INJECTION OF TREATED WASTEWATER FOR GROUND-WATER RECHARGE IN THE PALO ALTO BAYLANDS, CALIFORNIA, HYDRAULIC AND CHEMICAL INTERACTIONS--PRELIMINARY REPORT

By Scott N. Hamlin

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JAMES G. WATT, SECRETARY

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Federal Building, Room W-2235
2800 Cottage Way
Sacramento, California 95825

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CONVERSION FACTORS

For readers who prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
Å (Angstroms)	0.0000001	mm (millimeters)
acres	0.4047	hm^2 (square hectometers)
acre-ft (acre-feet)	0.001233	hm^3 (cubic hectometers)
acre-ft/yr (acre-feet per year)	0.001233	hm^3/a (cubic hectometers per annum)
feet	0.3048	meters
ft/d (feet per day)	0.3048	m/d (meters per day)
ft^2 (square feet)	0.09290	m^2 (square meters)
ft^2/d (feet squared per day)	0.09290	m^2/d (meters squared per day)
ft^3 (cubic feet)	0.02832	m^3 (cubic meters)
ft^3/d (cubic feet per day)	0.02832	m^3/d (cubic meters per day)
gal/min (gallons per minute)	0.00006309	m^3/s (cubic meters per second)
(gal/min)/ft (gallons per minute per foot)	0.0002070	m^2/s (meters squared per second)
μmho/cm at 25°C (micromhos per centimeter at 25 degrees Celsius)	1	μS/cm at 25°C (microsiemens per centimeter at 25 degrees Celsius)
min/ft^2 (minutes per square foot)	10.764	min/m^2 (minutes per square meter)

ALTITUDE DATUM

National Geodetic Vertical Datum of 1929: A 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. The datum is referred to as sea level in this report.

TRADE NAMES

The use of trade names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

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ABSTRACT

The U.S. Geological Survey, in cooperation with the Santa Clara Valley Water District, is studying the operation of the injection-extraction well network in the Palo Alto Baylands along the San Francisco Bay, California. The well network was designed to flush the shallow aquifer system of saline water and prevent further inland saline contamination. This study investigates clogging processes and solution migration in the vicinity of one injection well.

A review of the geologic history of the area and previous ground-water studies indicates that cyclic evaporative concentration of bay water and infiltration have generated a concentrated ground-water brine. Montmorillonite and illite are the primary clay minerals present in the shallow aquifer system. X-ray diffraction analysis of these clays showed a marked increase in the d-spacing of the crystal lattice when native hypersaline pore water was replaced by injection water. Chloride:magnesium and chloride:potassium ratios in the aquifer system changed during injection, most likely owing to ion-exchange reactions. Similar variations in chloride:boron, chloride:iron, and chloride:manganese ratios probably resulted from reduction-oxidation reactions. Ground-water quality appears to have been chiefly affected by the processes of dilution and dispersion.

Extraction pump test data yielded a transmissivity value of 960 feet squared per day and a storage coefficient of 5×10^{-4} for the lower aquifer. Vertical hydraulic conductivity of the upper confining layer was 0.08 foot per day.

INTRODUCTION

The need for potable water resources in the south San Francisco Bay area is growing steadily, while suitable reserves are declining. By the year 2000, net water demands in California might exceed supplies by as much as 6.6 million acre-ft/yr. Wastewater reclamation and reuse are expected to reduce this figure by at least 600,000 acre-ft/yr, about 10 percent (Asano and Wassermann, 1979).

A major factor contributing to reduced quality and quantity of water supplies is saline contamination of ground water. In Santa Clara County, deterioration of the underground water resource is most severe in the Palo Alto-Los Altos-north Mountain View area (Jenks and Adamson, 1973). This area, known as the Palo Alto Baylands, is a marsh bounded by the 1850 shoreline to the west and by the present margin of San Francisco Bay to the east. A shallow zone of hypersaline ground water, adjacent to and paralleling San Francisco Bay, is a source of contamination to adjacent freshwater zones. The hypersaline ground water is concentrated in an aquifer complex comprising the upper 50 feet of sediment. This shallow baylands aquifer system, which underlies the marsh, contains an upper (20-foot depth) aquifer separated from a lower (45-foot depth) aquifer by a leaky clay layer. A lower freshwater zone, the deep baylands aquifer system below 150 feet in depth, is isolated from the shallow baylands aquifer by a thick clay confining bed. The salt problem in the shallow aquifer system is aggravated by local ground-water overdraft, which has reversed the original bayward potentiometric gradient. Overdraft has also resulted in inland subsidence (Iwamura, 1980).

Among the objectives of the Santa Clara Valley Water District is the prevention of ground-water quality degradation in the aquifers supplying various municipalities and industries in their district. Saline degradation of ground-water supplies is found chiefly around the southern San Francisco Bay. To alleviate this problem, the Santa Clara Valley Water District has constructed a pilot injection-extraction well network in the Palo Alto Baylands to form a freshwater barrier against inland saline migration. The wells are arranged in a series of injection-extraction pairs that form two lines parallel to the bay front. This arrangement is intended to allow injection of reclaimed water from the Santa Clara Valley Water District's advanced wastewater-treatment plant and eventual extraction of this water through inland wells. The aquifer is thereby flushed of saline contamination, and a freshwater barrier is established. Correct location of the injection-extraction network in relation to the saline contaminant source and inland ground-water usage is essential to the success of this project. The location of the Palo Alto wastewater-reclamation study area is shown in figure 1.

Purpose and Scope

The injection facility offers an excellent opportunity to study and evaluate the effectiveness of wastewater injection as a method of water reuse. A major obstacle to injection operations is clogging (reduced specific capacity) resulting from introduction of foreign water into an aquifer system. This phenomenon limits the efficiency of any injection-recharge system. The present study attempts to determine factors that affect injection-well performance.

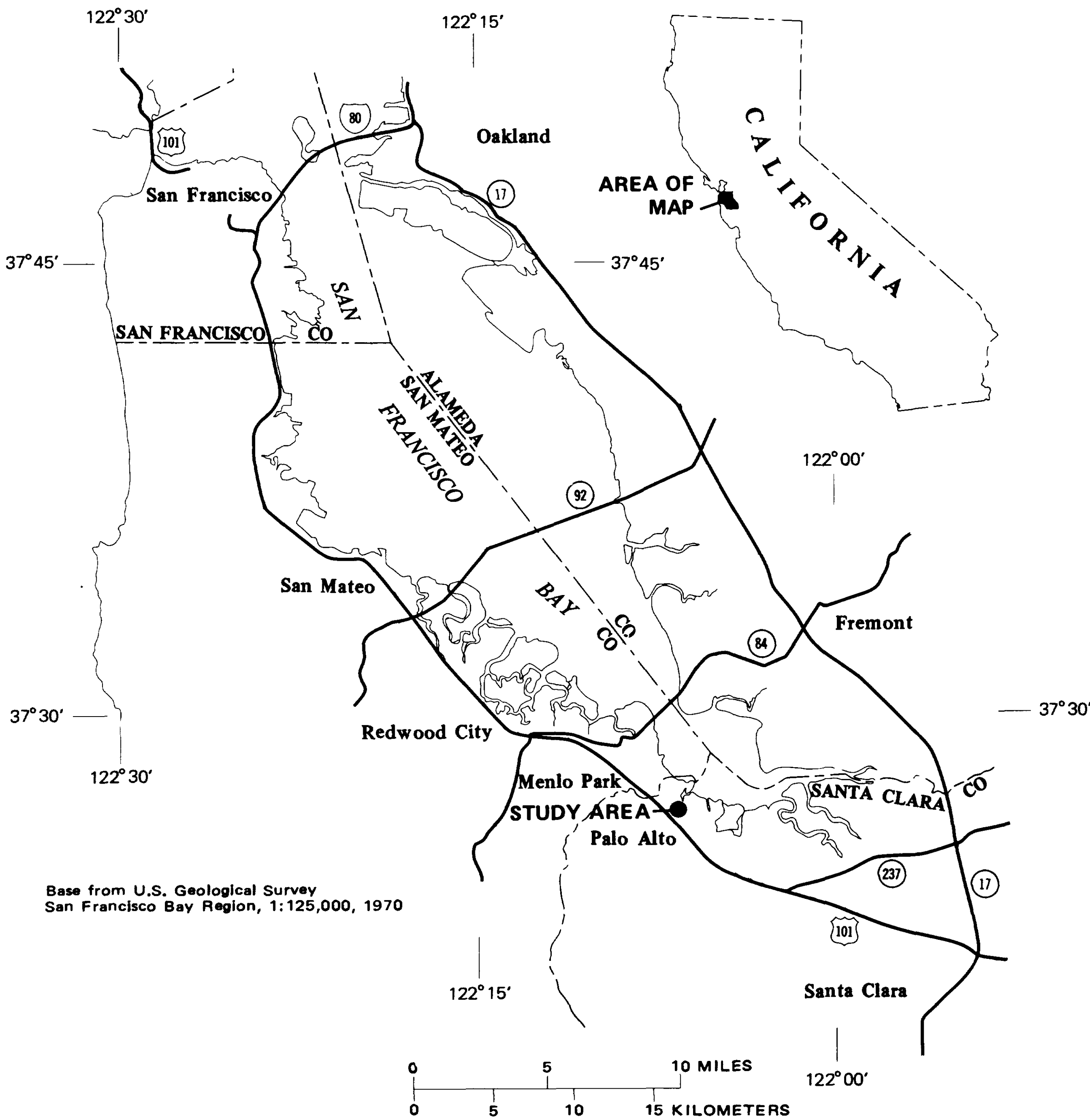


FIGURE 1. – Location of the wastewater-reclamation study area.

The objectives of this study are: (1) to define, both qualitatively and quantitatively, the clogging processes associated with injection, and (2) to determine the three-dimensional migration paths of injection water and native ground water.

In addition to Santa Clara Valley Water District wells, the Geological Survey has installed a network composed of 15 observation wells to monitor hydraulic and chemical changes during constant, low-level injection at well I6. The injection system is evaluated at an individual well (I6) and in the injection network as a whole. The locations of the Santa Clara Valley Water District injection well network and the U.S. Geological Survey study area are shown in figure 2.

The initial phase of study includes a quantitative compilation of clogging, water migration, and solute migration data. Information collected at injection wells I6 and I9 are used in this analysis of factors that control clogging and solution migration.

The final phase of the study involves a qualitative investigation of full-capacity injection at well I6. The primary goals are to determine (1) whether a saltwater barrier is produced and (2) whether salt contamination is further induced during the process. Santa Clara Valley Water District wells to be monitored include S10, S11, S12, S13, S14, S15, S16, S17, S25, M2, M3, and M4 (fig. 2).

Previous Investigations

Jenks and Adamson (1973) made the initial studies of the general area and recommendations for development of the injection network. Brown and Caldwell (1974) completed the actual test drilling and aquifer analysis to determine the specific layout of the injection field.

Roberts (1978a) investigated the injection process at well I2 in August 1977, when reclaimed water was injected into the shallow baylands aquifer system (45-foot aquifer). That pilot study focused on the short-term behavior of chemical constituents in the immediate vicinity of the injection well. Analyses of ion exchange, precipitation, and clogging data from that study indicated that the well was installed in a sand lens embedded in less permeable material, resulting in a low injection capacity. Geologic and well-test data indicated that well I1 was a more favorable test site because the aquifer is more homogeneous. The field study at well I1, which emphasized organic-contaminant behavior, began in August 1978. Water-quality monitoring during injection indicated adsorption and biodegradation of specific organic compounds.

Acknowledgments

Many people have assisted in various stages of the study, and their help is greatly appreciated. Personnel from the Santa Clara Valley Water District who had a major role in supporting the study are W. J. Sanchez, Jr., and Thomas Iwamura. Special thanks are due to Ronald Stanley, Santa Clara Valley Water District, who assisted in all field testing. The following U.S. Geological Survey employees contributed significantly to the study: Ken Stevens organized and supervised aquifer tests and data analysis, Wesley Danskin provided extensive assistance in water-quality fieldwork, and Allen Moench analyzed pump-test data to determine aquifer coefficients.

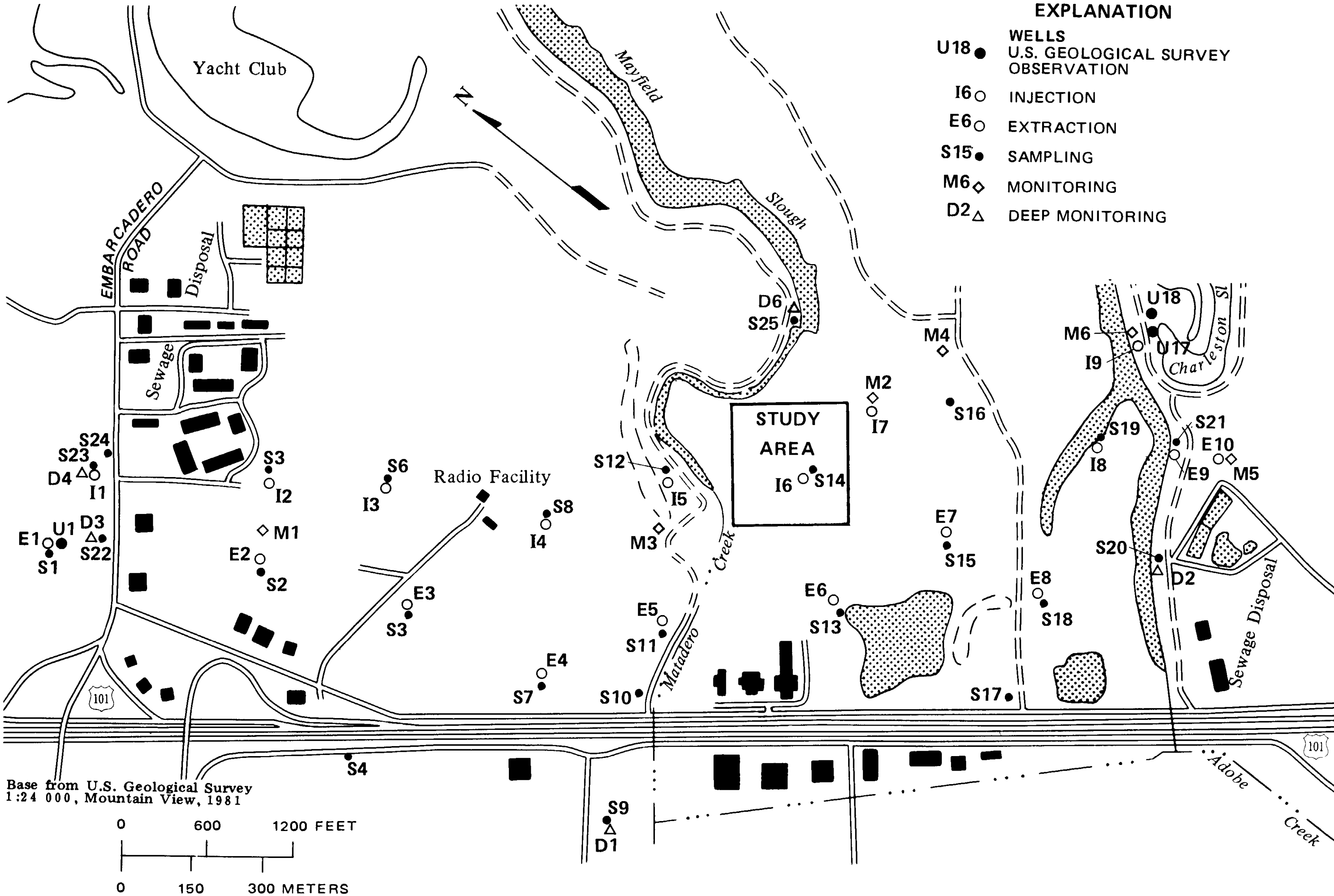


FIGURE 2. — Santa Clara Valley Water District injection well network and location of U.S. Geological Survey study area.

GEOLOGY

Lithology of the Shallow Baylands Aquifer System

Alluvial deposits forming the lower and upper aquifers of the shallow baylands aquifer system (fig. 3) were laid down during late Pleistocene and Holocene time, respectively. These deposits consist of clay, silt, sand, gravel, and rarely peat. Graded sequences are common beneath the contact with Holocene estuarine deposits. Quartz and albite are the dominant minerals.

Estuarine deposits and shallow baylands aquifer confining clays were laid down during late Pleistocene to Holocene time in the San Francisco Bay area. Pleistocene deposits, consisting of clay, silty clay, and occasionally sand and gravel, commonly contain gypsum. Later deposits, which commonly contain framboidal pyrite (bio-organic deposition), are characterized by the "rotten eggs" odor of hydrogen sulfide. Desiccated samples may contain gypsum, limonite, and jarosite.

The dominant clay minerals are montmorillonite and, to a lesser extent, illite. Clay minerals from several aqueous environments were analyzed by X-ray diffraction. Clays from core samples containing hypersaline pore water were X-rayed to determine the d-spacing (distance between parallel planes in the crystal lattice). The samples were then soaked in typical injection water and X-rayed again. The d-spacing in one sample increased from 14.7 Å to 19.6 Å as a result of clay hydration and expansion.

Geologic History

The evolution of the shallow baylands aquifer system can be explained in terms of a changing depositional environment in response to sea-level fluctuations and tectonic movement. Figure 4 is a time-stratigraphic correlation of sediments in the study area. The Holocene and upper Pleistocene alluvial deposits correlate with the upper and lower aquifer zones within the shallow baylands aquifer system discussed in detail in the "Hydrology" section.

Geologic events affecting the present aquifer system occurred during the Quaternary period. During the last Pleistocene glacial advance between about 70,000 and 10,000 years ago, sea level stood as much as 300-400 feet below its present elevation (Helley and Lajoie, 1979). The streams presently draining into the bay were merely tributaries of a large river flowing through the bay region from the Central Valley and across a broad, now submerged, coastal plain between the narrow canyon that is now the Golden Gate and the Farallon Islands. During this period, about 20,000 years ago, the lower aquifer of the shallow baylands aquifer system was deposited in freshwater conditions. Camels, bison, mammoths, sloths, and horses roamed the broad inland valleys, whose nearly flat floors were covered by freshwater marshes and open coniferous woodlands.

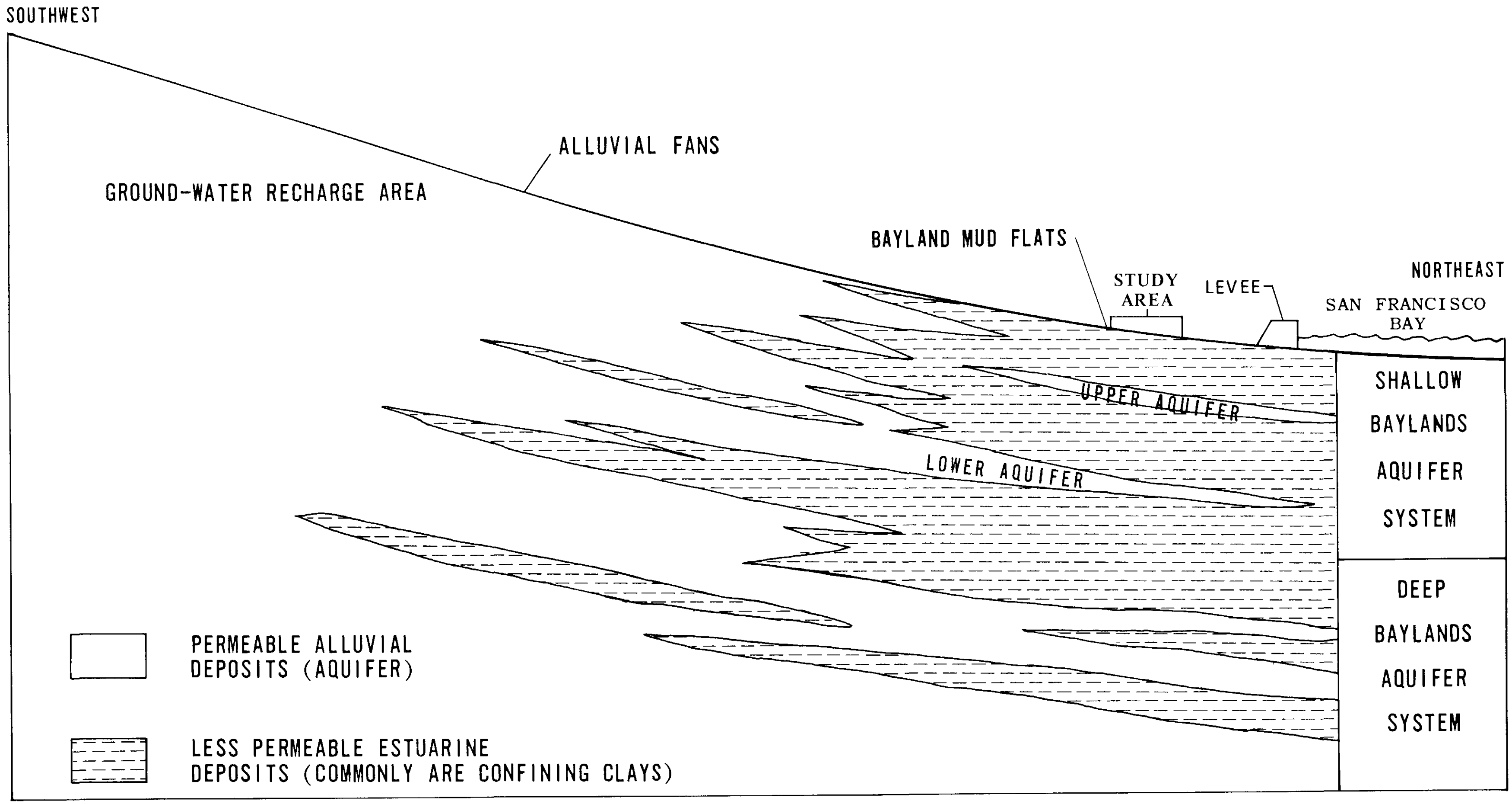


FIGURE 3. – Schematic cross section showing the baylands aquifer systems.

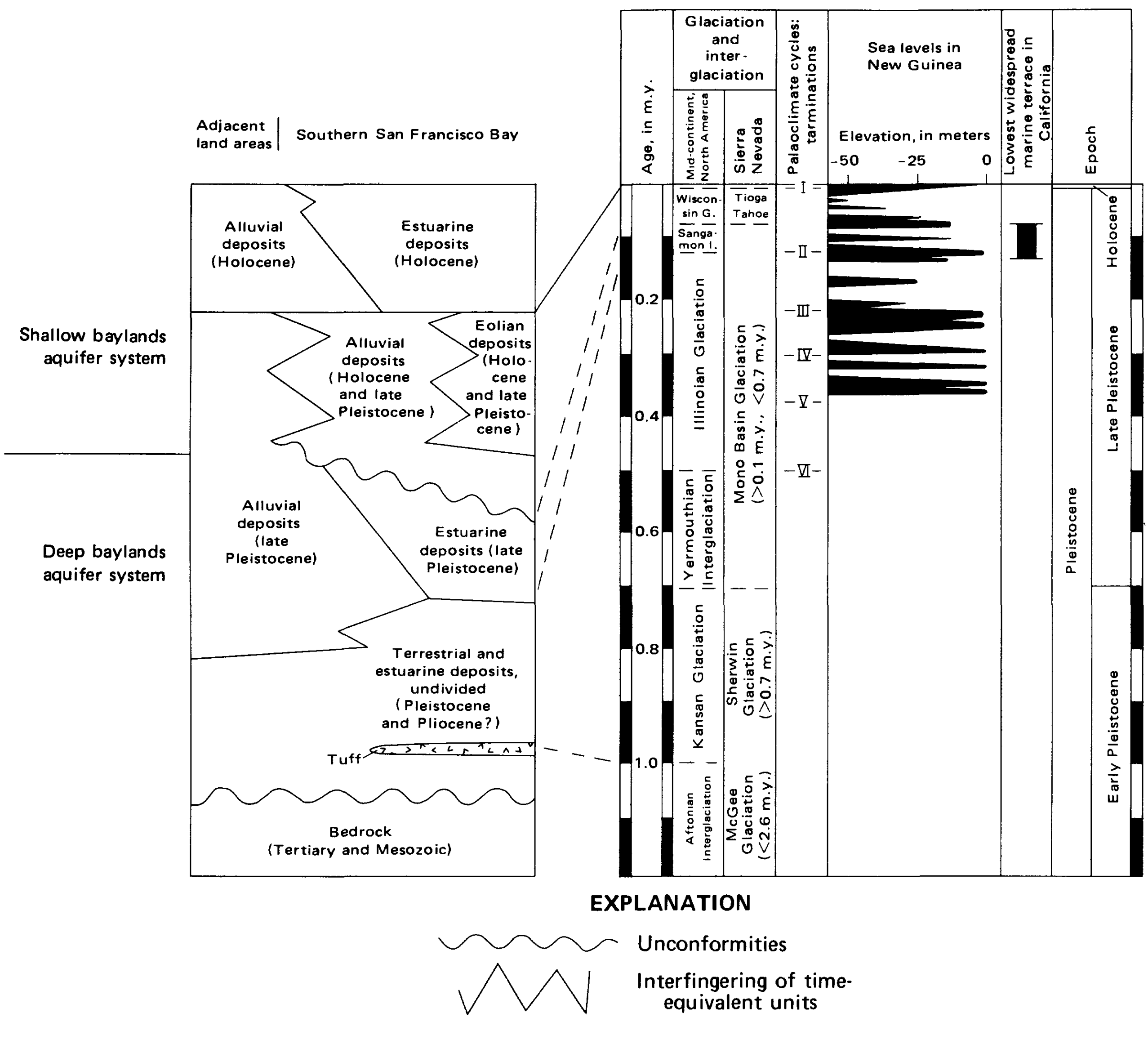


FIGURE 4. — Chronology of sediments under southern San Francisco Bay and correlation with baylands aquifer systems. (Modified from Atwater, Hedel, and Helley, 1977.)

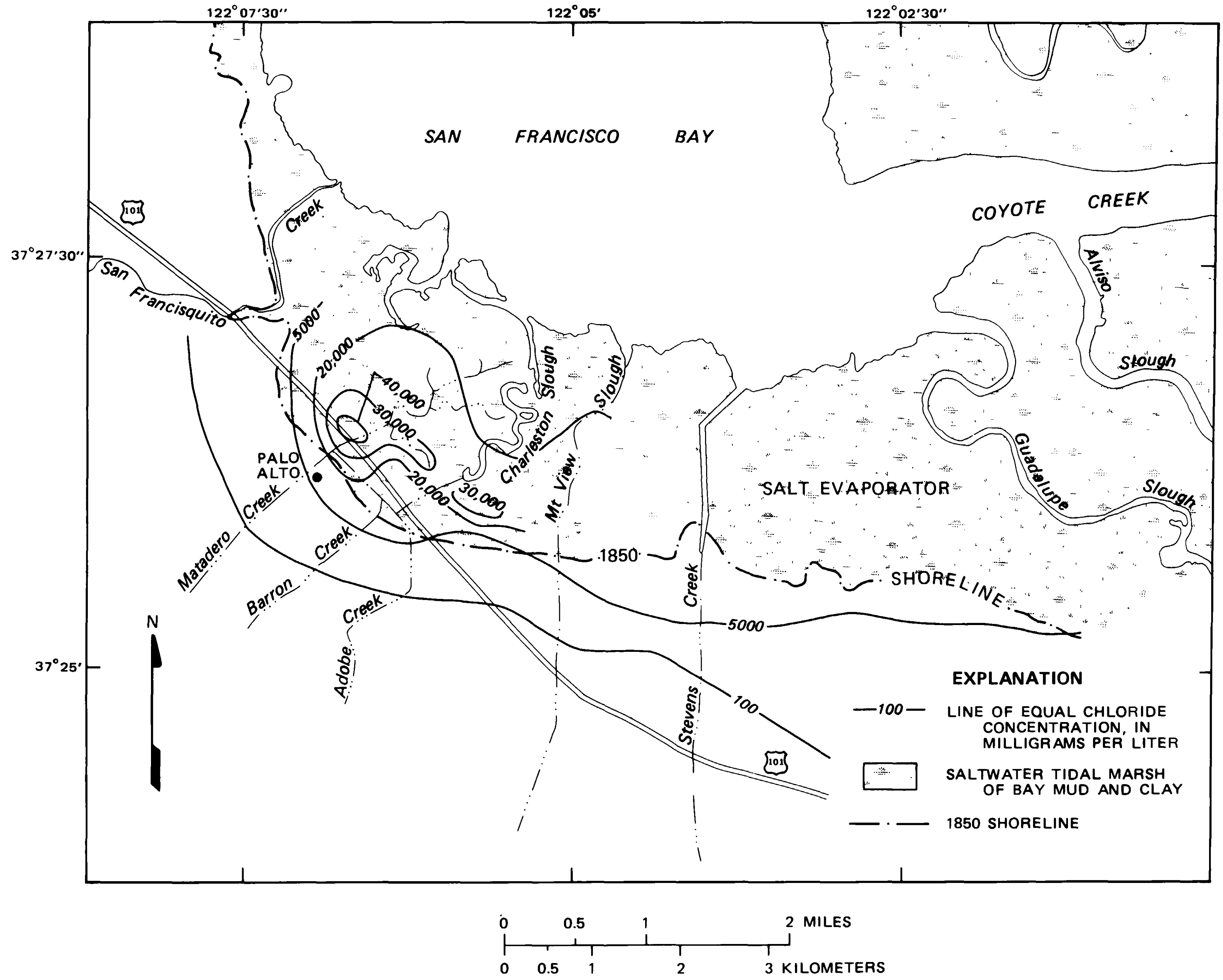


FIGURE 5. — Marsh distribution, present and 1850 shorelines, and chloride contours.

About 15,000 years ago the sea level rose as glaciers in the northern latitudes began to melt. The local record of Holocene sea-level changes indicates that the rising sea entered the Golden Gate 10,000-11,000 years ago. During this time the upper aquifer of the shallow baylands aquifer system was deposited in a predominantly freshwater environment. The estuary reached the vicinity of Menlo Park about 8,000 years ago, and at the same time the character of the bay changed to a predominantly saline environment. Subsequent shoreline changes have been more gradual because of a decrease in the rate of sea-level rise since 5,000-6,000 years ago, at which time the bay reached its present level. As the declining rate of sea-level rise was approached and surpassed by the rate of sediment accumulation, progradation of mudflats and salt marshes took place. Most bayward growth of marshes occurred within the last several thousand years.

The earliest European settlers in the bay area gathered salt that was naturally precipitated from tidal lagoons and along the margins of the bay. When these deposits were depleted around 1860, artificial evaporating ponds were constructed. Figure 5 compares the present with the 1850 shoreline and shows the correlation between chloride contours in the shallow baylands aquifer system and salt-marsh distribution.

Local Structure

The layout of the injection well network in the study area and location of sections developed from geologic and geophysical analysis are shown in figure 6. Sections A-A', B-B', and C-C' (figs. 7 through 9) show a downward slope of the lower aquifer from north to south and from east to west with a slight downwarped trough plunging south-southwest. The strata in this area are composed of alluvial-fan material interfingered with estuarine clay deposited during a period of tectonic activity and sea-level fluctuation.

Geologic data were compiled during the installation of the U.S. Geological Survey observation-well network (fig. 10), and sections were constructed. Sections X-X' and Y-Y' (figs. 11 and 12) within the study area depict a general gentle downslope in the lower (injection) aquifer from the northwest to the southeast and a slight trough trending in this direction. Contour lines in figure 13, a plan view, show an ancient drainage to the southeast. This buried drainage may be a factor controlling freshwater and saltwater flow patterns during injection. Heterogeneous permeability due to variations in aquifer composition may be the primary factor controlling solution migration. Composition and distribution of aquifer materials can be correlated directly to flow patterns. An increase in the relative fraction of fine and expandable clay minerals (montmorillonite) can result in a decreased hydraulic conductivity. The lower aquifer is heterogeneous in composition, both laterally and vertically. Graded or channelized coarse matrix material accepts injected water more readily than fine, less permeable sediment. Note the position of the injection-well screen in relation to the bottom of the lower (injection) aquifer in figure 11. Freshwater introduced at the top of the lower aquifer may ride over the denser saltwater and not completely purge this zone.

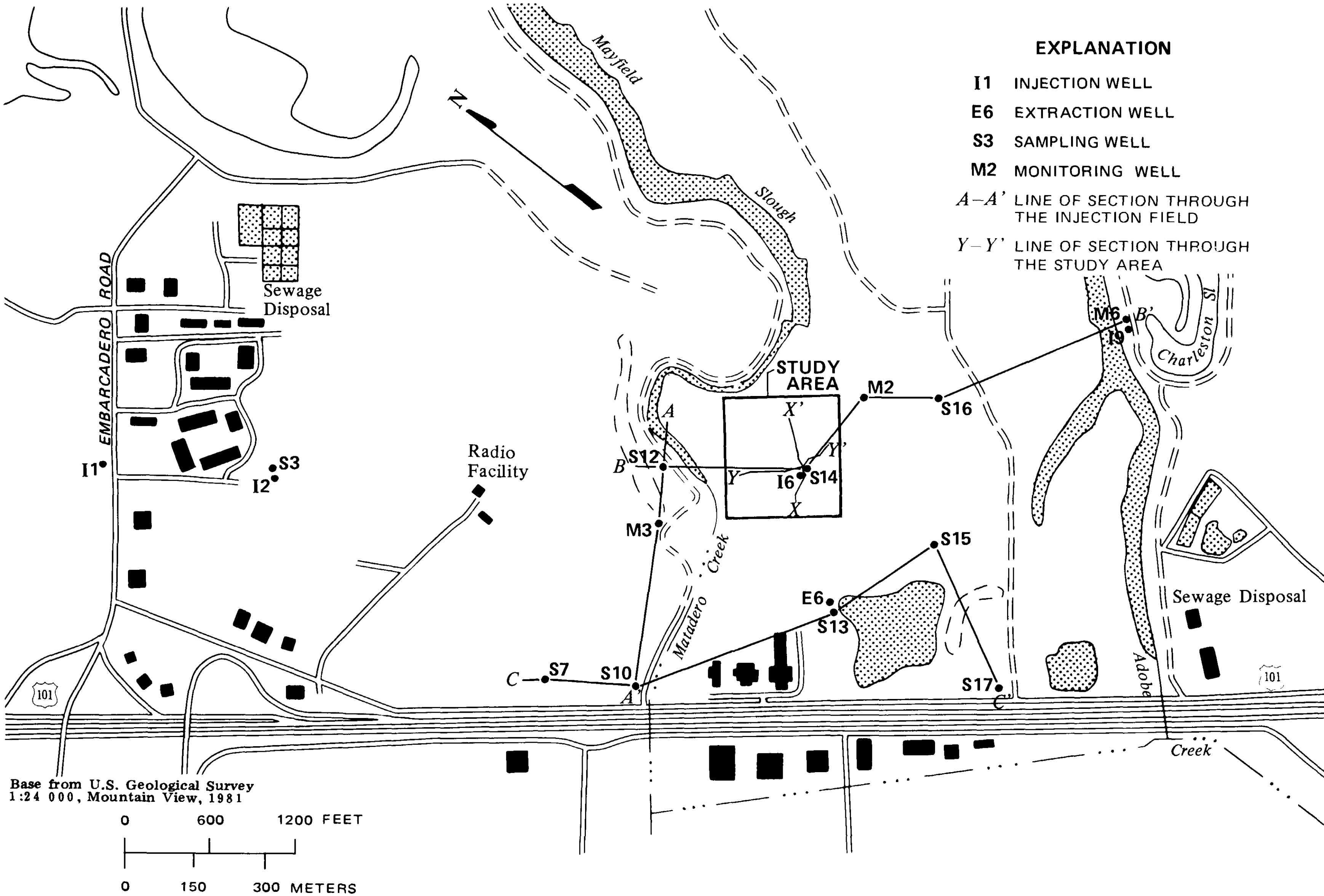


FIGURE 6. — Location of logged wells and geologic sections.

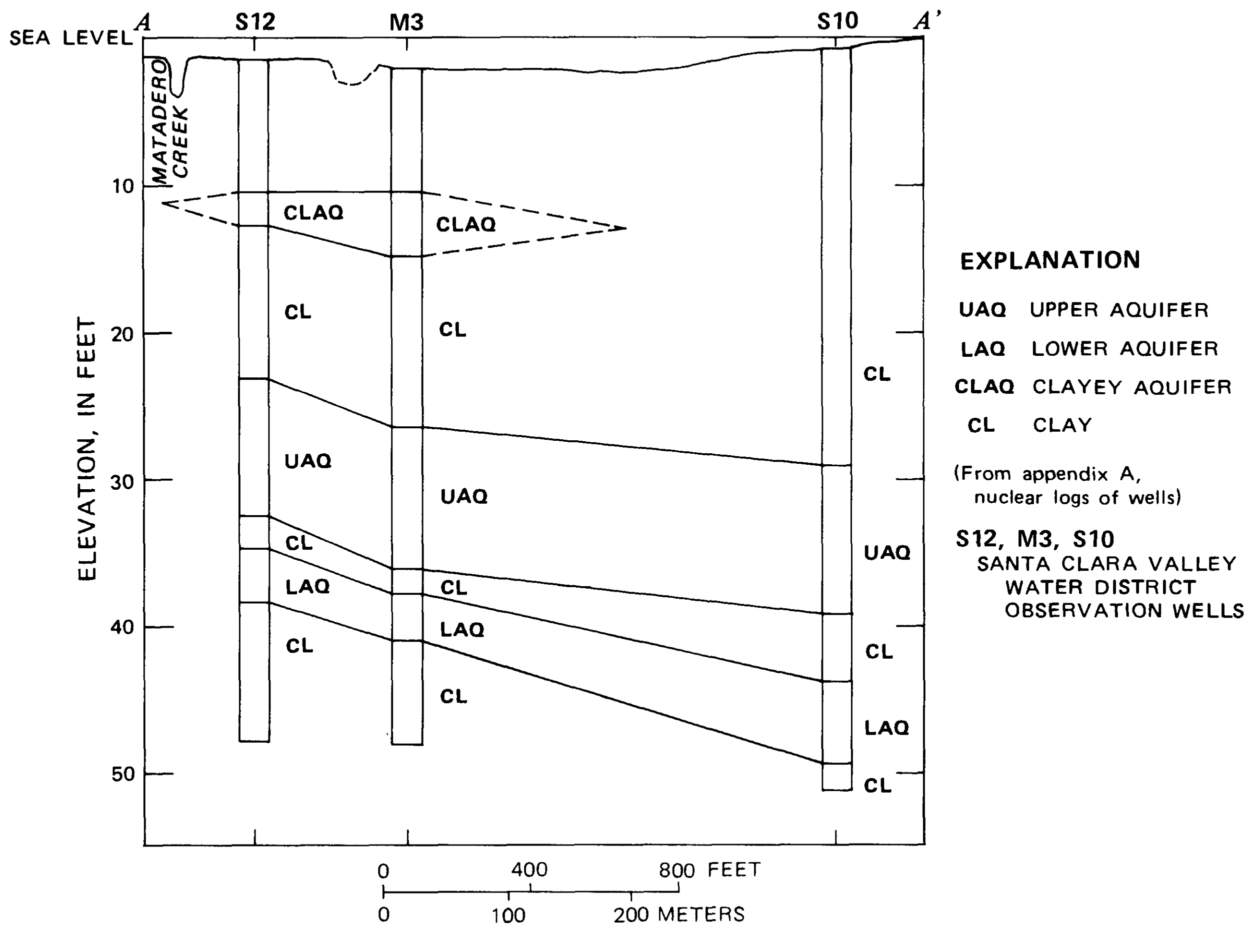
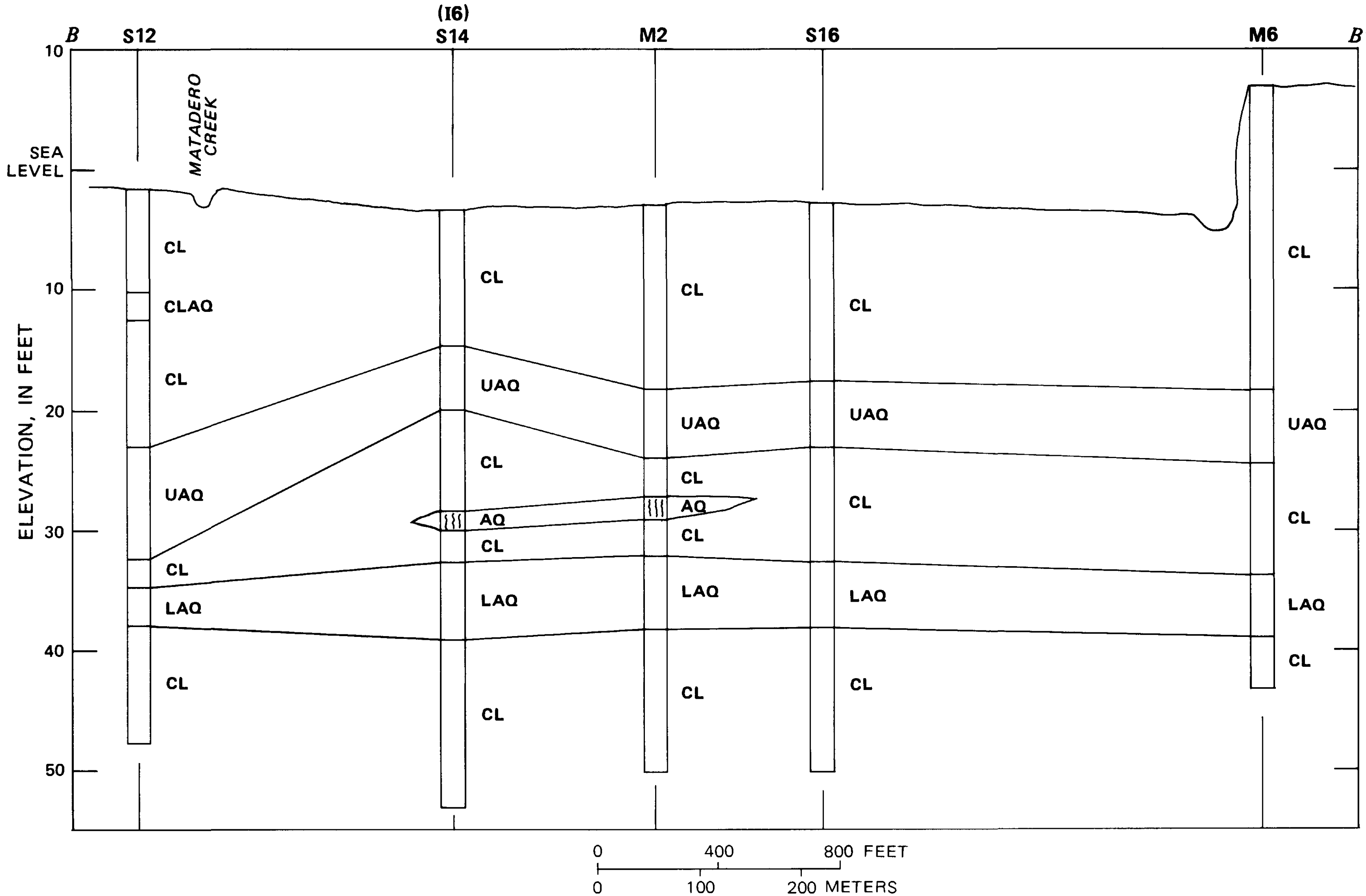


FIGURE 7. – Geologic section A–A' through the injection field.



EXPLANATION

AQ AQUIFER MATERIAL
UAQ UPPER AQUIFER
LAQ LOWER AQUIFER

CLAQ CLAYEY AQUIFER
CL CLAY
(From appendix A, nuclear logs of wells)

S12, S14, M2, S16, M6, SANTA CLARA VALLEY WATER DISTRICT OBSERVATION WELLS

FIGURE 8. – Geologic section B–B' through the injection field.

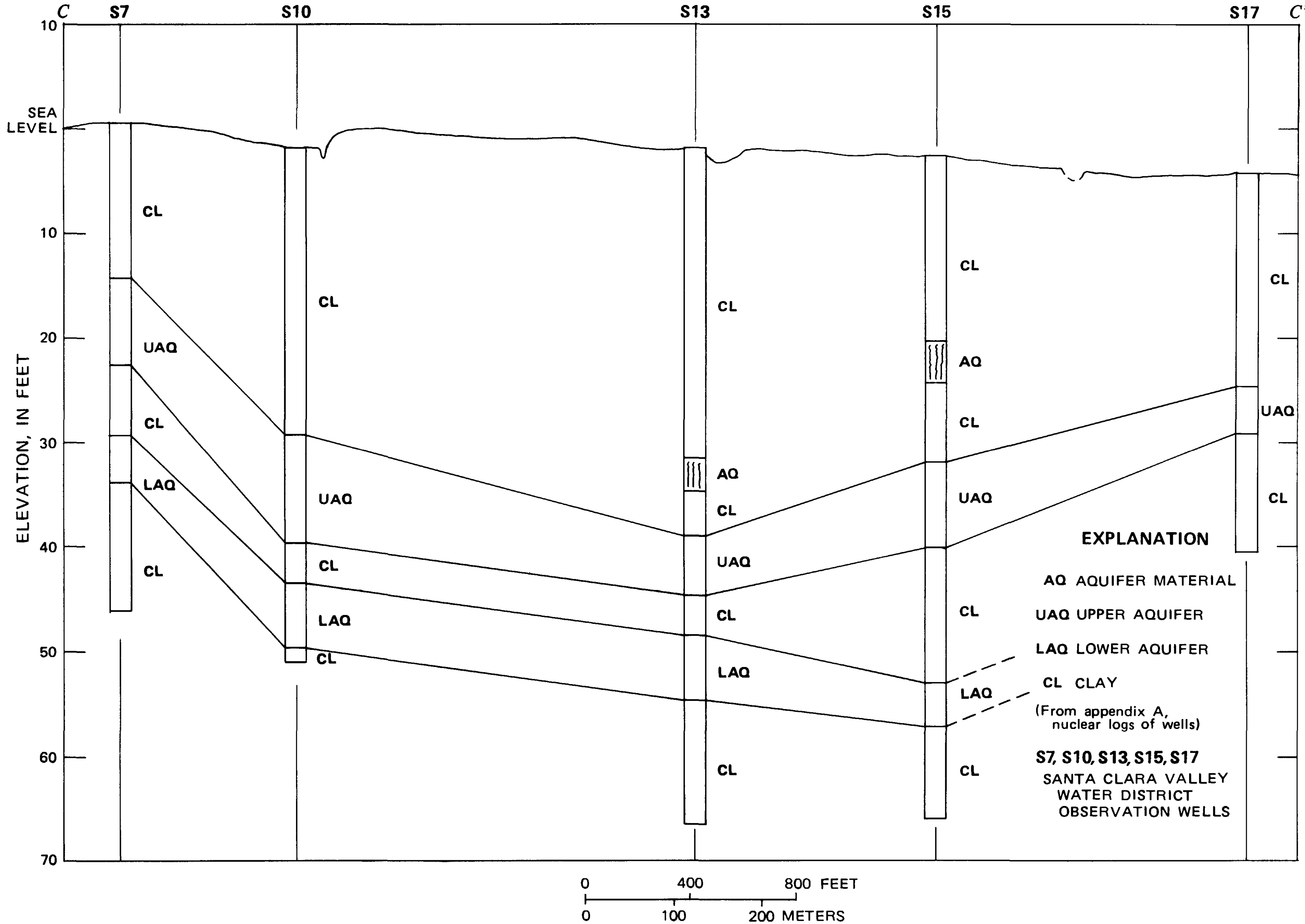


FIGURE 9. – Geologic section *C–C'* through the injection field.

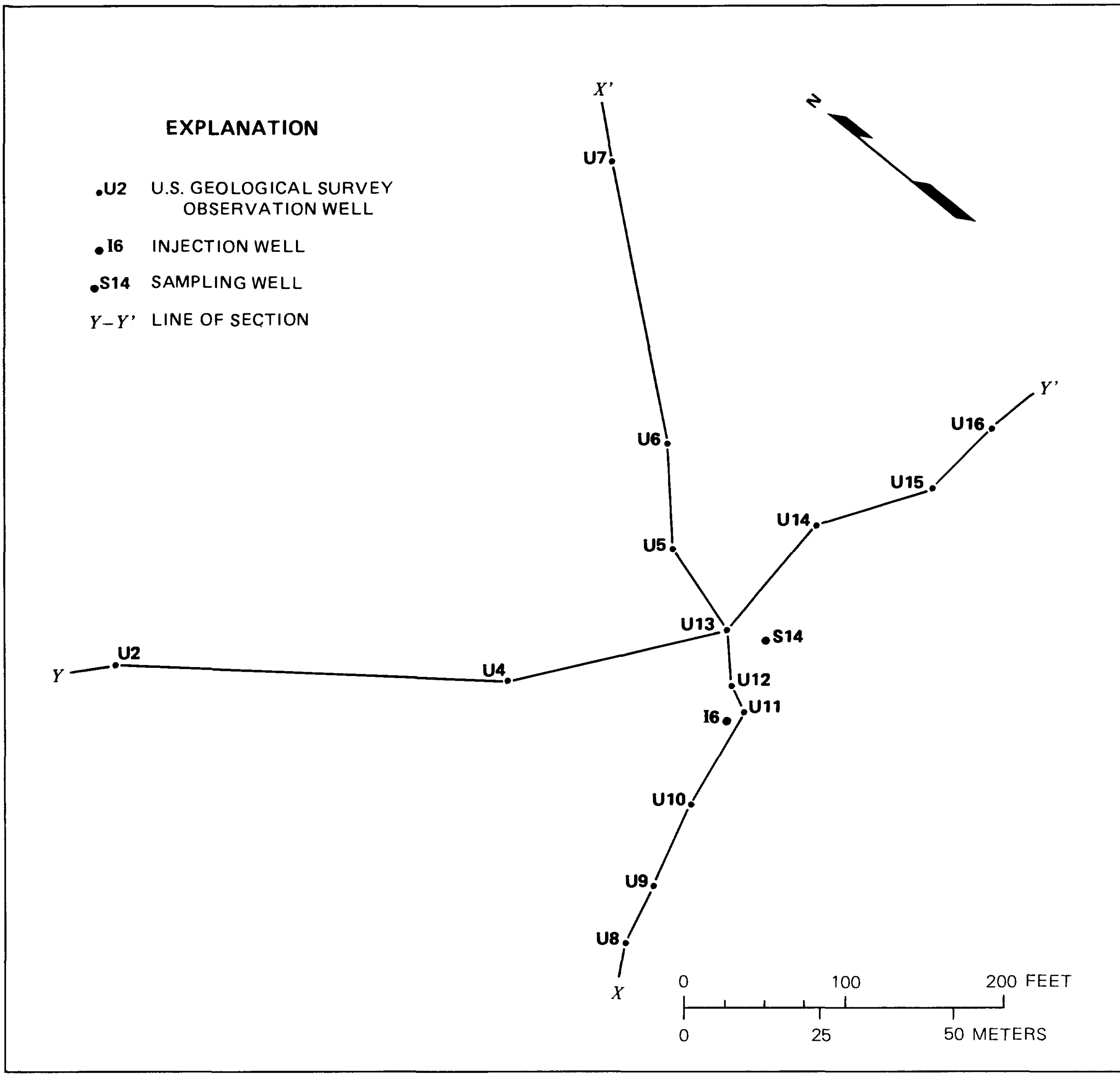


FIGURE 10. -- Location of the U.S. Geological Survey observation well network and sections in the study area.

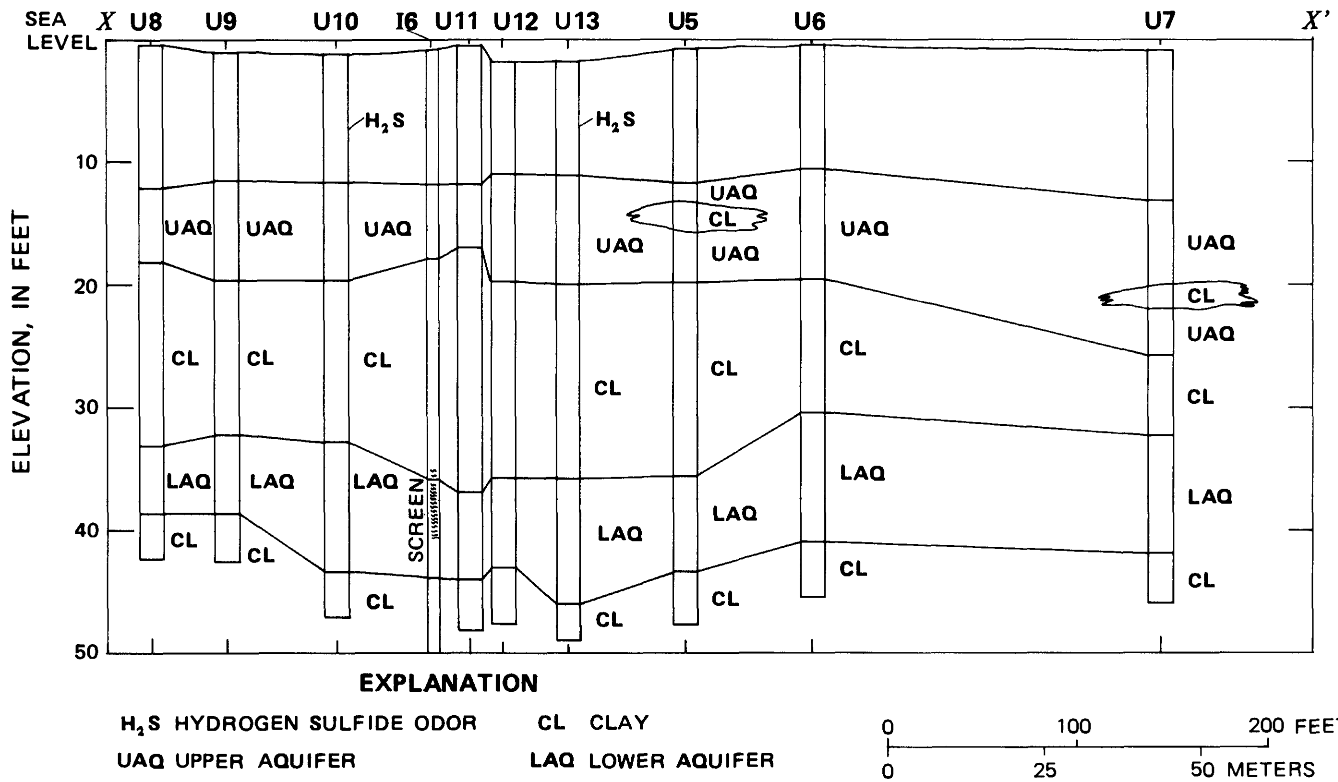


FIGURE 11.– Geologic section X–X' showing study area structure.

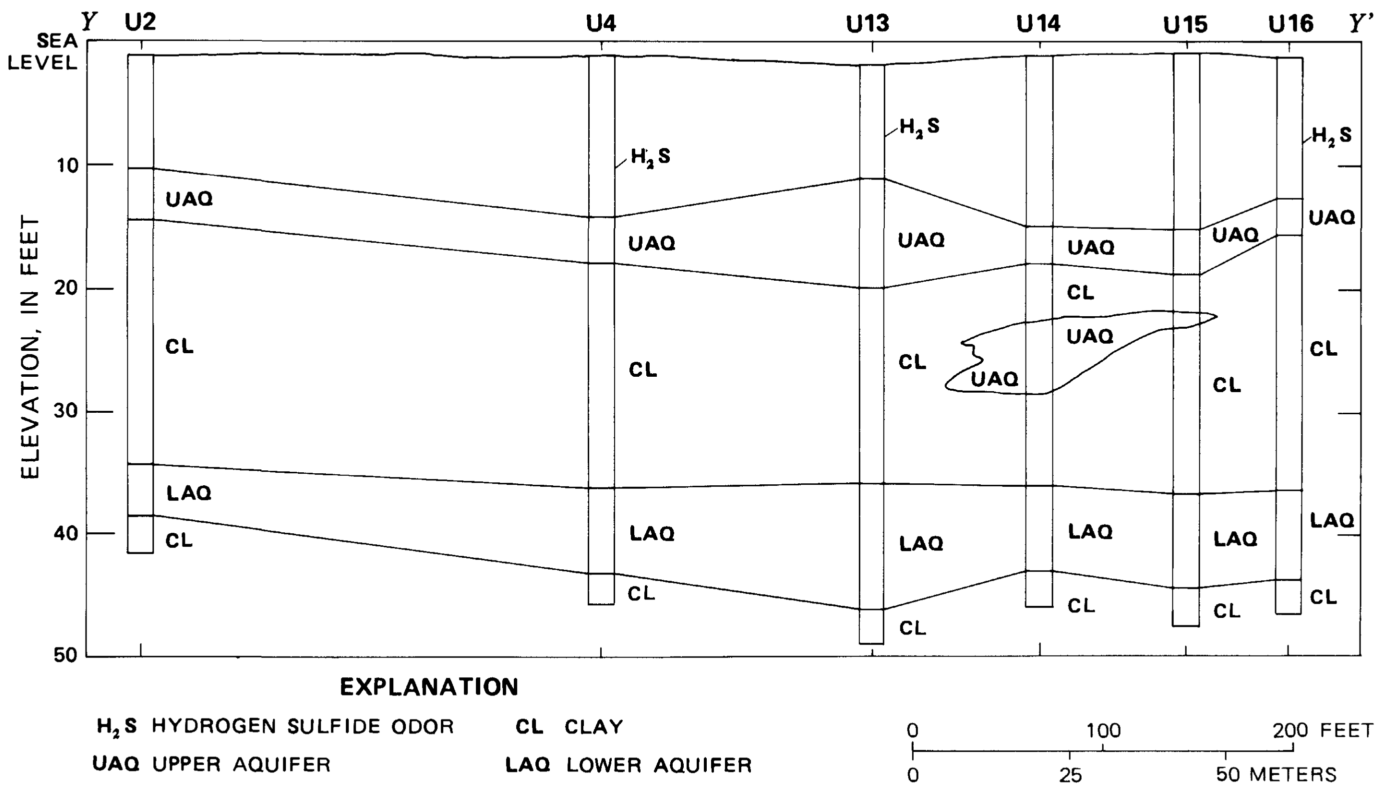


FIGURE 12. — Geologic section *Y–Y'* showing study area structure.

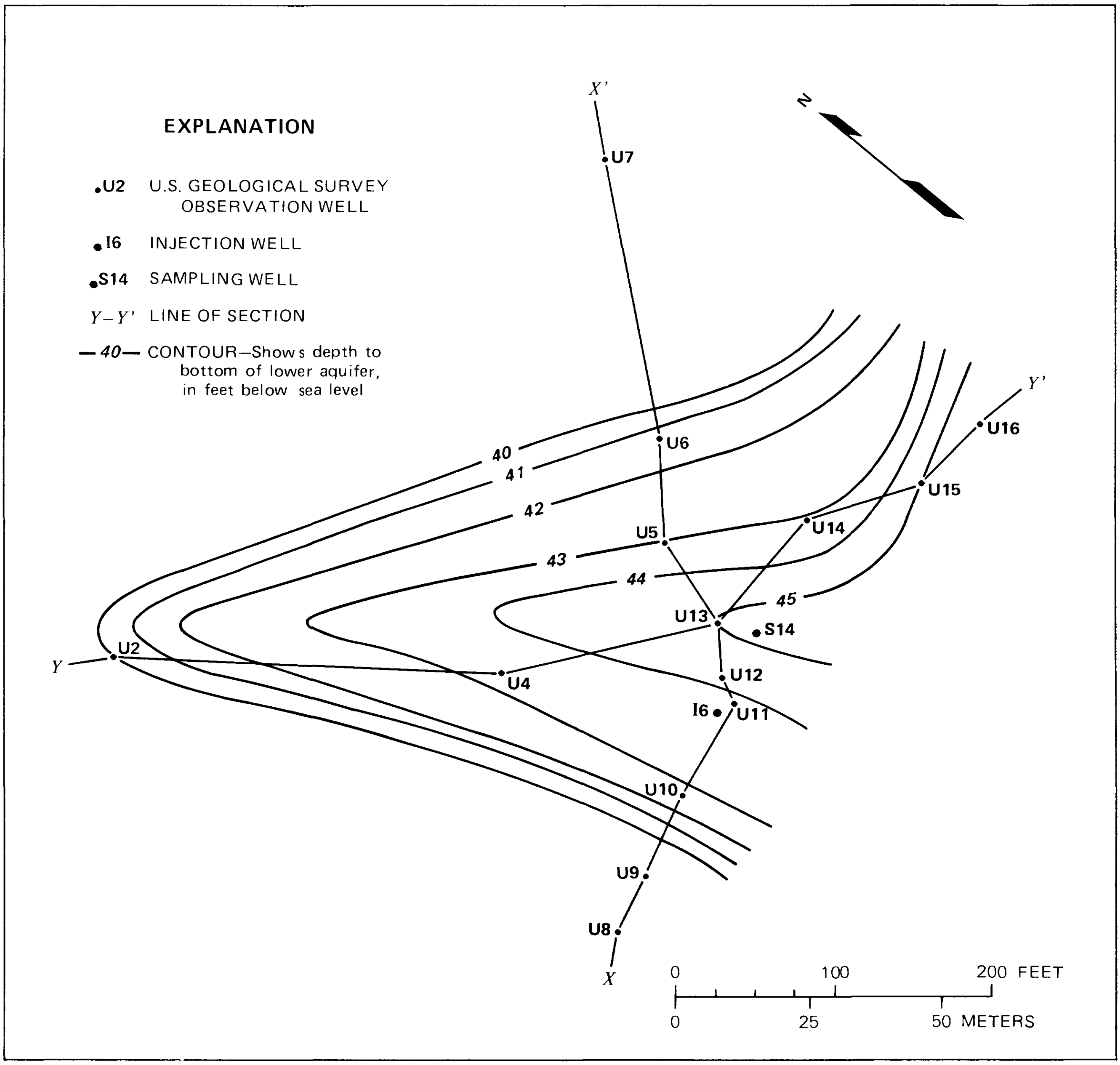


FIGURE 13. – Depth to bottom of the lower (45-foot) aquifer near well I6.

HYDROLOGY

Occurrence of Ground Water

The deep baylands aquifer system contains freshwater and is confined in the south bay area under an extensive clay layer, which separates the two systems at a depth of approximately 150 feet. The deep baylands aquifer system probably extends westward to an area in which the ground-water body is virtually one unconfined zone (fig. 3).

Shallow Baylands Aquifer System

Saline water has concentrated in the shallow baylands aquifer system under the salt marshes. Injection of treated wastewater into the lower aquifer (45-foot depth) of the shallow baylands aquifer system is intended to improve degraded ground water and preserve adjacent freshwater. Within the alluvium, ground water generally is unconfined. The clay between the upper and lower aquifers of the shallow baylands aquifer system forms a leaky confining layer. No unsaturated zone occurs between the two aquifers, and hydraulic heads are higher in the upper aquifer.

Recharge to the shallow baylands aquifer system is by infiltration from streams, surface spreading of rainfall water, and subsurface inflow. Figure 14, a ground-water-level contour map of the study area prepared for the lower (45-foot) aquifer, shows apparent recharge from Mayfield Slough (fig. 6) to the north and northwest. Within the baylands, the ground-water potentiometric surface is virtually flat. At times, when heavy pumping occurred inland (west of U.S. 101), the gradient was inland from San Francisco Bay.

Deep Baylands Aquifer System

Ground water in the deep baylands aquifer system, which is characteristically fresh, occurs in several aquifers separated by clay layers. Beneath the baylands, the deep and shallow baylands aquifer systems apparently are not hydraulically connected.

Recharge to the deep baylands aquifer system comes principally from the unconfined zone west of the pinched-out confining bed (fig. 3). Where the potentiometric surface of the deep baylands aquifer is below that of the shallow baylands aquifer, very slow vertical percolation may occur. Localized saline contamination has resulted from defective well construction and (or) inadequate well-abandonment procedures, which allow leakage from the shallow saline system (Iwamura, 1980).

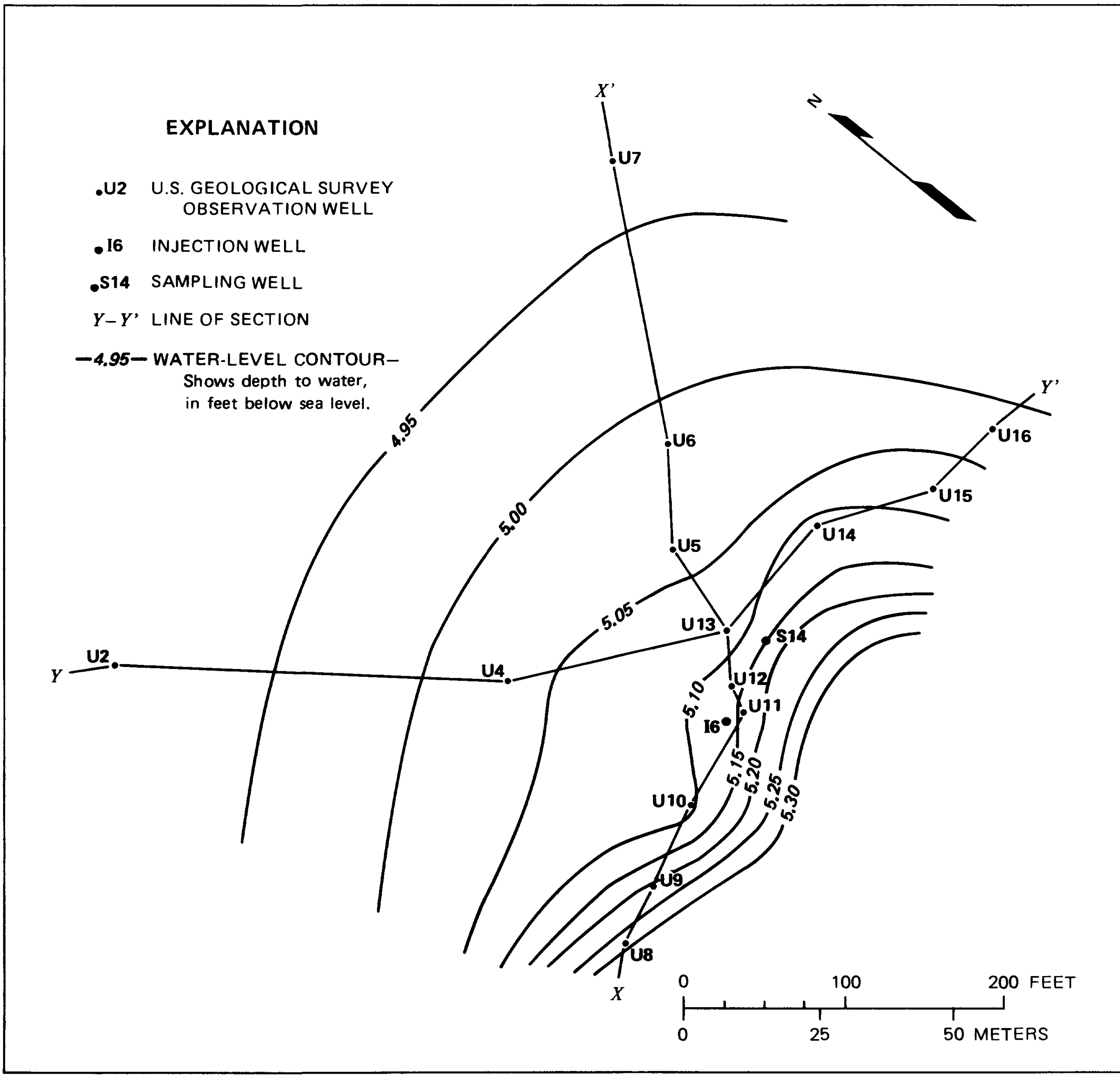


FIGURE 14. – Depth to water in the lower (45-foot) aquifer near well I6.

Aquifer Hydraulic Analysis

Conceptual Model

Analysis of ground-water data to determine aquifer characteristics requires an understanding of the geologic framework. The shallow baylands aquifer is conceived as a four-layer system as shown in figure 15. Layer 1, containing the uppermost aquifer, is treated as a source bed with good hydraulic connection to the land surface. An intermediate leaky clay confining bed, layer 2, separates the upper unpumped aquifer from the lower pumped aquifer, layer 3. This lower aquifer is underlain by a confining clay layer, layer 4. To reduce the numerical complications of three-dimensional analysis, ground-water flow is assumed to be horizontal in the aquifers (layers 1 and 3) and vertical in the leaky clay confining bed (layer 2).

In the vicinity of I6, a salinity gradient exists between the upper and lower aquifers as shown in figure 15 by the electric guard-log. A guarded-electrode system was used to measure formation resistivity through conductive drilling mud in an uncased hole. This electrical logging tool is focused and gives good vertical resolution and penetration. A sharp drop in electrical resistance is seen between the upper ground water (layers 1 and 2) and the lower more saline ground water (layer 3), indicating a density layering of ground water. Preinjection specific-conductance values for the upper and lower aquifers were 35,000 and 70,000 μmho/cm at 25°C, respectively.

Aquifer Testing

<u>Layer 1</u>.--Brown and Caldwell (1974) made hydraulic tests in the upper (20-foot) aquifer in the vicinity of injection well I1. Drawdown data were collected while water was being pumped at 8.6 gal/min (1,650 ft^3/d). Both drawdown and recovery data were analyzed using the leaky-artesian formula of Hantush and Jacob (1955). Leakage was noted from the 45-foot aquifer and from the overlying soil layer. Interpretation was complicated by the inherent error associated with the small magnitude of drawdown; however, the recovery data were considered adequate for hydraulic analysis. The transmissivity was 470 ft^2/d, and the storage coefficient was 0.002.

<u>Layer 3</u>.--In September 1980 an extraction test was run at well I6 in which water from the lower (45-foot) aquifer was withdrawn at a rate of 1,930 ft^3/d. Drawdown was measured at observation wells U11 (20 feet from I6) and S14 (55 feet from I6) and at the pumped well I6 for a period of 1,500 minutes. Water levels were recorded by Stevens Type F recorders coupled with Keck water-level followers using modifications described by M. S. McBride and S. P. Larson (U.S. Geological Survey, written commun., 1972). Water-level measurements were made at the rate of 10 per log cycle of drawdown. The plan of the test area is shown in figure 10, and drawdown data are shown in Appendix B. Distant observation wells S13 shallow and deep (1,000 feet from I6) were measured with a steel tape, and they showed no appreciable drawdown during the test.

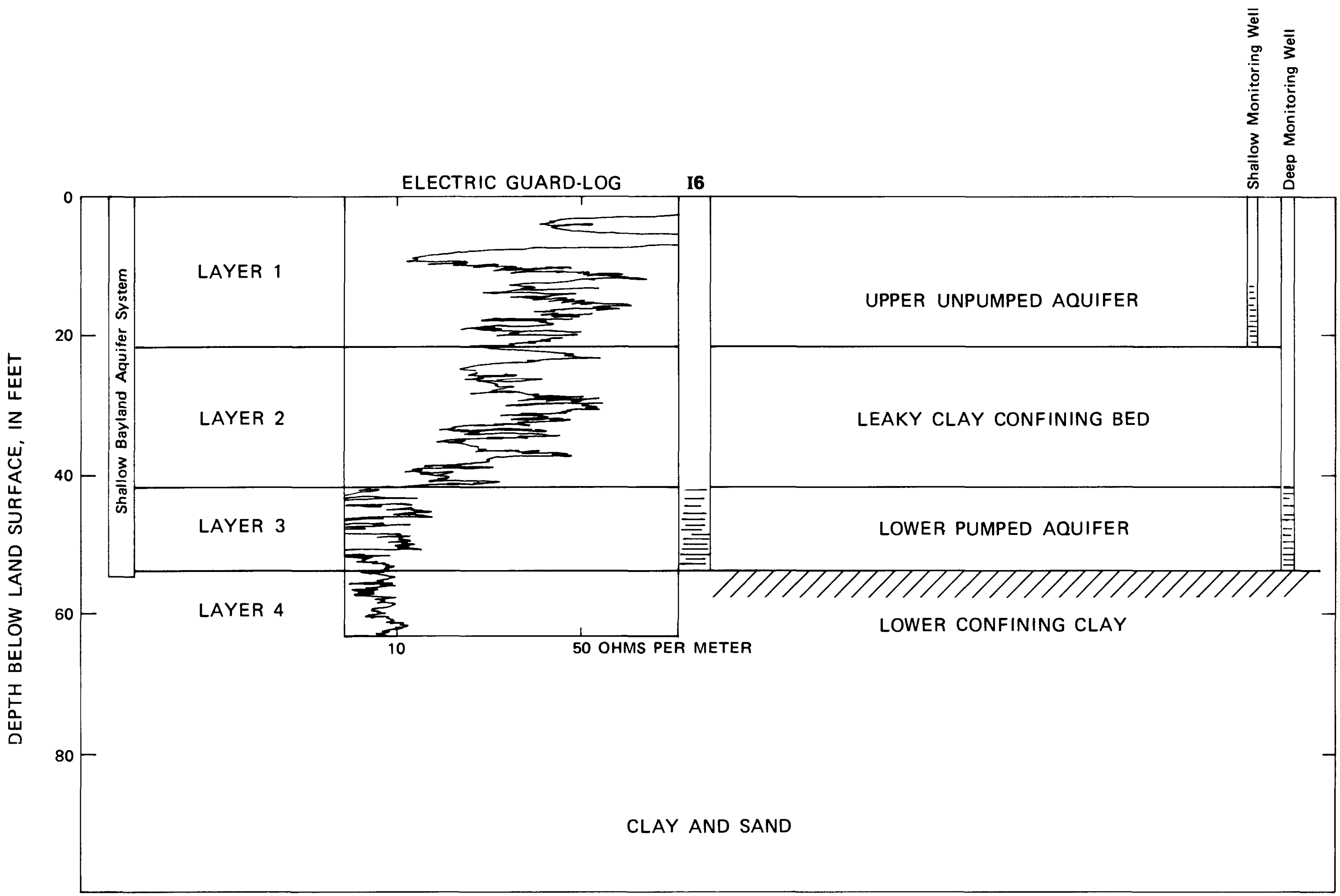


FIGURE 15. – Generalized geohydrologic cross section of the study area.

In order to take into consideration the leaky-artesian, nonequilibrium characteristics of the test data from this aquifer, the modified Hantush method (Hantush, 1961) of analysis was used. This method of hydraulic analysis accounts for storage of water in the confining bed and assumes constant head, or zero drawdown, in the upper aquifer.

The analysis of data by this method consists of attempting to match one of the family of type curves to the data using a superposition procedure. The type curves are generated through the basic equation:

$$H(u,\beta) = \int_u^{\infty} \frac{e^{-y}}{y} \operatorname{erfc}\left(\frac{\beta/\sqrt{u}}{\sqrt{y\ (y-u)}}\right) dy \tag{1}$$

where

$$u = \frac{r^2 S}{4Tt},$$

$$\beta = \frac{r}{4b}\left(\sqrt{\frac{k'Ss'}{kSs}} + \sqrt{\frac{k''Ss''}{kSs}}\right),$$

y = the variable of integration
k = hydraulic conductivity of the main aquifer,
k', k'' = hydraulic conductivities of the confining layers,
b = thickness of aquifer,
S = bSs } storage coefficients of the main aquifer
S' = $b'Ss'$ } and of the confining layers,
S'' = $b''Ss''$ } respectively,
Ss, Ss', Ss'' = specific storage,
r = radial distance from observation well to pumped well,
T = transmissivity, and
t = time since pumping began.

Transmissivity is determined from the following relationship:

$$T = \frac{Q}{4\pi s} H(u,\beta), \tag{2}$$

where Q = flow rate, and
s = head change (drawdown or head buildup).

The drawdown data for observation wells U11 (r = 20 feet) and S14 (r = 55 feet) have been plotted with respect to time normalized by radius squared (fig. 16). A match to the $H(u,\beta)$ type curve was made at $H(u,\beta) = u = 1$. This corresponds to an s value of 0.16 feet and a t/r^2 value equal to 1.8×10^{-4} min/ft^2. Through algebraic manipulation, transmissivity, T, was determined to be 960 ft^2/d. Similarly, the storage coefficient S of the pumped aquifer was calculated to be 5×10^{-4}. This value falls within the range for confined aquifers, between 10^{-5} and 10^{-3}.

An upward break in slope, approaching a Theis response (confined non-leaky aquifer), in the drawdown data probably indicates the effect of drawdown in the upper aquifer. This effect is not accounted for in the modified Hantush (1961) method, which assumes constant head in the layers above the pumped aquifer. Drawdown in the unpumped aquifer reduces the head differential between upper and lower aquifers which, in turn, reduces downward leakage

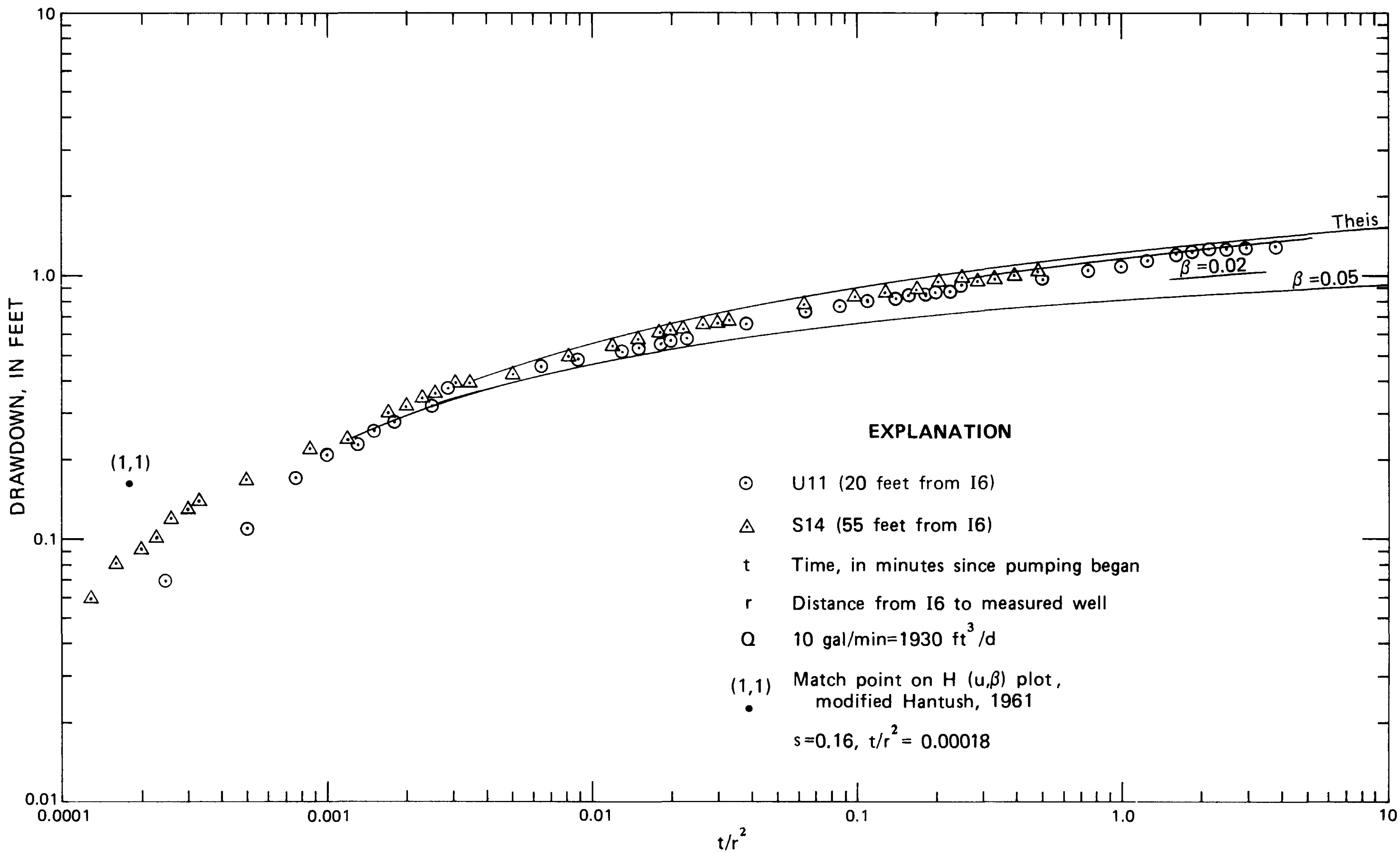


FIGURE 16. — Drawdown data at well I6 from September 24, 1980, extraction test.

through the confining layer, thereby increasing drawdown in the lower pumped aquifer. To determine the vertical permeability of the confining layer, A. F. Moench (written commun., May 1981) has analyzed drawdown data from observation wells completed in the upper and lower aquifers at the same radius (fig. 17). This method of analysis incorporated the two-aquifer theory of Neuman and Witherspoon (1969) and a method for evaluating the equations described by A. F. Moench and Akio Ogata (written commun., 1981). The data plot was matched to the theoretical type curve shown in figure 18, yielding an estimated vertical hydraulic conductivity of 0.08 ft/d. Application of this technique required known values of pumped-aquifer transmissivity and storage, as computed above, and known thicknesses of the aquifers and intervening confining layer. It was assumed that the lower, confining layer (layer 4 in fig. 15) contributed no flow to the aquifer. An aquifer test done in the upper aquifer can more clearly define the calculated vertical hydraulic conductivity of the upper confining layer.

Ken Stevens (U.S. Geological Survey, written commun., Sept. 1980) has analyzed aquifer-test data from Brown and Caldwell (1974) and Stanford University (Albert J. Valocchi, Stanford University, written commun., 1980) to determine aquifer characteristics. At injection well I1 the following values were determined: transmissivity, 530 ft^2/d; storage coefficient, 1×10^{-4}; and vertical conductivity, 1 ft/d. Transmissivity was 400 ft^2/d at injection well I2. The higher value for transmissivity at injection well I6 (960 ft^2/d) may be explained by the presence of very coarse aquifer material, possibly the axis of an ancient drainage channel, in the vicinity of the injection well.

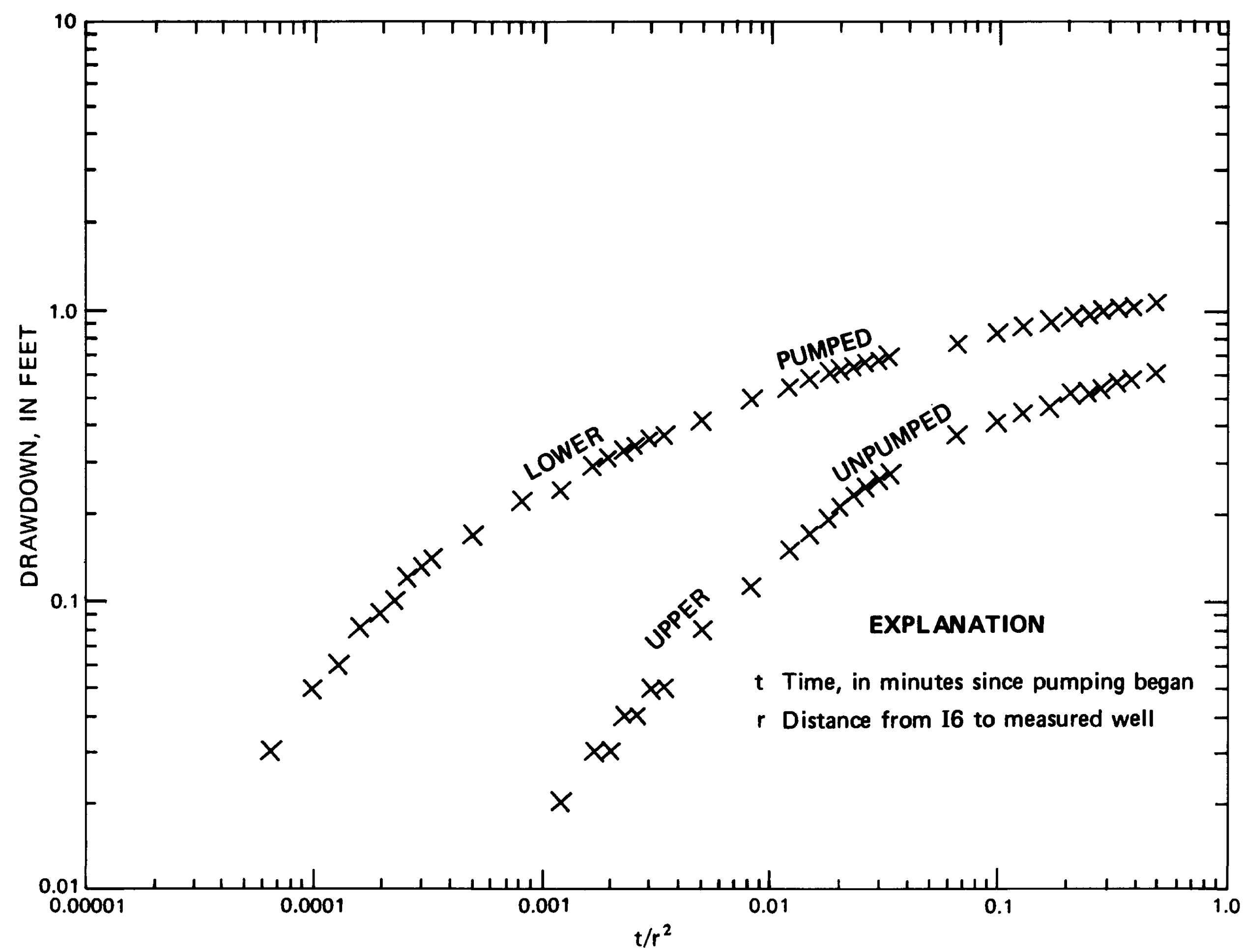


FIGURE 17. – Drawdown in the upper (S14-Shallow) and lower (S14-Deep) aquifers during the September 24, 1980, extraction pump test.

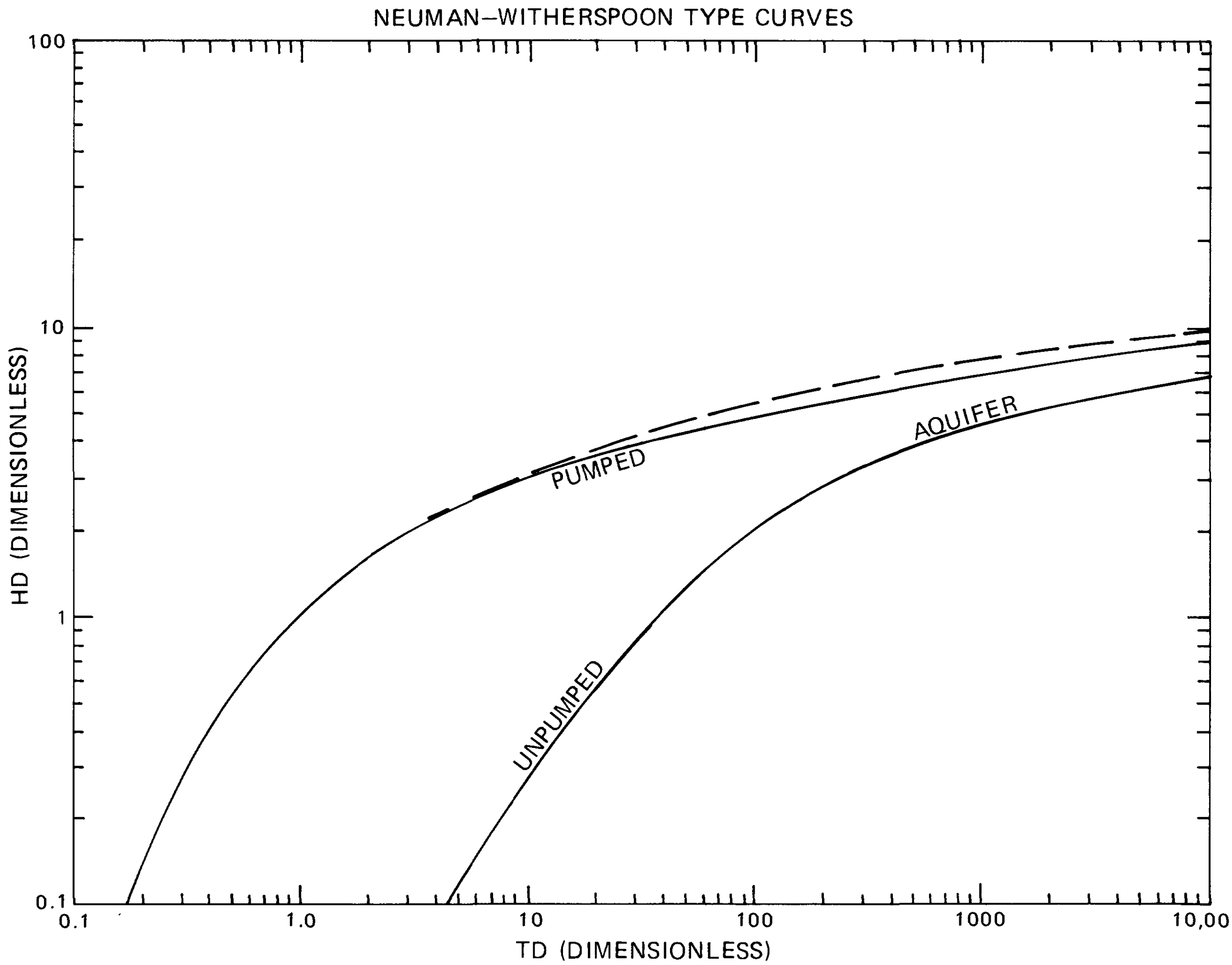


FIGURE 18. – Type curves for drawdown in a two-aquifer system separated by a leaky confining bed.

WATER QUALITY

Analytical Interpretation

Concentration of dissolved solids in the study area decreases both toward and away from the bay. Apparently, a "ridge" of concentrated brine occupies the shallow baylands aquifer system in this vicinity. The shape of this ridge, delineated by chloride concentration contours (fig. 5), is a product of (1) recharge from local streams, surface percolation, and bay water infiltration; and (2) the mechanisms that have produced the hypersaline brine: evaporative concentration, percolation, and ion-exchange reactions. Figure 19 shows lines of equal chloride concentration in the lower (45-foot) aquifer within the study area.

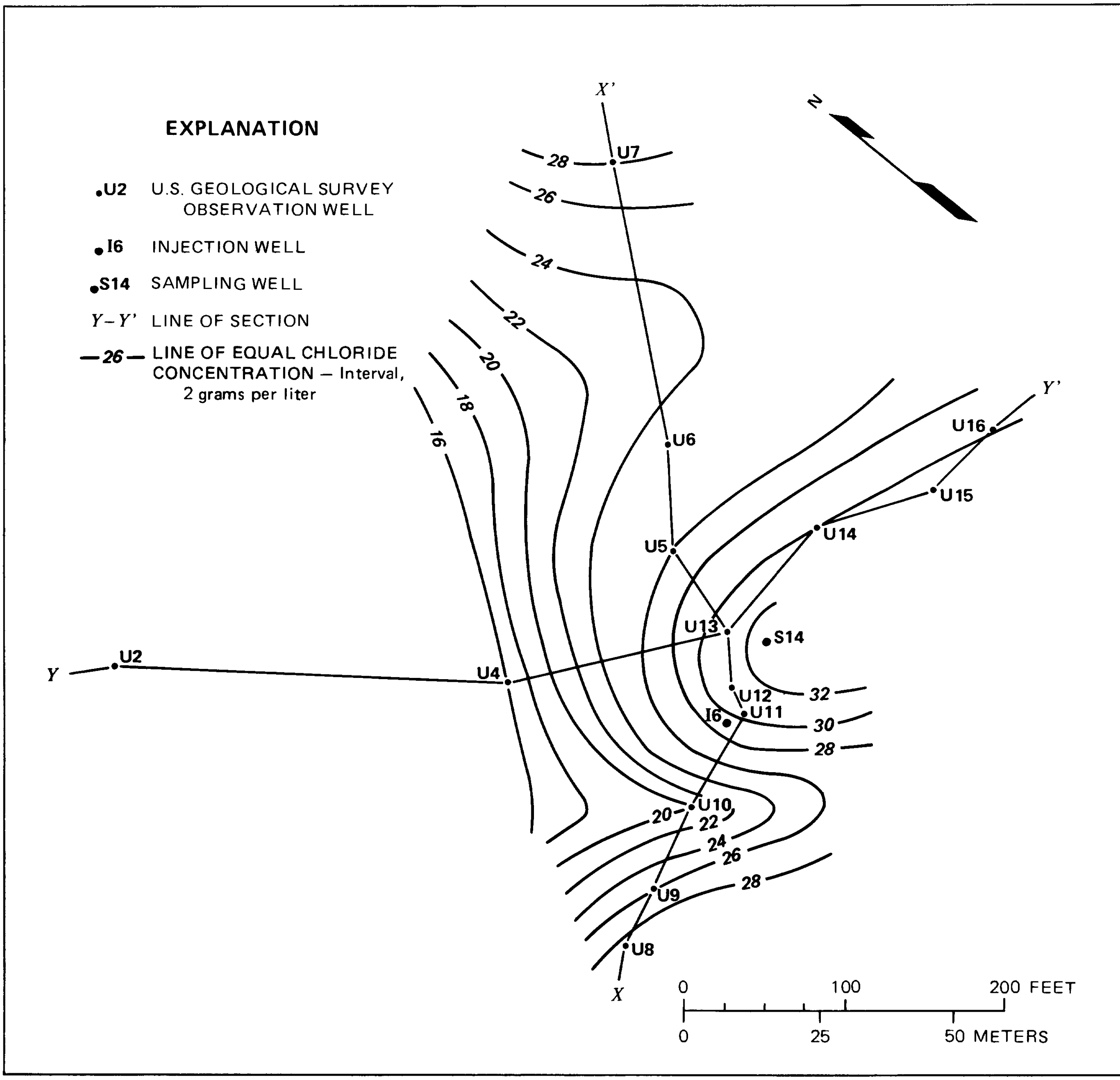


FIGURE 19. – Chloride concentration in the lower (45-foot) aquifer near well I6.

Various chemical constituents and ratios indicate geochemical processes in the ground-water system. Chloride, the major anion of seawater, moves through the aquifer at nearly the same rate as the intruding water. Where no other saline contamination exists, increasing chloride concentration can be considered an indication of sea water contamination. Ionic ratios are useful in differentiating between water types, such as bay water and ground water. Absolute concentrations of individual dissolved constituents may vary during such physical processes as dispersion, dilution, and evaporative concentration, whereas ionic ratios remain constant. Chemical interactions between solutions and between solutions and solids alter these ionic ratios. Hence, ionic ratios can be used to discriminate between physical and chemical interactions involved in the genesis of a particular water type. Cl:Br ratios are commonly used to classify water types. A low Ca:Mg ratio may indicate seawater contamination, as magnesium concentration in seawater is much greater than that of calcium.

Chloride, other major ions, and some trace metals show similar proportions in seawater, bay water, and ground water as indicated in table 1. The Cl:Br ratios in ground water and seawater are nearly identical (Kharaka, U.S. Geological Survey, written commun., 1977). Samples taken at well I2 yielded values for chloride and bromide concentration of 3,450 mg/L and 11.6 mg/L, respectively. The calculated Cl:Br ratio is 297, as compared to an average value of 292 for sea water. Major ions in the saline ground water are approximately twice the corresponding concentration in seawater. Ca:Mg ratios, ranging between 0.30 and 0.39, are also similar in seawater, bay water, and ground water. Seawater, bay water, and ground water have similar ratios of $Cl:SO_4$, Cl:Mg, Cl:Na, Cl:Ca, and Cl:K (table 1). The SAR (sodium adsorption ratio), which is highest for ground water, indicates a high tendency for sodium replacement of adsorbed calcium and magnesium in the geologic matrix. These observations support the theory that the shallow ground water has been derived chiefly from concentrated bay water.

Measurements of the stable isotope ratios of hydrogen and oxygen provide evidence that the formation brines in the study area have a history of exposure to evaporative conditions (Roberts and others, 1978b). Roberts' isotopic data plotted in a regression analysis produced a straight line, which suggests that the ground water was formed by mixing two different types of water. These data, along with dissolved-solids concentrations, are shown in table 2. From the intercept and slope of this regression line the author has postulated that these types are a mixture of imported water and seawater concentrated by evaporation. The highly saline ground-water samples showed the highest concentration in ^{18}O. Evaporation tends to fractionate the heavier ^{18}O in the liquid phase and the lighter ^{16}O in the vapor phase. Relatively constant values for major ionic ratios among sea, bay, and ground water support the theory of cyclic evaporative concentration. Thus, the hypersaline water is most likely a product of cyclic evaporitive concentration of saline bay water and downward solute transport by surface percolation. Higher density brine tends to accumulate in the lower aquifer zone and to grade upward into fresher water.

Pilot Injection Test

Ground-water quality was monitored during June and July 1980 from the start of injection at well I9, located at the southern end of the injection network (fig. 2). Table 3 shows concentrations of various constituents in ground water in observation well U17 (about 31 feet from injection well I9), before and after one month of injection. Also shown are drinking water regulations and a chemical analysis of the injected water to illustrate the effectiveness of injection in replacing and upgrading ground-water quality.

Major ion concentrations of ground water have been reduced primarily by the processes of dilution and dispersion. Cl:Na, Cl:Ca, and $Cl:SO_4$ ratios show little change during injection, indicating simple dilution of ground water by injection water. Cl:Mg and Cl:K ratios, however, do vary noticeably during injection. Ion-exchange reactions between clays and organic compounds in the aquifer probably account for these variations. Cl:B, Cl:Fe, and Cl:Mn ratios also vary most likely as a result of reduction-oxidation reactions. These effects are superimposed on the proportional mixing of ground and injection water, yielding intermediate values for ionic ratios. Copper and arsenic concentrations remained constant during ground-water dilution and replacement by injection water. With respect to major ion concentrations, ground-water quality has greatly improved in the immediate vicinity of injection well I9.

TABLE 1. - Chemical constituents of seawater, bay water, and ground water in the vicinity of well I6

Constituent and characteristics	Seawater[1]	Bay water[2]	Ground water
	Milligrams per liter		
Cl	19,000	14,700	27,900
Na	10,500	8,400	15,800
SO_4	2,700	2,200	3,350
Mg	1,350	1,000	2,180
Ca	400	315	840
K	380	380	480
SiO_2	6.4	--	13
B	4.6	3.8	6
F	1.3	1	.2
Fe	.01	.10	.34
As	.003	--	.002
Cu	.003	--	.008
Mn	.002	--	15.5
Ag	.0003	--	0
Cd	.00011	--	.011
$CaCO_3$ (Alkalinity)	116	150	815
	Ratios		
SAR[3]	56	52	65
Ca:Mg	.30	.32	.39
$Cl:SO_4$	7.04	6.68	8.33
Cl:Mg	14.1	14.7	12.8
Cl:Na	1.81	1.75	1.77
Cl:Ca	47.5	46.7	33.2
Cl:K	50	39	58
Cl:Fe	1,900,000	147,000	82,000
Cl:Mn	9,500,000	--	1,800
Cl:B	4,130	3,870	4,650

[1]From Hem, 1970.
[2]From Iwamura, 1980.
[3]SAR (sodium adsorption ratio) $\equiv (Na) \Big/ \sqrt{\frac{Ca + Mg}{2}}$

TABLE 2. - Dissolved solids and stable isotope determinations for shallow ground water in the injection field

(From Roberts and others, 1978c)

Well number	Dissolved solids (mg/L)	Deviation from Standard Mean Ocean Water, in parts per thousand	
		Oxygen-18 $\delta^{18}O$	Deuterium δD
I1-lower	4,250	-6.20	-49.8
I1-upper	6,600	-7.22	-55.1
M3-lower	58,100	-1.65	-22.5
S1-lower	4,800	-5.73	-43.8
S3-lower	44,900	-2.16	-26.5
S3-upper	9,260	-5.57	-43.3
S7-lower	51,800	-0.71	-19.2
S7-upper	45,500	-2.12	-25.8
S9-lower	22,600	-5.53	-45.5
S10-lower	35,300	-3.38	-32.8
S11-lower	23,200	-4.79	-39.9
S12-lower	67,700	-2.28	-26.3
S25-lower	62,300	-2.24	-26.5

TABLE 3. - Chemical constituents of injection and ground water near injection well I9[1], and drinking-water regulations

Constituent	Ground water: Before injection	Ground water: After 1-month injection	Injection water	Drinking-water regulations[2]
		Milligrams per liter		
Cl	26,000	800	300	250
Na	15,000	640	200	
SO_4	3,400	160	120	250
Mg	2,000	39	24	
Ca	750	24	72	
K	390	24	13	
SiO_2	19	13	10	
B	4.8	7.2	6.8	
F	.3	2.0	1.9	[3]1.8
Fe	.24	.03	.03	.3
As	.004	.003	.003	.05
Cu	.014	.011	.019	1.0
Mn	7.2	.120	.010	.05
Ag	0	0	0	.05
Cd	.001	0	.004	.01
$CaCO_3$ (Alkalinity)	680	220	280	
		Ratios		
SAR[4]	65	19	5.2	
Ca:Mg	.38	.62	3	
$Cl:SO_4$	7.6	5	2.5	
Cl:Mg	13	21	12.5	
Cl:Na	1.7	1.3	1.5	
Cl:Ca	35	33	4.2	
Cl:K	67	33	23	
Cl:Fe	108,000	27,000	10,000	
Cl:Mn	3,610	6,670	30,000	
Cl:B	5,420	111	44	

[1]Sampled at observation well U17 located 31 feet from injection well I9.
[2]From U.S. Environmental Protection Agency, 1976 and 1979.
[3]Concentration based on mean annual maximum daily air temperature in the study area.
[4]Sodium adsorption ratio.

SUMMARY AND CONCLUSIONS

The geologic history and hydrologic analysis of the baylands provides evidence that the source of the hypersaline ground water is salt-marsh evaporative concentration and percolation. This process differs from the classic model of saltwater intrusion, in which saline water is derived directly from adjacent ocean or bay water. The present bay shoreline did not reach the Palo Alto area until 8,000 years ago, and most bayward growth of salt marshes has occurred since then. Salt deposits were formed naturally in this marsh environment. Isotope data from Roberts and others (1978b) indicate that evaporative concentration and percolation processes have resulted in formation of the hypersaline brine locally within the shallow baylands aquifer system. Water-quality contouring in the area also shows a definite correlation with the boundaries of salt-marshes (fig. 5). The injection well network bisects the zone of greatest saline concentration under the salt marsh. The effectiveness of the injection system is reduced by the widespread distribution of hypersaline ground water and by aquifer discontinuity.

The shallow baylands aquifer system has been hydraulically modeled as a zone roughly 50 feet thick, consisting of an upper (20-foot) aquifer separated from a lower (45-foot) confined aquifer by a leaky-clay confining bed. A thick clay zone below the shallow baylands aquifer system acts as a confining bed. The calculated transmissivity of the lower aquifer was 960 ft^2/d, and the storage coefficient was 5×10^{-4}. The vertical hydraulic conductivity of the upper confining layer was estimated to be 0.08 ft/d. Flow of injection and mixed ground water is governed by this anisotropic horizontal-vertical permeability and also by the freshwater-saltwater density contrast.

Water-quality data collected during injection at well I9 indicate that dilution and dispersion were the major processes in the ground-water system. Chloride was treated as a conservative tracer to which the other ions were compared. Sodium, calcium, and sulfate showed little change as a result of injection. Magnesium and potassium, however, changed noticeably, most likely owing to ion-exchange reactions. Boron, iron, and manganese also varied, probably from oxidation-reduction reactions. Overall, ground-water quality was greatly improved by injection of freshwater.

X-ray analysis showed that clay minerals from aquifer core samples collected near well I6 prior to injection expanded when soaked in typical injection water. These clays, predominantly montmorillonite and illite, apparently reduce permeability by a reduction of porosity and (or) by clay dispersion and subsequent filtration within the aquifer matrix. Clay hydration and expansion may be expected to result from injection. Clay expansion restricts permeability by (1) reducing porosity and (2) producing a hydraulic barrier by dispersion and filtration (McNeal and others, 1966). Water that is high in calcium can be injected first to reduce clay hydration and expansion by replacing the highly expandable sodium ionic layer present in the clays. Subsequent freshwater injection would not produce as great a reaction with a calcium-ion interlayer.

FUTURE STUDIES

Objectives of the next phase of study are directed toward gaining a more complete understanding of the hydraulic and geochemical characteristics of the shallow baylands aquifer ground-water system. The injection process is to be evaluated at well I6 to determine clogging mechanisms, water migration, and water-quality modification.

Extensive sampling for chlorides throughout the well network can help to define the nature of the saltwater contamination and the effects of injection on its distribution and propagation. By defining flow patterns within the well field, a potentiometric survey of existing wells can clarify understanding of both the mechanism of contamination and the injection process.

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$$H(u,\beta) = \int_u^\infty \frac{e^{-y}}{y} \operatorname{erfc}\left(\frac{\beta/ u}{\sqrt{y\ (y-u)}}\right) dy$$

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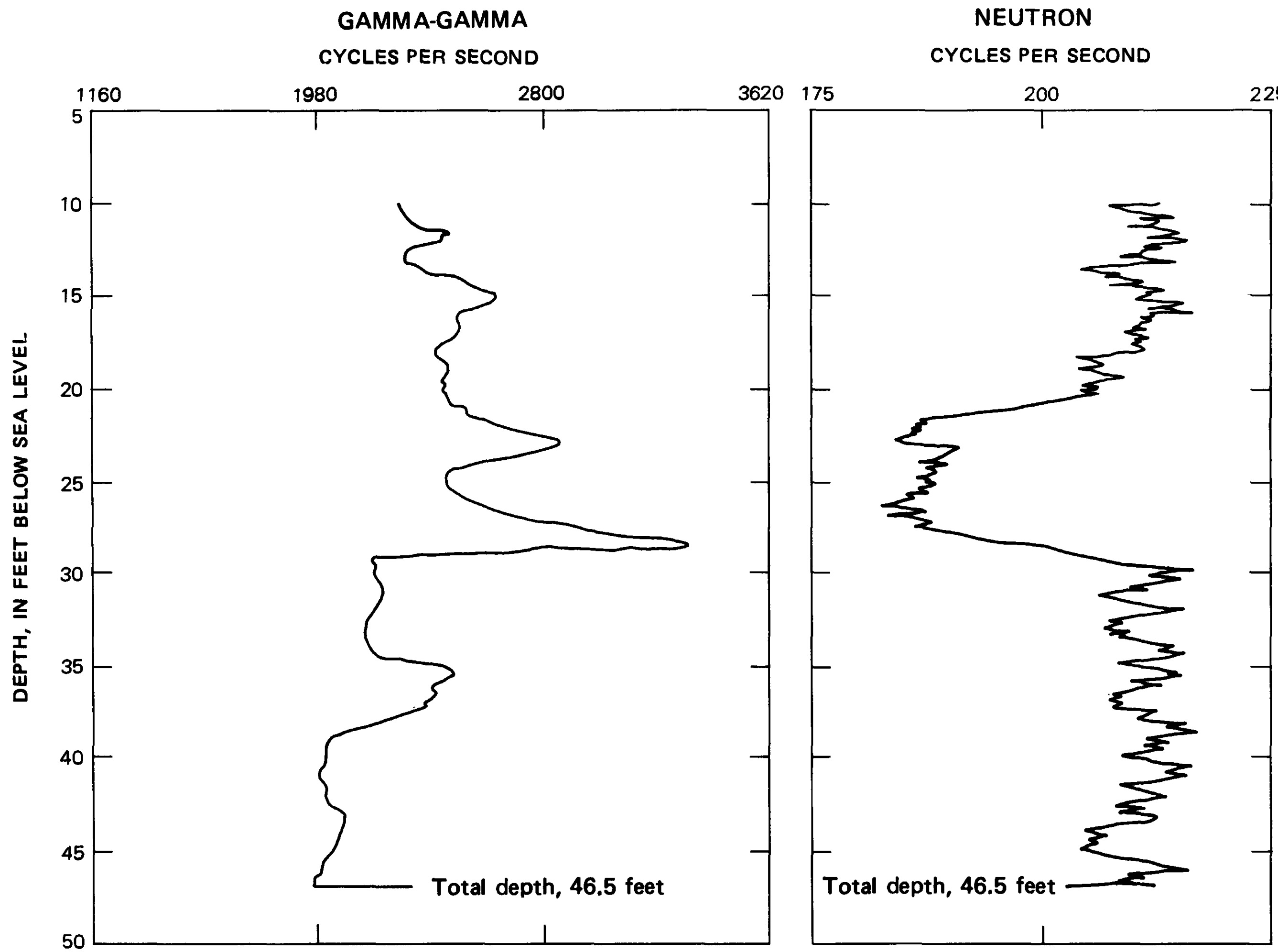
APPENDIXES

APPENDIX A. — Nuclear logs of wells



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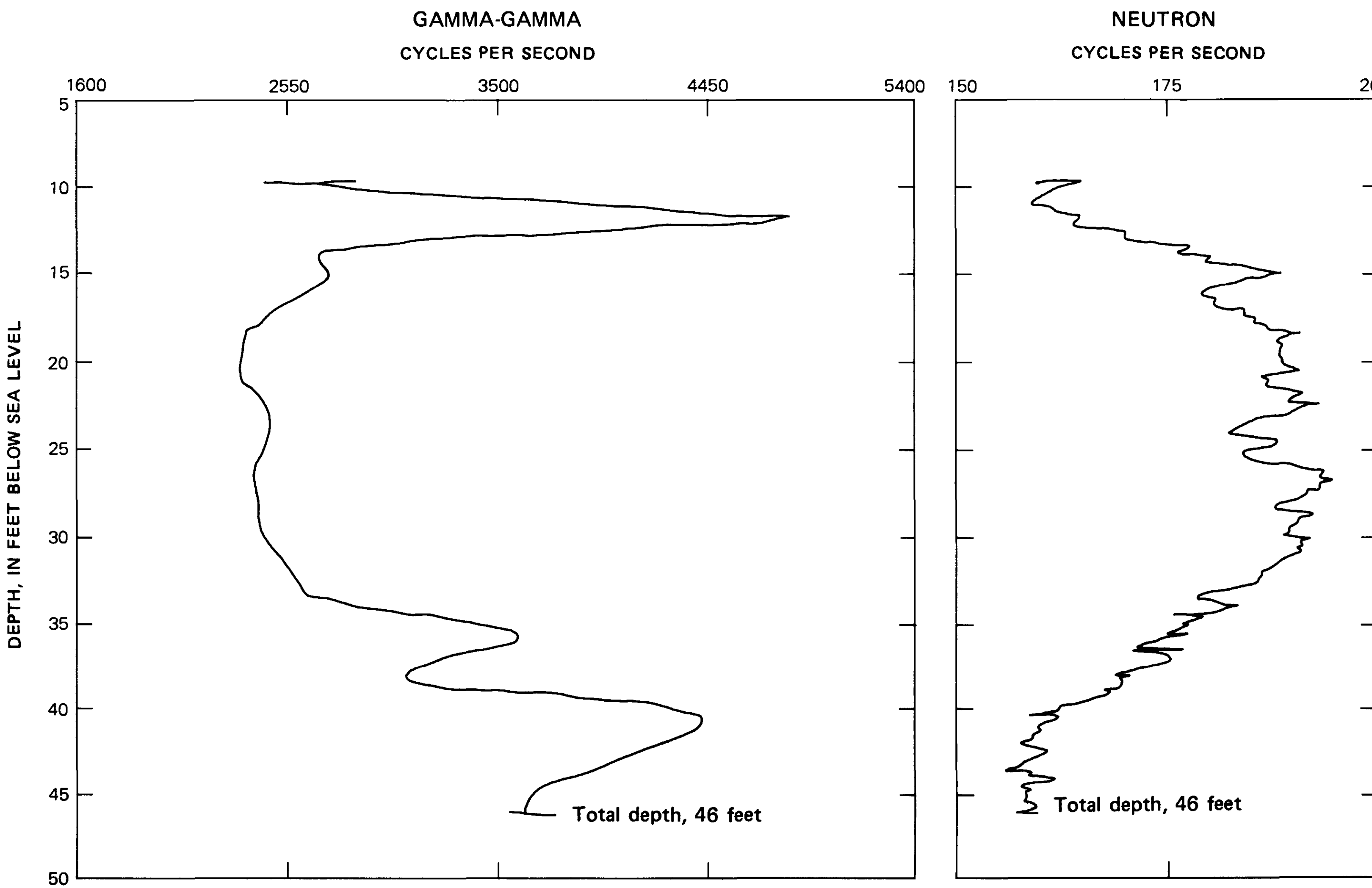

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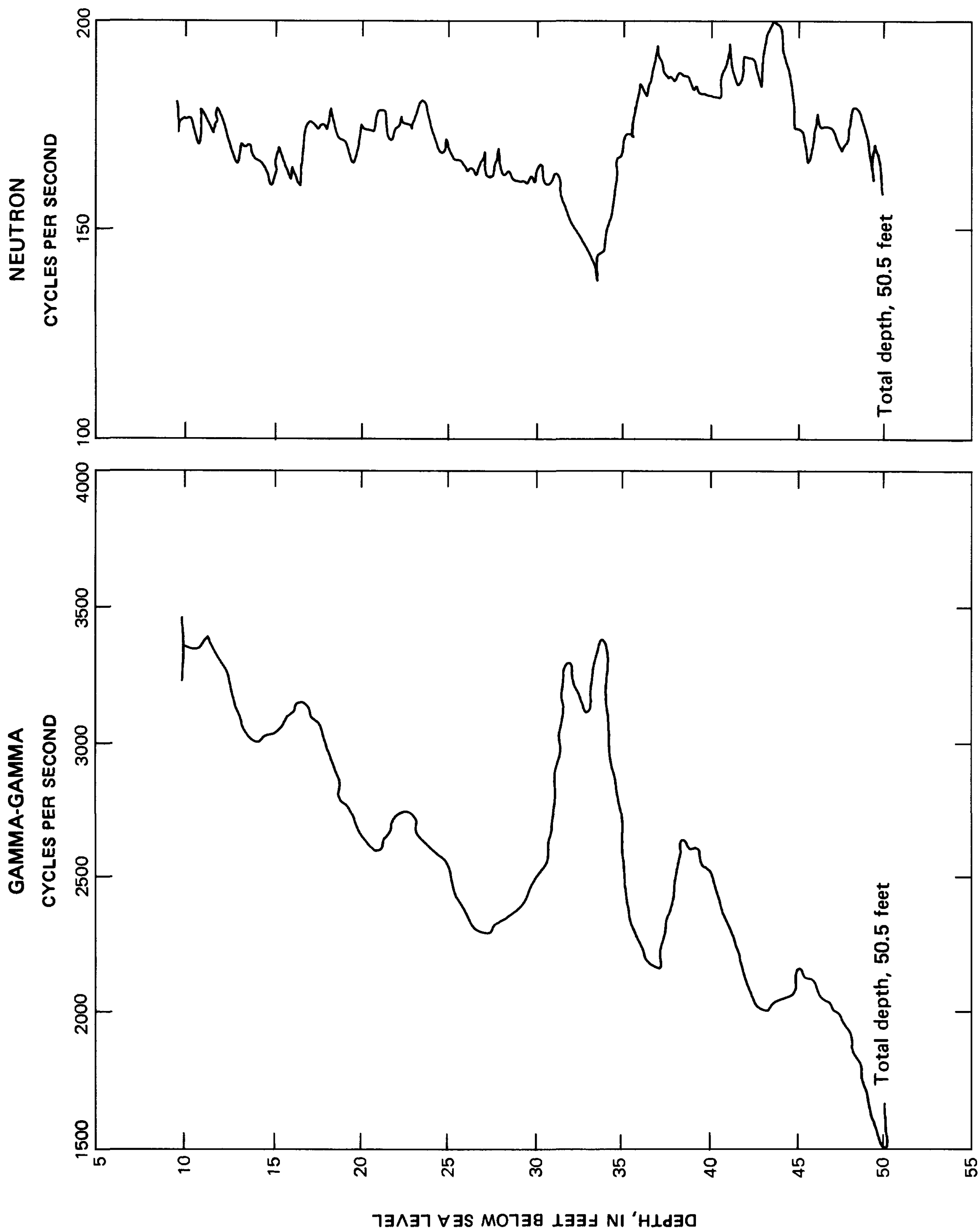

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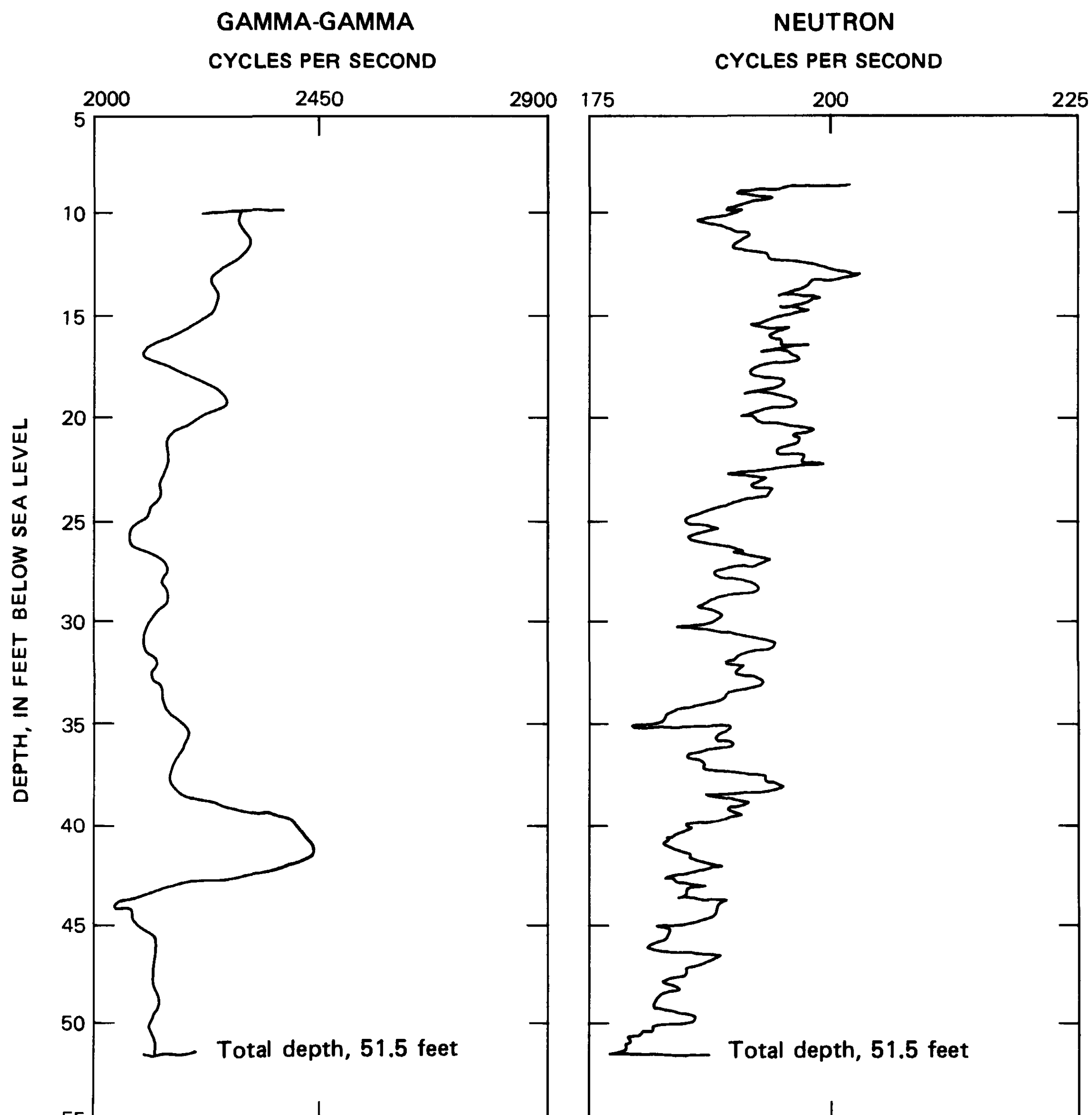

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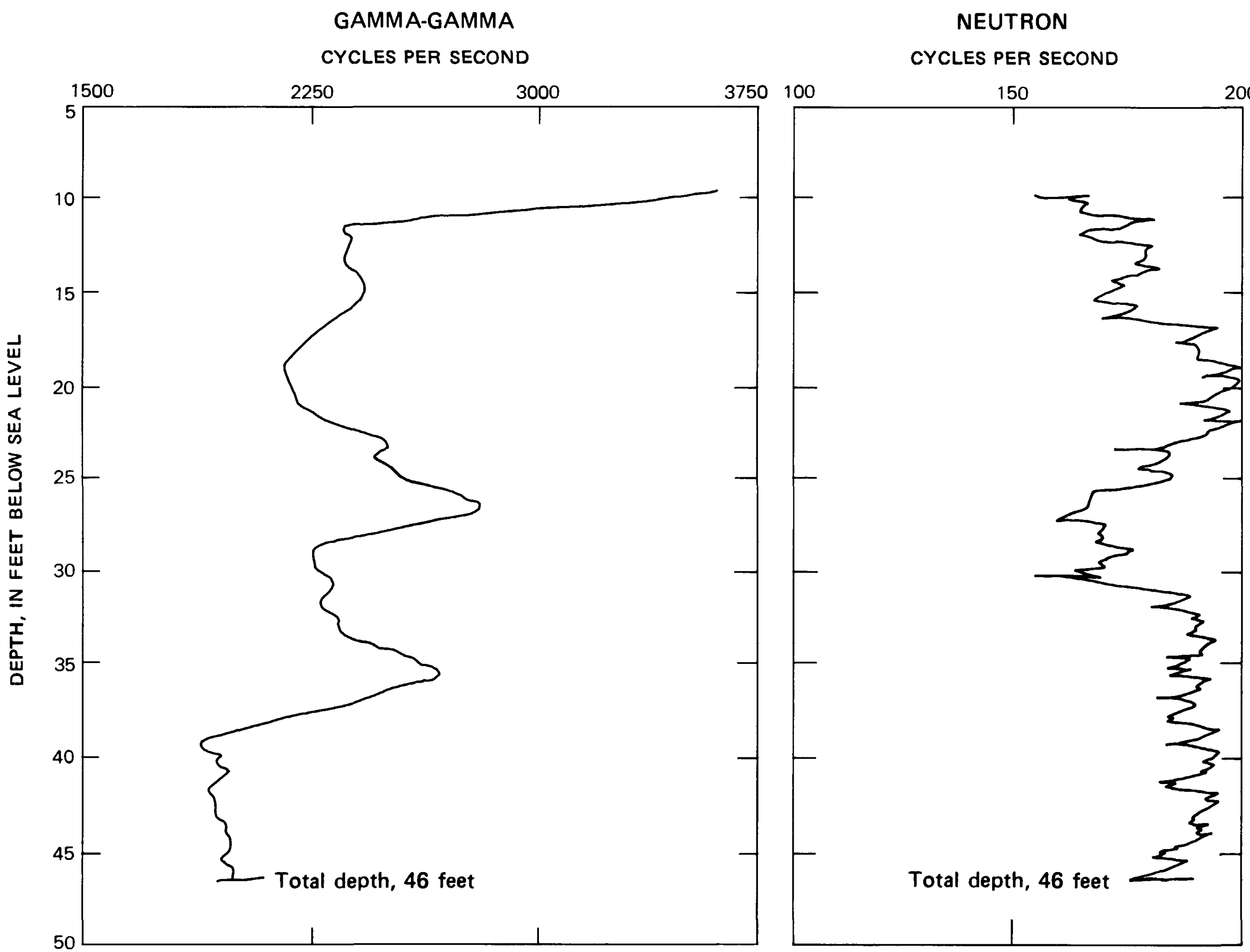

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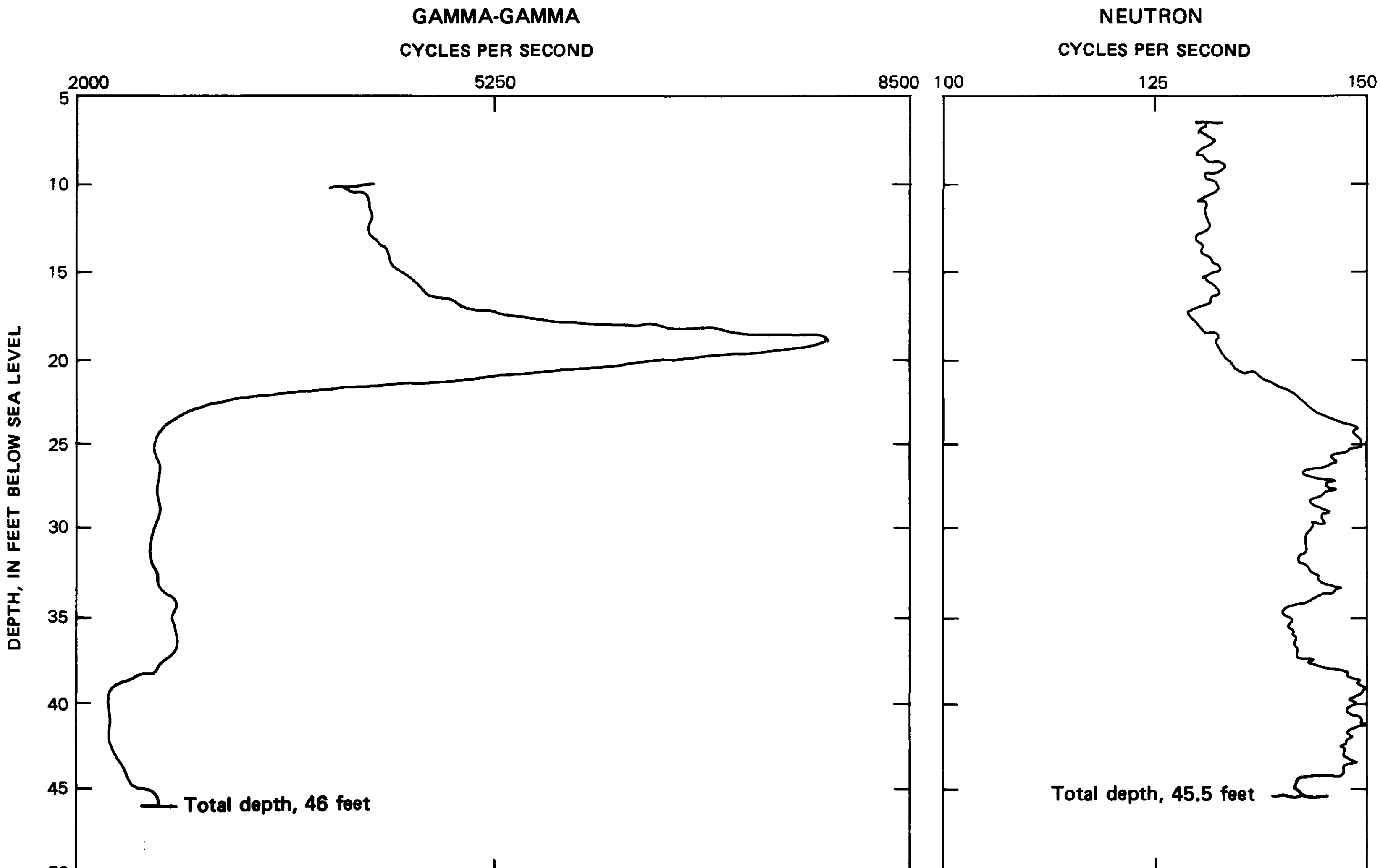

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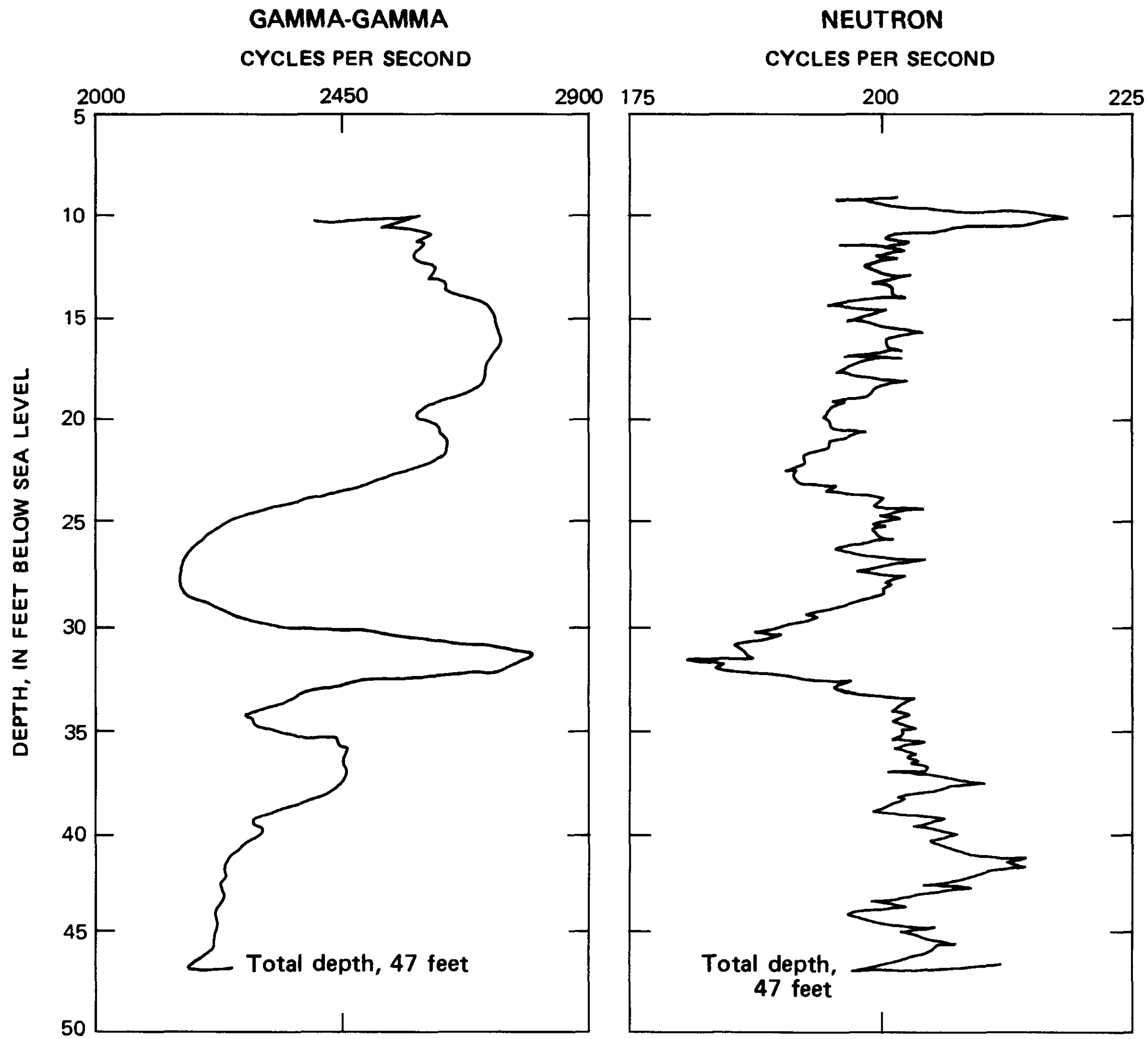

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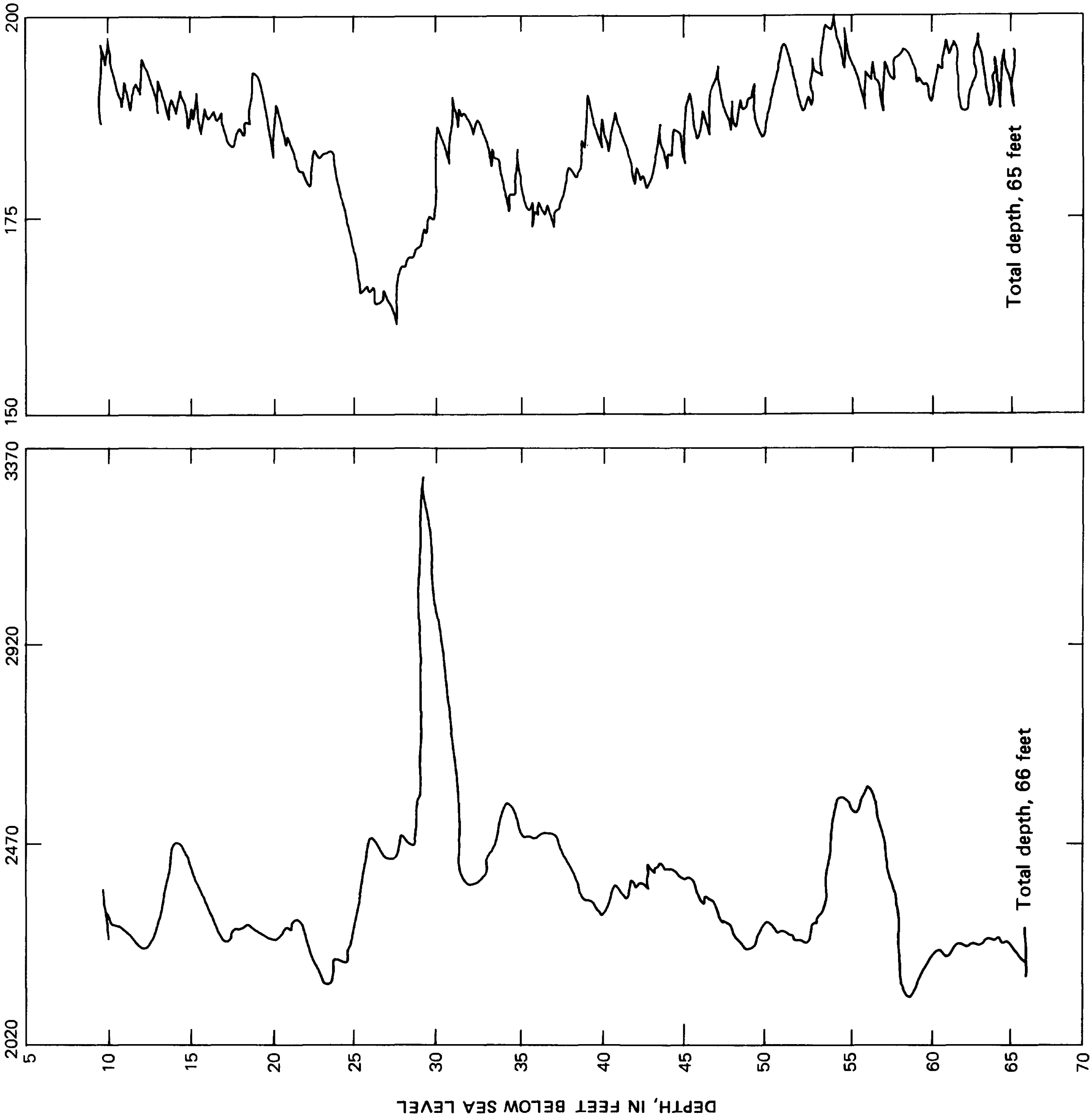

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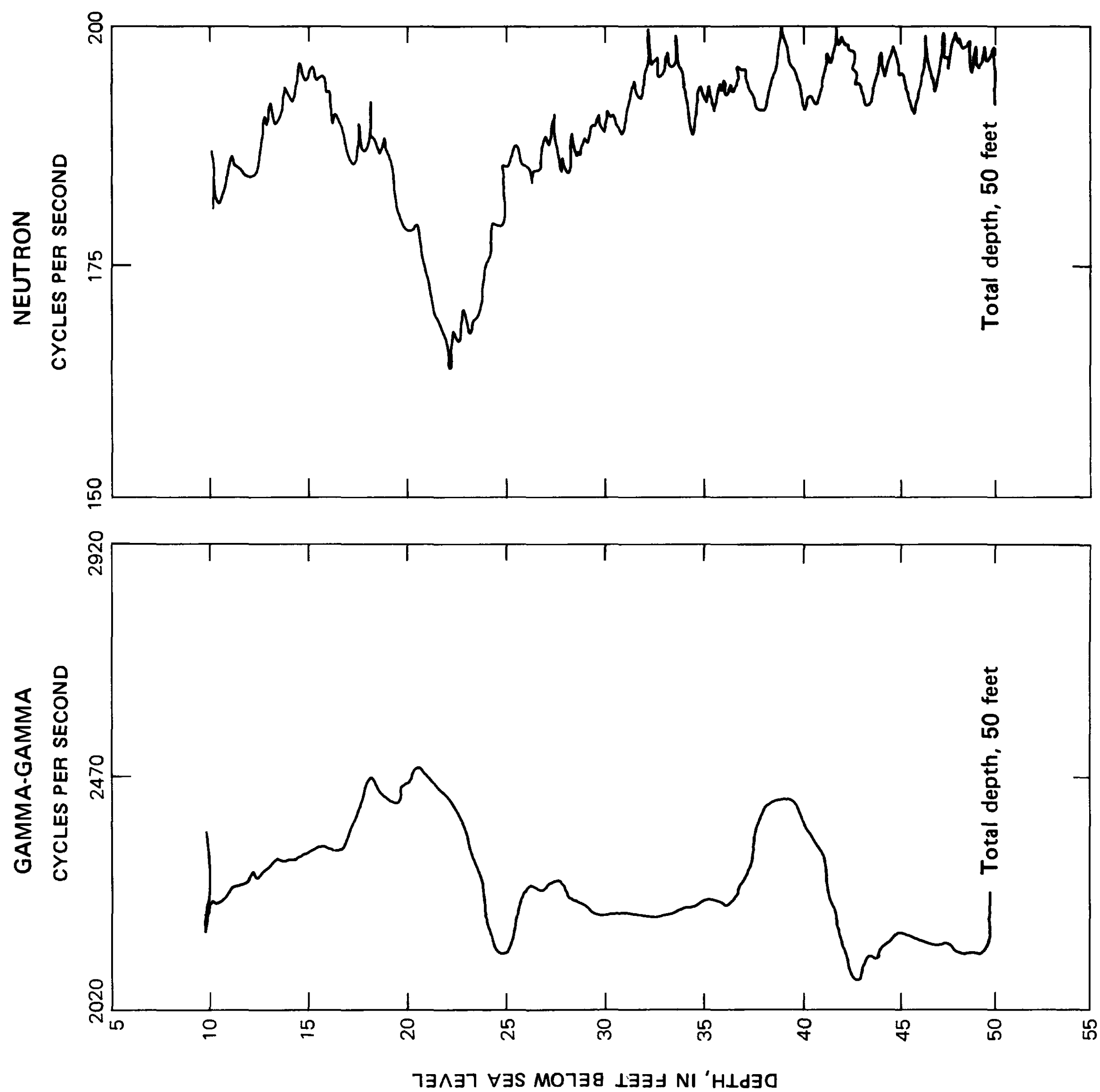
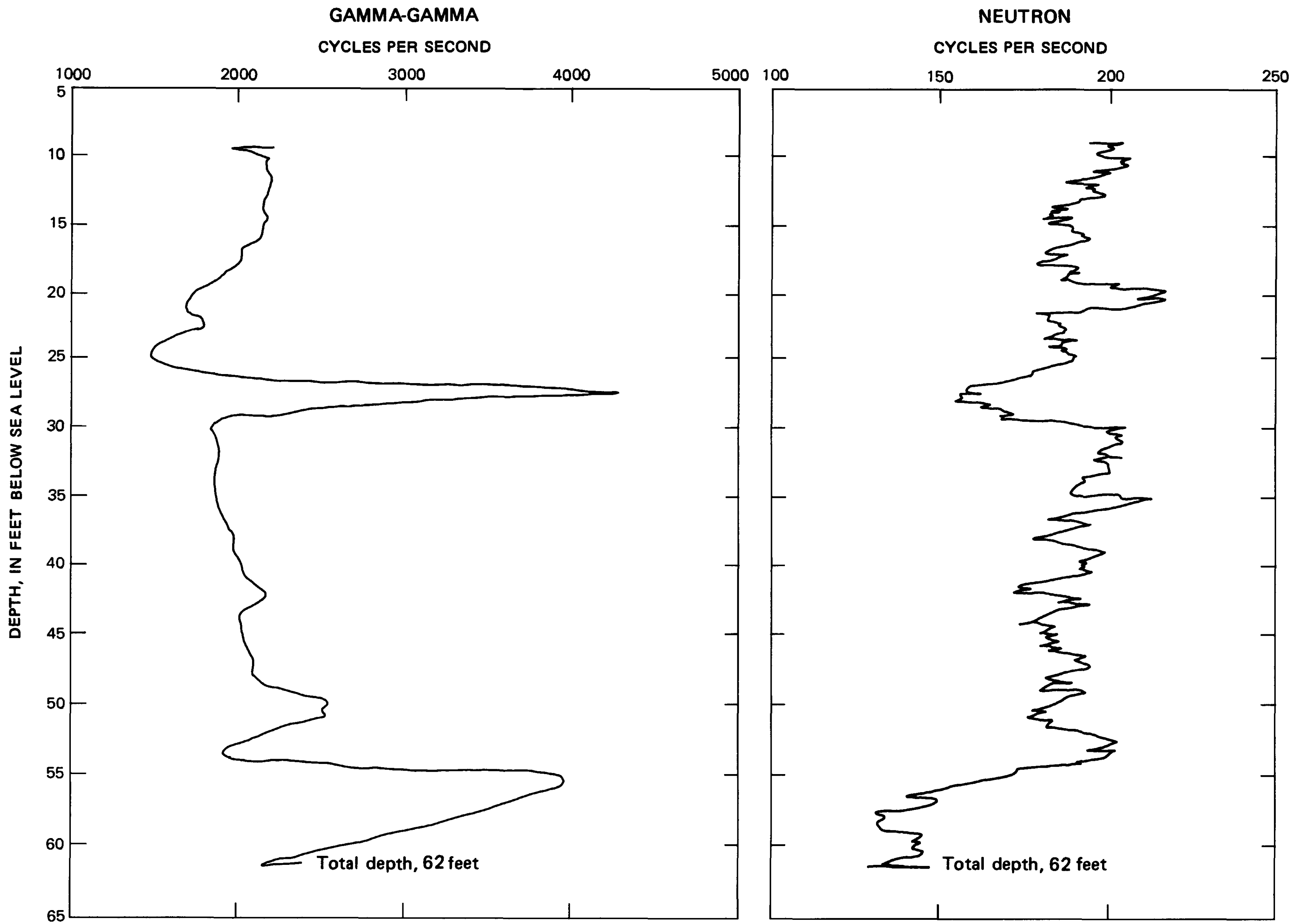


Nuclear log of well S14.



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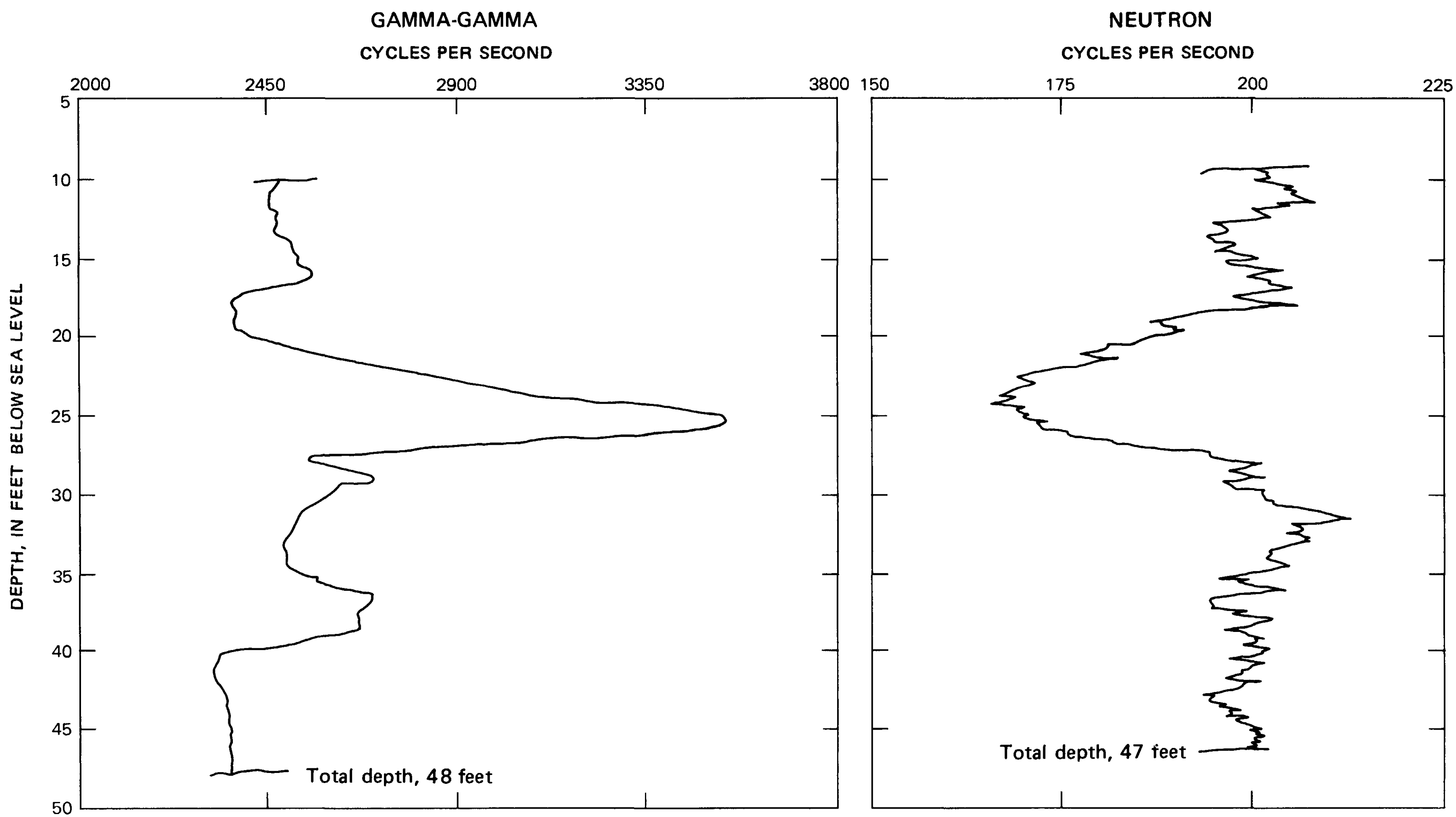
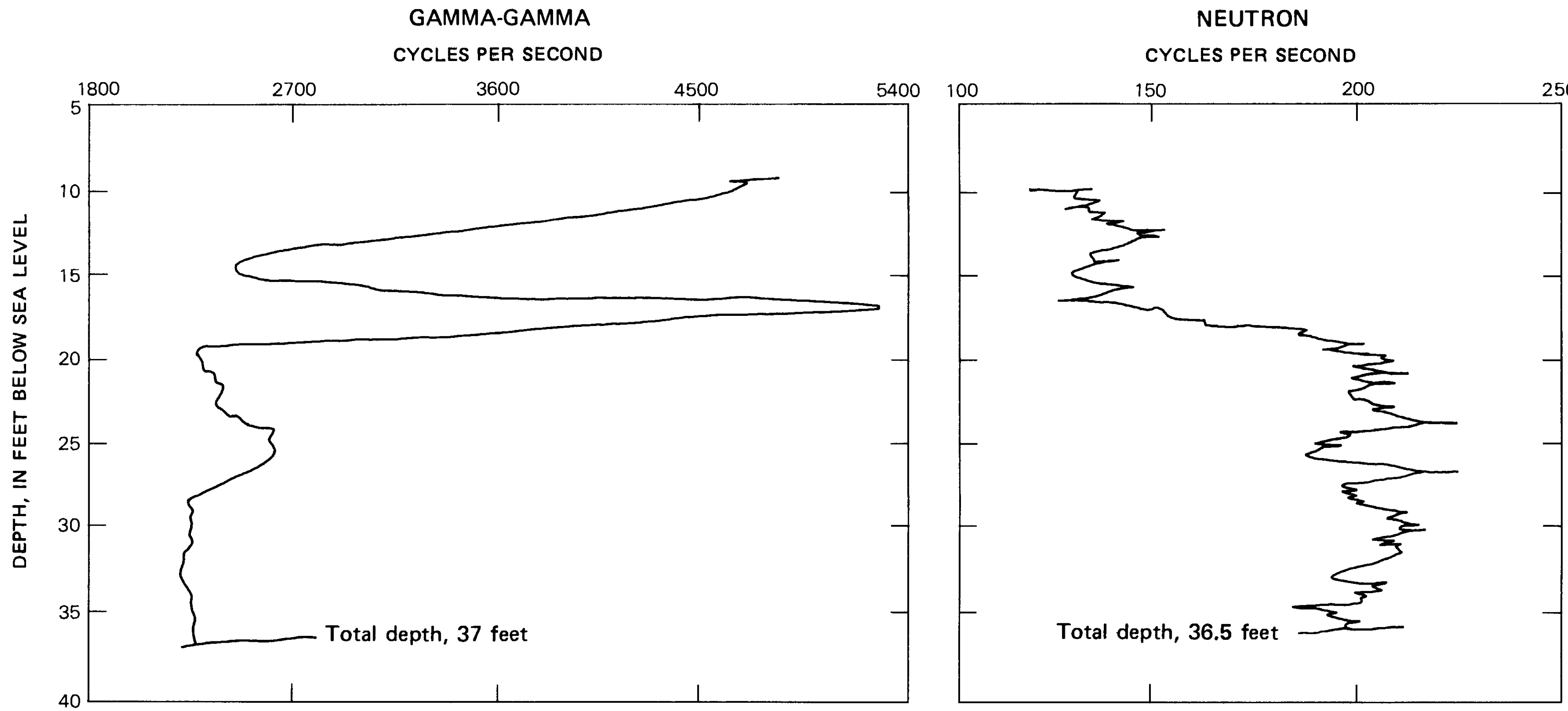


Nuclear log of well S16.



Nuclear log of well S17.

APPENDIX B. - Drawdown data for I6 extraction test, September 24, 1980, beginning at 0936 hours

[t=time, in minutes; r=distance from pumped well, in feet; s=drawdown, in feet]

Time	S14 Deep r=55		S14 Shallow r=55	U11 r=20		I6 Pumped well r=1	
	t/r^2	s	s	t/r^2	s	t/r^2	s
0.1	3.3×10^{-5}	0.01	0.00	2.5×10^{-4}	0.07	0.1	0.28
.2	6.6×10^{-5}	.03	.00	5.0×10^{-4}	.11	.2	.40
.3	9.9×10^{-5}	.05	.00	7.5×10^{-4}	.17	.3	.50
.4	1.3×10^{-4}	.06	.00	1.0×10^{-3}	.21	.4	.57
.5	1.6×10^{-4}	.08	.00	1.3×10^{-3}	.23	.5	.62
.6	2.0×10^{-4}	.09	.00	1.5×10^{-3}	.26	.6	.65
.7	2.3×10^{-4}	.10	.00	1.8×10^{-3}	.28	.7	.69
.8	2.6×10^{-4}	.12	.00			.8	.71
.9	3.0×10^{-4}	.13	.00			.9	.74
1.0	3.3×10^{-4}	.14	.00	2.5×10^{-3}	.32	1	.75
1.5	5.0×10^{-4}	.17	.00	3.8×10^{-3}	.38	1.5	
2.5	8.3×10^{-4}	.22	.01	6.3×10^{-3}	.45	2.5	.89
3.5	1.2×10^{-3}	.24	.02	8.8×10^{-3}	.48	3.5	.93
5	1.7×10^{-3}	.29	.03	1.3×10^{-2}	.52	5	.97
6	2.0×10^{-3}	.31	.03	1.5×10^{-2}	.53	6	1.00
7	2.3×10^{-3}	.33	.04	1.8×10^{-2}	.55	7	1.02
8	2.6×10^{-3}	.34	.04	2.0×10^{-2}	.57	8	1.03
9	3.0×10^{-3}	.36	.05	2.3×10^{-2}	.58	9	1.05
10.25	3.4×10^{-3}	.37	.05			10.25	1.07
15	5.0×10^{-3}	.42	.08	3.8×10^{-2}	.65	15	1.12
25	8.3×10^{-3}	.49	.11	6.3×10^{-2}	.72	25	1.20
35.5	1.2×10^{-2}	.54	.15	8.8×10^{-2}	.77	35.5	1.23
45	1.5×10^{-2}	.57	.17	1.1×10^{-1}	.80	45	1.26
55	1.8×10^{-2}	.60	.19	1.4×10^{-1}	.83	55	1.29
62	2.0×10^{-2}	.61	.21	1.6×10^{-1}	.84	62	1.31
70	2.3×10^{-2}	.63	.23	1.8×10^{-1}	.86	70	1.33
80	2.6×10^{-2}	.65	.25	2.0×10^{-1}	.88	80	1.35
90	3.0×10^{-2}	.67	.26	2.3×10^{-1}	.89	90	1.36
100	3.3×10^{-2}	.68	.28	2.5×10^{-1}	.91	100	1.38
200	6.6×10^{-2}	.77	.37	5.0×10^{-1}	1.00	200	1.47
300	9.9×10^{-2}	.83	.41	7.5×10^{-1}	1.05	300	1.52
400	1.3×10^{-1}	.87	.44	1.00	1.08	400	1.56
500	1.7×10^{-1}	.89	.46	1.25	1.16	500	1.57
650	2.1×10^{-1}	.93	.51	1.63	1.20	650	1.62
750	2.5×10^{-1}	.95	.52	1.88	1.23	750	1.64
850	2.8×10^{-1}	.97	.54	2.13	1.25	850	1.66
1,000	3.3×10^{-1}	.99	.56	2.50	1.26	1,000	1.67
1,200	3.9×10^{-1}	1.00	.57	3.00	1.28	1,200	1.69
1,500	4.9×10^{-1}	1.03	.60	3.75	1.30	1,500	1.71
1,560	5.2×10^{-1}					1,560	1.72