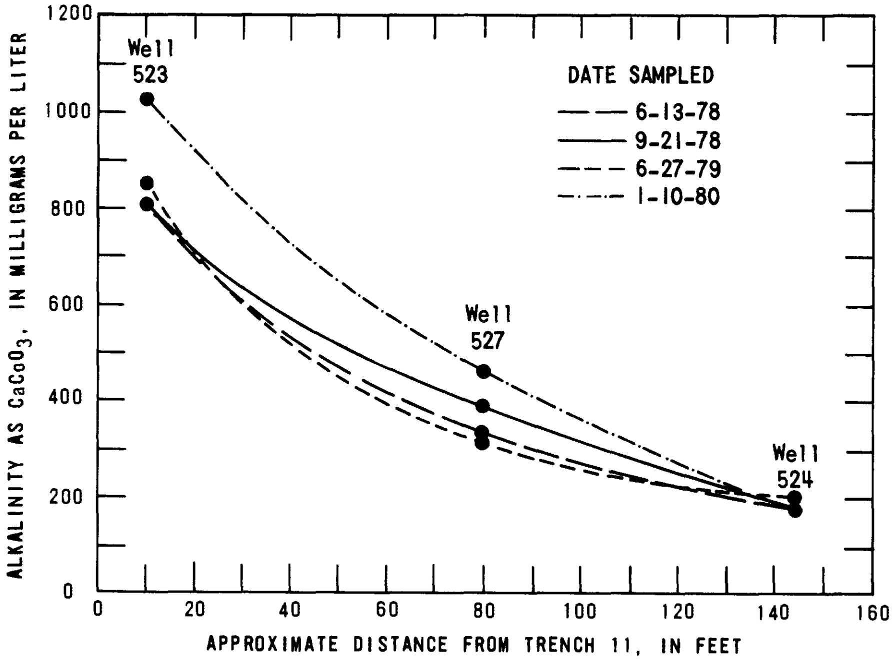


Figure 44.-- Alkalinity in water from selected wells versus distance from trench 11.

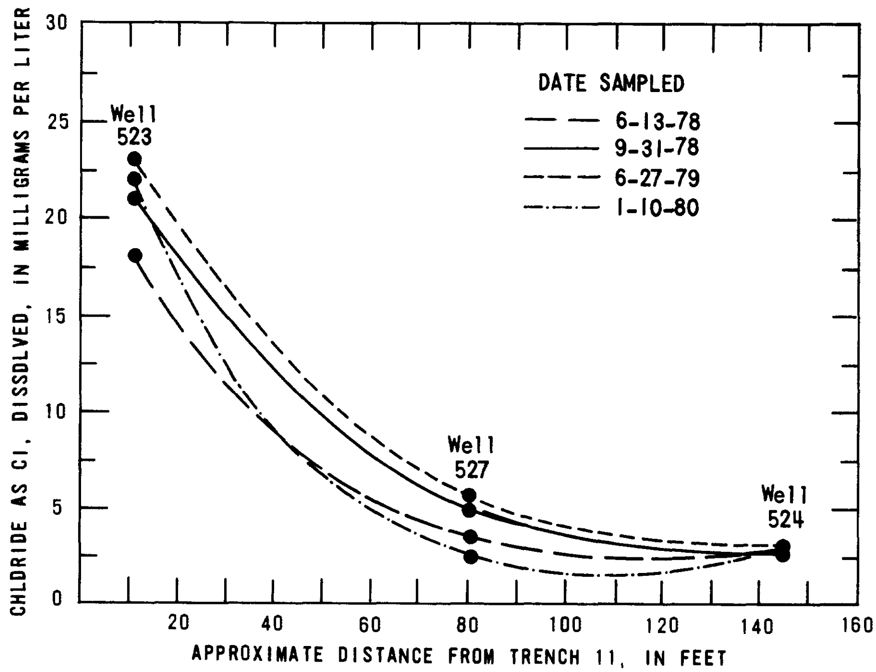


Figure 45.-- Chloride in water from selected wells versus distance from trench 11.

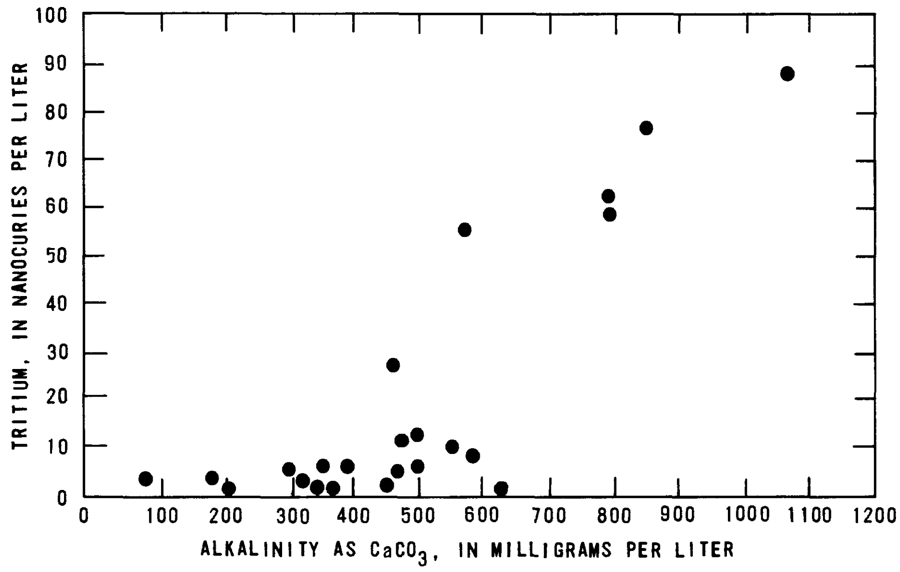


Figure 46.-- Concentrations of alkalinity versus tritium in water from selected wells.

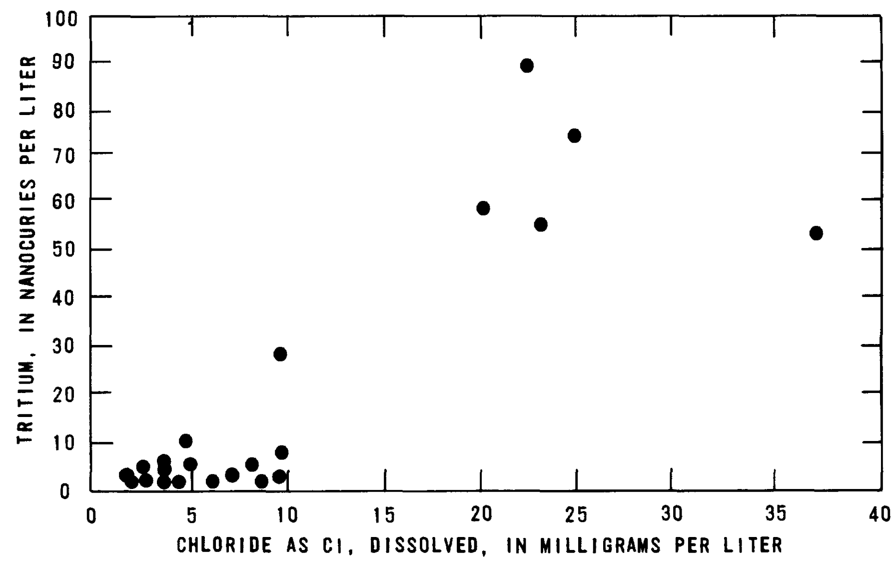


Figure 47.-- Concentrations of dissolved chloride versus tritium in water from selected wells.

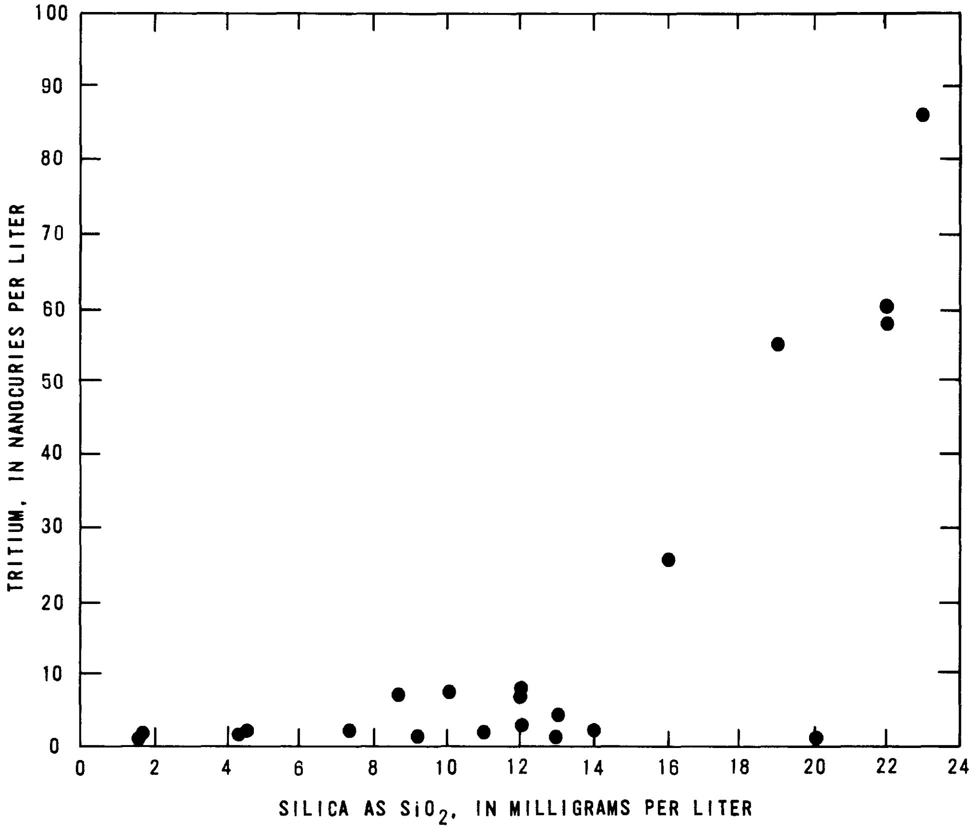


Figure 48.-- Concentrations of dissolved silica versus tritium in water from selected wells.