Location and Characteristics of the Interface Between Brine and Fresh Water From Geophysical Logs of Boreholes in the Upper Brazos River Basin, Texas

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By W. S. KEYS *and* L. M. MACCARY

ORIGIN AND MANAGEMENT OF SALT SPRINGS AND SEEPS IN THE UPPER BRAZOS RIVER BASIN, TEXAS

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By W. S. KEYS and L. M. MACCARY

ABSTRACT

The Brazos River flows through the eastern part of the Permian Basin in Texas and is one of the largest sources of water in the State. Unfortunately, brine springs and seeps flowing into the Brazos River contribute an average daily load of about 1,650 tons of sodium chloride to the Possum Kingdom Reservoir, and the change in chemical quality of this water affects its usefulness. An understanding of the occurrence, source, geologic controls, and chemical composition of the brine is necessary before engineering methods can be devised to control the discharge of brine into the river.

This report describes how borehole geophysics was used during a test-drilling program in the upper Brazos River basin to determine the location, characteristics, and relation to lithology of an interface between brine and overlying fresh to slightly saline water. The analysis of several different types of geophysical well logs enabled the accurate location of the interface, proved that it was quite sharp, and showed that the interface was not related to lithology in most places. Some logging tools responded to the interface in open holes; others detected it through casing. For example, single-point-resistance and spontaneous-potential logs were responsive to the interface in many open holes, whereas the neutron-epithermal-neutron and neutron-gamma log combination could be used to find the interface behind well casing. Caliper logs were used to locate fracture zones, which contained brine in some areas and gas in others. All of these logs along with the natural gamma were used to identify and correlate the lithologic units penetrated by the test holes. Natural-gamma and neutron logs helped to distinguish anhydrite from gypsum. Natural-gamma and neutron logs, thus, were useful for determining the depth of hydration of gypsum, which is related to the position of the brine–fresh-water interface. Neutron logs were calibrated in percent porosity by use of core analyses, and the natural-gamma logs were found to be semiquantitatively related to grain-size distribution and to the hydraulic conductivity of the core samples. Fluid-temperature and fluid-resistivity logs provided quantitative data on the chemical composition and movement of fluids in the test holes. Analysis of a large number of commercial electric logs from oil wells in the Brazos River basin showed that many of these logs can also be used to determine the characteristics and location of the interface.

From the study, it is concluded that certain suites of geophysical logs can be used to establish the position and character of the interface between brine and overlying fresh water. The logs showed that the change in quality from brine to fresh water occurs within a vertical interval of several feet and that, although in places the interface may be controlled by lithology, regionally it transects lithologic boundaries. Logs were also used to estimate porosity and hydraulic conductivity, to locate brine-transmitting fracture zones, to measure chemical and physical characteristics of the brine, and to identify specific lithologies, such as halite, gypsum, and anhydrite. Logs of the test holes in the study area provided a convenient and inexpensive way of laterally and vertically extrapolating the more costly core data. Furthermore, geologic and interface information determined in the study area can be extended to the rest of the upper Brazos River basin by use of geophysical logs.

INTRODUCTION

The Brazos River traverses the eastern part of the Permian Basin and is one of the largest sources of water in Texas; however, brine springs and seeps flowing into the Brazos River contribute an average daily load of about 1,650 tons of sodium chloride to the Possum Kingdom Reservoir (approx. 80 miles east of Stonewall County), and the increase in salinity limits the usefulness of this water. An understanding of the occurrence, source, geologic controls, and chemical composition of this brine is essential to the consideration of engineering methods to control the discharge of brine into the Brazos River and other streams. The geologic and hydrologic framework are briefly described by Stevens and Hardt (1965). Other chapters in Professional Paper 809 on the origin and management of salt springs and seeps in the upper Brazos River basin, Texas, describe the extent, thickness, geologic relationship, and geochemistry of the brine and other waters in the area and the problems of management and control of the salt springs and seeps. Specific reference to these chapters is made at appropriate places in the text. This chapter and the others in the Professional Paper 809 series are the result of an investigation carried on in the upper Brazos River basin from 1963 to 1970.

In brief, the salt springs and seeps seem to originate as discharge points of a widespread body of sodium chloride brine whose upper part lies at moderate to shallow depths in the Permian rocks. The brine is overlain by relatively fresh water of a calcium sulfate type, and the contact between the two water bodies is rather sharp in most places. It is referred to as an interface, though actually there is a transitional zone.

Borehole geophysics was used extensively during a test-drilling program in the early phases of the upper Brazos River basin study to determine the usefulness of well logging in recognizing and mapping the interface between brine and the overlying fresh to slightly saline water. During the early phases of the study, corehole C–1 and most of the test holes were drilled in the northeastern part of Kent County and the northwestern part of Stonewall County; however, a few test holes were located in central Stonewall County, and one was located in southern King County, Tex. Additional test holes were later drilled in Stonewall, Kent, Fisher, and Garza Counties—making a total of 38, including the corehole. That part of the upper Brazos River basin in which holes T–1 through T–37 and corehole C–1 are located is the study area of this chapter. The locations of these test holes are shown in figure 1. Construction records of test holes C–1 and T–1 through T–37 will be included in another chapter of this professional paper. Logging and log interpretation were done by personnel of the research project on application of borehole geophysics to geohydrology. All the test holes were logged, and both the logging techniques and the significant findings from log interpretation are included in this chapter of the report.

The results of geophysical logging during the testhole study showed that certain characteristic log responses such as baseline shifts, decreases in average resistivity, and sudden increases in noise with depth could be used as a guide to indicate the position of the interface in approximately 150 oil-company electric logs already available for the upper Brazos River basin.

Borehole geophysical tools and techniques provide: identification of lithology and fracture zones in a single test hole; comparison of stratigraphic units and fracture zones within the area explored by test holes; data on chemical quality and temperature of fluid; recognition of the depth of the freshwater–brine interface; and a knowledge of the implicit relationships between porosity, hydraulic conductivity, and clay content. Actually, the water above the brine ranged in quality from fresh to slightly saline. Fresh water contains less than 1,000 ppm (parts per million) of dissolved solids. Slightly saline water contains 1,000–3,000 ppm of dissolved solids, and brine contains more than 35,000 ppm. Throughout the text, the water above the interface is referred to as fresh although technically it may be slightly saline. Logs were also used to select the most representative core samples for laboratory analyses. Furthermore, logs reduced the need for extensive coring by permitting vertical extrapolation of laboratory values for core samples and lateral extrapolation of these core values to noncore holes. This report discusses the geologic and hydrologic problems that were studied by logging and how the various geophysical logs were interpreted to assist in their resolution. The principles of the various logging techniques are not described in detail in this report. For more detailed information on logging methods and equipment as applied to water-resources investigations see Keys and MacCary (1971).

Hydrologic interpretations of data compiled from the borehole geophysics described herein, analyses of water quality, pumping and packer tests, and core analysis will be discussed in another chapter of this Professional Paper series.

The authors acknowledge the contribution of Well Reconnaissance, Inc., of Dallas, Tex., for the very considerable effort expended in developing the logging equipment described and for their complete cooperation in making needed modifications. Cooperation of the many petroleum companies in allowing use of their logs of shallow test holes is also acknowledged.

Edwin R. Bullard, Jr., formerly with the research project, obtained some of the commercial logs and did much of the interpretive study of these electric logs.

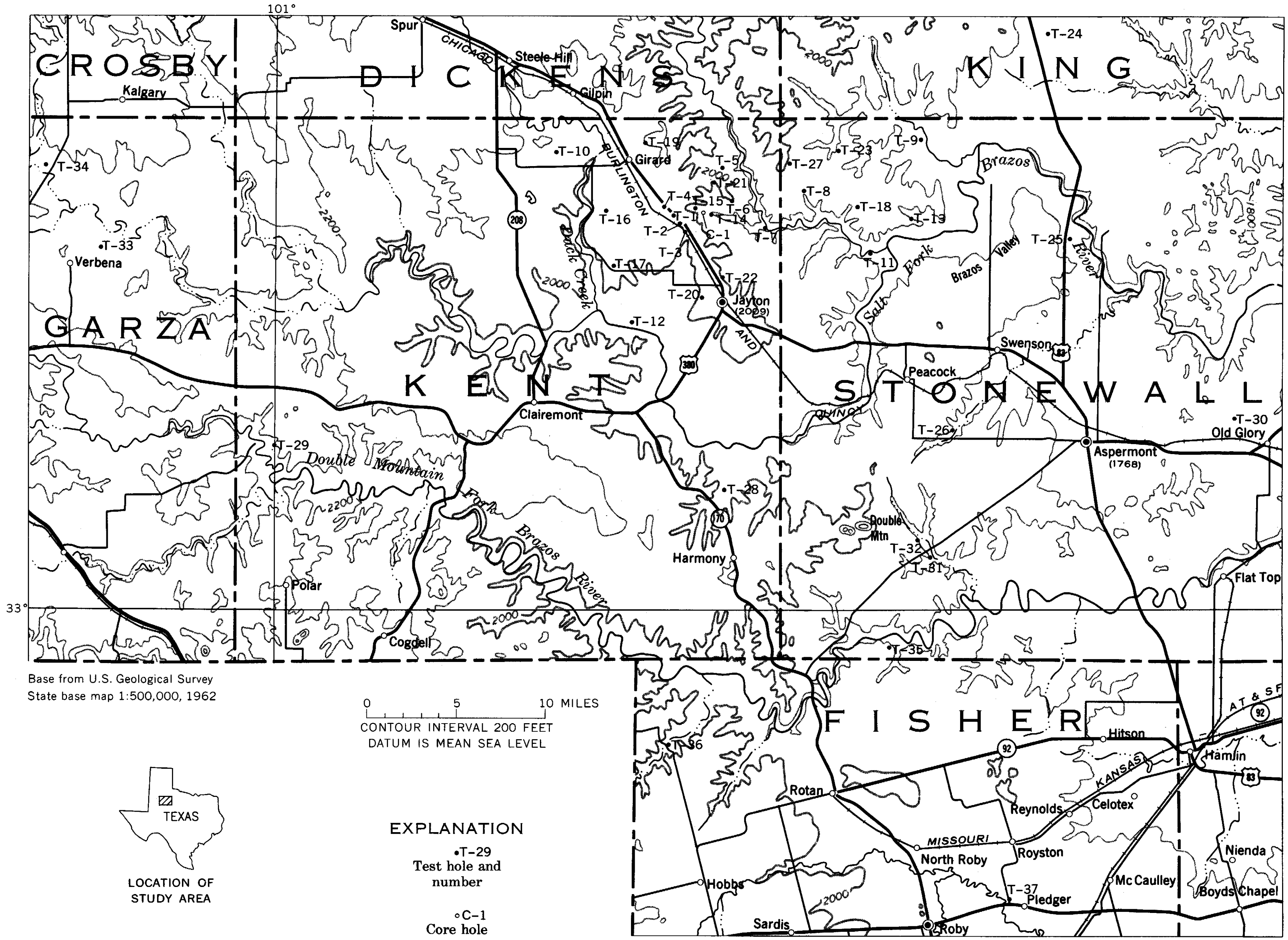

FIGURE 1.—Location of test holes and the study area.

INTERPRETATION OF GEOPHYSICAL LOGS FROM STUDY AREA

In any study utilizing borehole geophysics, it is advisable to log with all available methods, because each one measures different parameters of the borehole environment. Geophysical logs are synergistic; that is, multiple interpretation of a suite of logs provides more information than the sum of data from individual logs. For this reason, a comprehensive suite was run, and multiple interpretations were made in order to maximize the information density at each site. Time-lapse logging was also employed so that changes in borehole environments could be detected.

Figure 2 is typical of the suites of logs run on each hole and is an example of the synergistic nature of geophysical logs.

The caliper log indicates changes in borehole size, a parameter which is related to rock mechanics, rock solubility, and drilling technique. Zones of hole enlargement, shown by the caliper log, cause extraneous effects on point-resistance, gamma-gamma, and neutron logs. (For example, see fig. 2 at the 190-ft depth.) The gamma-gamma probe responds to changes in apparent bulk density, that is, to changes in mineralogy, porosity, saturation, and borehole size within the volume of investigation or zone sampled by the log. The natural-gamma sonde responds to natural radiation intensity, which is higher in clays and shales than in clastics, carbonates, and chemical precipitates. The spontaneous-potential log is a record of the natural potentials developed between the borehole fluid and the surrounding rock material and is related to the relative porosities of the rocks and to the salinity of the water that they contain. The point-resistance probe measures the resistance offered by the rocks to the passage of an electrical current, and the log is therefore related to water-saturated porosity and water quality and depends, to a lesser extent, on mineralogy. The neutron probe responds uniquely to the presence of hydrogen and thus gives an undifferentiated measurement of water-saturated porosity, water of crystallization, and sorbed water.

The synergistic character of the logs is due to the fact that each type of log actually measures a different parameter, and when several are analyzed together, each will tend to support or contradict conclusions drawn from others.

Composite interpretation of logs and other types of comparisons of various geophysical logs were the basis for arriving at conclusions regarding the lithology of the rocks and the quality of the contained water in the project area. For example, combined interpretation of the gamma and neutron logs shows that no significant gypsum beds are present in hole T–14 (fig. 2). Such beds are identified by low gamma intensity and high-neutron porosity. A combined interpretation of several logs can also be used to determine effective porosity. For hole T–14, the natural-gamma log suggests that the high-neutron porosity zone indicated below a depth of 300 feet on the neutron log is clay or shale rather than permeable sand but that the high-neutron porosity zone above 100 feet represents permeable rocks that have a relatively low clay content. The permeable zone is indicated by a relatively high porosity on the neutron and gamma-gamma logs, relatively low intensity radiation on the natural-gamma log, and by a low resistance on the single-point log. That the most permeable zone is above 100 feet was borne out by pump and packer tests.

In the following pages the kinds of information obtained are categorized according to the types of logs run: namely, electric logs, fluid logs, caliper logs, and nuclear logs. Electric logs provide two types of information: spontaneous potential and point resistance. Fluid logs provide both fluid-resistivity and fluid-temperature measurements. Nuclear logs include natural-gamma, gamma-gamma, and neutron logs.

Most of the commercial electric logs borrowed for this study were made in holes drilled for stratigraphic information between 1949 and 1952. Most of these were spontaneous-potential and single-point-resistance logs apparently made with single-conductor type equipment. Very rarely were multi-electrode logs of oil wells continued up through the shallow ground-water zone of interest in the study area. In general, the sensitivity of the logs made in stratigraphic holes is very low, and information on fluid levels or mud resistivity is not available from the log headings. Approximately 150 of these logs were studied in detail for baseline shifts that would indicate the position of the interface between brine and fresh water. Other logs of better sensitivity, which were made between 1965 and 1968, were also obtained from oil companies. Many logs demonstrated baseline shifts or decreases in average resistivity in places where the more porous rocks were saturated with brine. Interface data interpreted from these logs agree closely with the interface position from all other sources. Test hole T–27 was located near both the older and newer oil company test holes partly to check the accuracy of the interface depth picked. The data obtained on all the oil

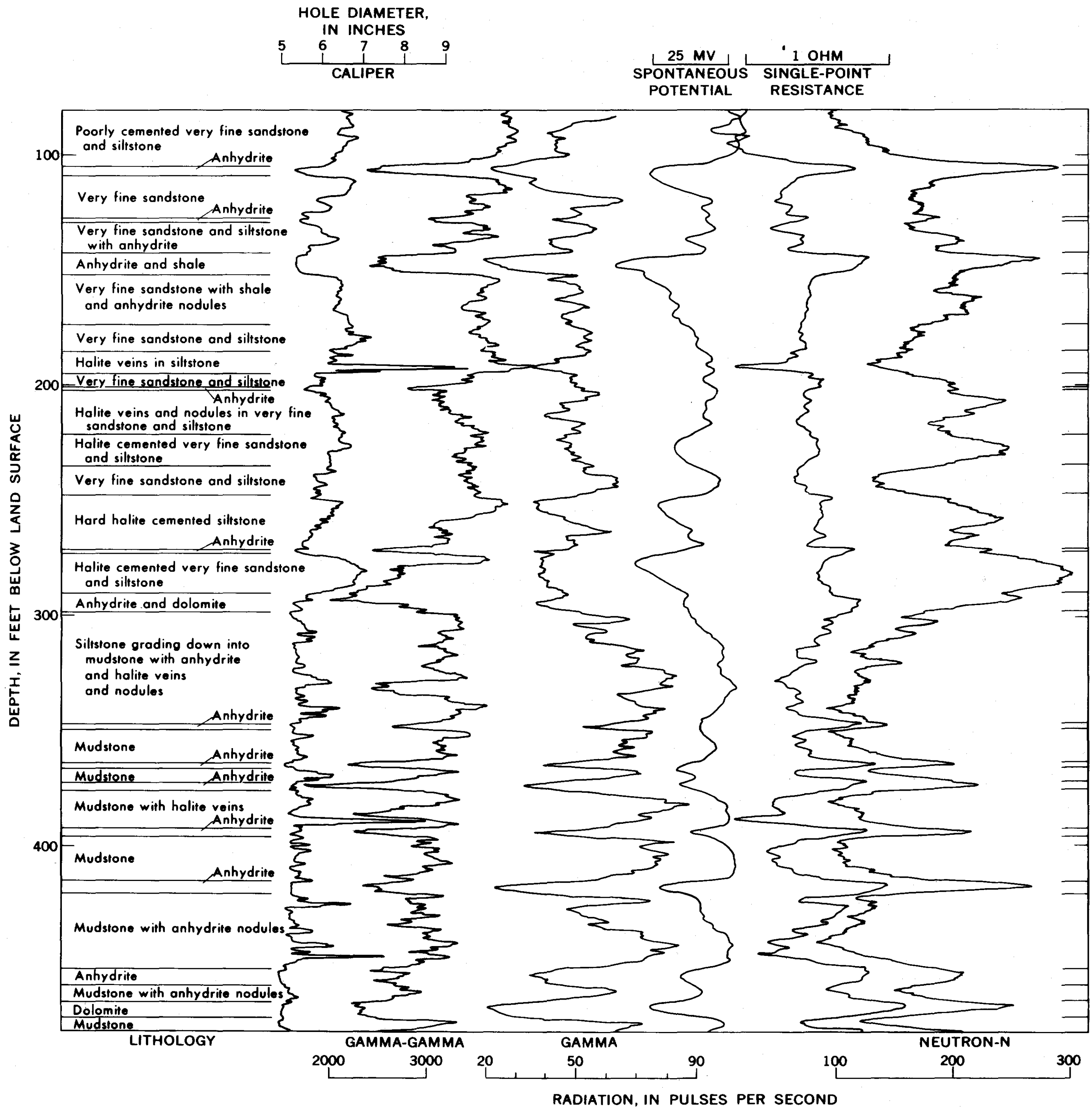

FIGURE 2.—The relationships of six different geophysical logs to lithology; hole T–14.

company logs agrees closely with the interface depth identified on the log of well T–27. The interpretive assumption was that the upper shift in a hole filled with drilling mud represents the water table and the lower shift the position of the interface. It is possible, however, that neither shift represents a fluid-column interface that coincides with the actual interface in the rock. No water-level data are available for the period when the commercial logs were made. A comparison of a recent water-level map with levels derived from interpretation of older commercial logs showed many discrepancies. Many of these logs, however, exhibit a sharp increase in noise and loss of lithologic detail below a certain depth. Because it was found during the test-hole logging that a much improved SP log could be made if the hole had been flushed with fresh water, it is possible that increased noise and decreased lithologic detail on the log indicates saltier fluid in the hole and possibly in the formation. Other commercial logs made in shallow oil-company test holes which were carefully washed and then refilled with water of the proper salinity yielded high-quality SP logs. Many of these SP logs show shifts of large magnitude at depths consistent with interface data from all other sources in the vicinity.

Data from commercial electric logs, together with logs made by the U.S. Geological Survey, were compiled on maps, and information on the interface taken from these maps was used to construct the contour map of the interface which will be included in another chapter of this report. Data from commercial logs were also used to substantiate and extend laterally the stratigraphic correlations based on logs made by project personnel.

DATA FROM ELECTRIC LOGS

SPONTANEOUS POTENTIAL

Spontaneous-potential (SP) logs are records of the natural potentials developed between the borehole fluid and the surrounding rock materials. The main uses of the spontaneous-potential curve are for correlating geologic units, determining bed thickness, and distinguishing nonporous from porous rocks in shale-sandstone and shale-carbonate sequences.

In general, the SP curve resembles the natural-gamma log in the study area (fig. 2). Clean sands are shown as deflections to the left, and shales as deflections to the right. However, lithologic responses on SP logs are not unique. Therefore, an interpretation of some SP curves if made without benefit of the lithologic log and other types of geophysical logs could easily lead to erroneous conclusions. For example, the sharp peaks in the negative direction (to the left) on the SP curve of hole T–14 (fig. 2) might be identified as sand beds, whereas they are actually anhydrite beds, as shown by the gamma and neutron logs. Because both anhydrite and sand have a strong negative self potential and produce similar peaks on the SP log, there is nothing inherent in the log itself on which to base a lithologic distinction; sand and anhydrite, however, can be clearly distinguished by their different responses on the natural-gamma, neutron, and resistance logs. The interpretation of the SP curve for hole T–14 is further complicated by the fact that all the sediments in this hole are very fine grained clastics or chemical precipitates, and therefore the strong interbed contrasts found in boreholes penetrating shales and sandstones are absent. Because in the study area nearly the same direction and magnitude of deflections can be found for mudstone, siltstone, very fine grained sandstone, anhydrite, and halite, use of the log as a lithologic tool was limited.

Many SP logs were not useful for picking the interface depth or for geologic correlation for other reasons. If borehole fluids are very salty, the spontaneous potential may be virtually nonexistent, and it is possible for the polarity to reverse (positive deflections for sand beds and negative deflections for shale beds) if the borehole fluid is more saline than the interstitial fluids. This problem of excessive conductivity of the brine in the test hole was extreme in the study area, and a typical SP curve was obtained only in a few holes that were flushed with fresh water immediately before logging.

In spite of the limitations of the SP log as an interpretive tool in the study area, the sudden loss of lithologic detail, an increase in noise of fluctuations on the SP curve below a certain depth, or a sharp baseline shift was found to be helpful in some places for picking the position of the fresh-water–brine interface.

POINT RESISTANCE

Point-resistance devices measure the electrical resistance, in ohms, of the earth materials lying between a logging electrode and a current-return electrode which is located either at the surface or elsewhere in the borehole. In a homogeneous, infinite medium, the resistance is proportional to the resistivity of the medium, the value of which can be obtained from resistance measurements by applying suitable correction factors. In the heterogeneous, finite environmental medium, the resistance is affected by the resistivity of the borehole fluid, the resistivity of the nearby earth materials, irregularities in borehole size, resistance of the logging cable, and the grounding resistance of the current-return electrode. The point-resistance tool (also called single-point tool) provides a nonlinear curve which usually increases or decreases in magnitude in response to increases or decreases in formation resistivity. The main use of the point-resistance logs are for geologic correlation, location of bed boundaries, and location of fractures.

Generally a more resistive bed gives a sharp deflection to the right and less resistive bed a deflection to the left regardless of bed thickness. Very small deflections on the single-point curve have been found to be significant and a great aid to stratigraphic correlation in the study area. The resistance log in figure 2 shows sharp deflections to the left at about 180 feet, 380 feet, and at 450 feet. The low-resistance peaks probably result from the effect of fluid-filled hole enlargements partly caused by fractures. The fracture zone at a depth of 180 feet has been located at approximately the same stratigraphic position in other drill holes in the area by means of single-point and caliper logs. (See fig. 6.)

In figure 2, large deflections to the right in the resistance curve occur at 100 feet, 140 feet, and from about 340 feet to the bottom of the hole. These deflections are due to the high resistivity of anhydrite beds.

Because the point-resistance probe is so strongly affected by the salinity of borehole fluids, a marked shift of the log baseline to the left would be evidence that the probe has crossed the fresh-water–brine interface in the hole. The actual interface in the rocks, however, may not coincide in depth with this shift, because the natural hydrostatic head may have been altered by the drilling. Theoretically, an electric logging tool with a greater radius of investigation or a neutron tool would identify the interface in the rocks. Figure 3 is an example of the effect of the interface on a single-point log. The large shift of the log baseline at about 250 feet marks the position of the interface. This depth probably represents the

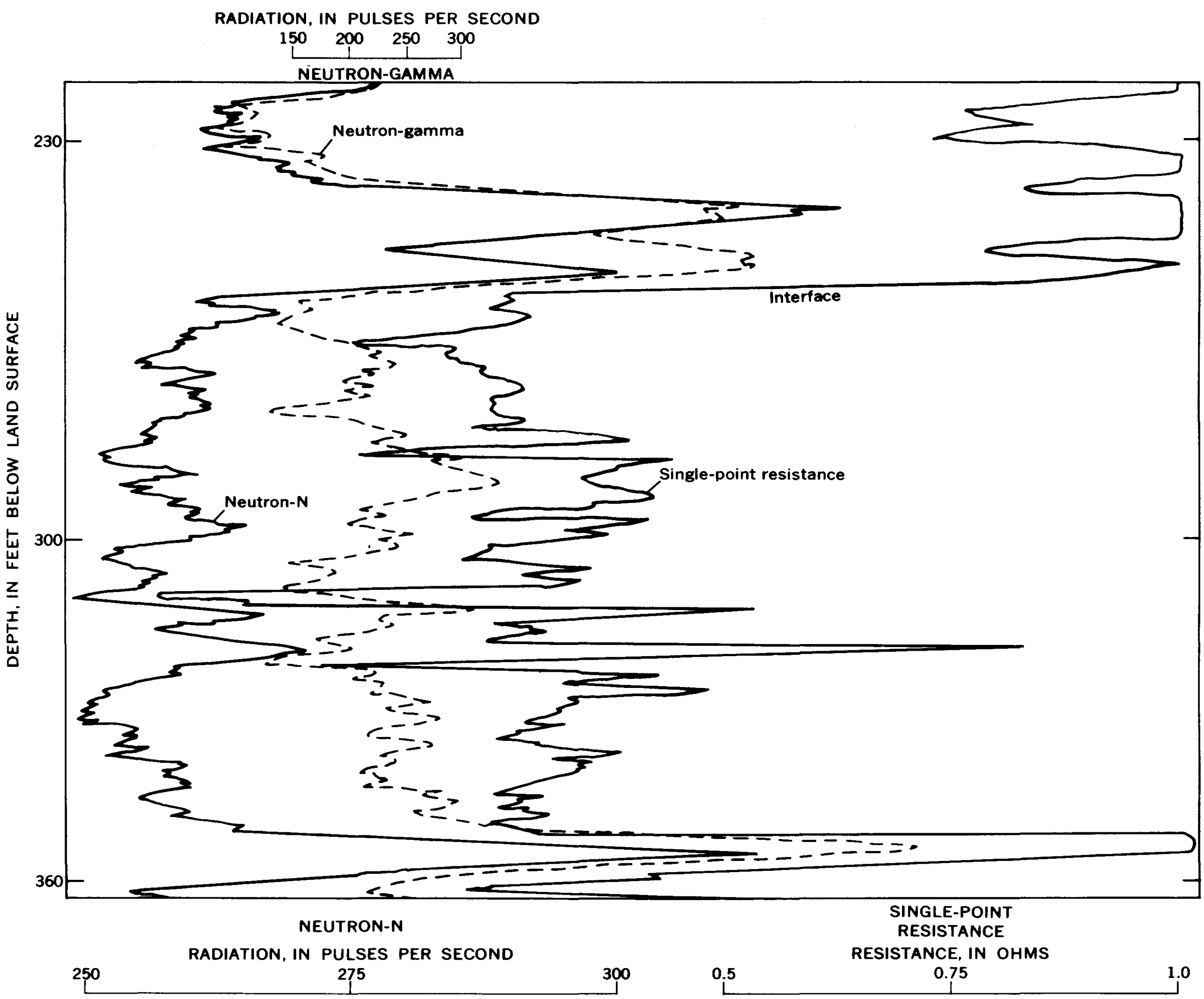

FIGURE 3.—Location of the brine–fresh-water interface from geophysical logs, hole T–18.

interface both in the borehole and in the rock, because the neutron logs also show a deflection at the same horizon. The neutron logs will be discussed in detail in subsequent paragraphs.

DATA FROM FLUID LOGS

FLUID RESISTIVITY

Fluid-resistivity logs are a continuous record of the resistivity of the fluid as the sonde traverses the borehole. The electrical resistance is measured between two accurately spaced ring electrodes in a fluid cell of known cross-sectional area. Because the area and length are known, the resulting resistances are converted directly into ohm-meters, and the resultant curve is recorded as resistivity.

The right-hand log in figure 4 shows a marked deflection in the fluid-resistivity log caused by changes in chemical quality of the borehole fluid. Fluid resistivity of the fresh water (from water level to a depth of 470 feet) ranged downward from 1.3 ohm-meters to 0.72 ohm-meter. The large shift of the log to the left at 470 feet records the entrance of the electrodes into brine in the borehole. (Note the 1:10 change of scale in the lower half of fig. 4.) The resistivity of the brine ranged from 0.001 ohm-meter to a maximum of 0.06 ohm-meter. The fresh-water–brine interface was uniquely defined by the large differences in resistivities of the two fluids in well T–19. Because this tool samples only the fluid in the borehole, the interface in the rocks might be at some other depth; however, the shift on the neutron log on the left side of figure 4 indicates that the interface in the borehole fluid coincides with the actual one present in the surrounding rocks.

TEMPERATURE

Temperature logs are continuous-depth records of the temperature of the fluid immediately surrounding a sensor in a borehole. These logs can provide information on the source and the movement of water and on the thermal conductivity of rocks.

The center log of figure 4 shows the temperature profile from water level to a depth of about 550 feet in test hole T–19. The profile makes an orderly progression from 68°F at the water surface to 71°F at the bottom of the hole, a gradient of about 1°F per 100 feet. The uniformity of the slope and the absence of irregularities indicates that there was no circulation of ground water in the well bore. Apparently this well had attained thermal equilibrium with the environment during the time interval between drilling and logging.

Fluid-resistivity and temperature logs can be used to estimate dissolved-solids content, in parts per million, because of the known relationships between resistivity, temperature, and sodium chloride concentration. Rather accurate salinity estimates can be made on the basis of these relationships for the brine in the upper Brazos River basin because sodium chloride is the dominant constituent in the brine. Most well-logging service companies publish charts or tables showing the relationships. In figure 4, for example, the 71°F value on the middle log aligns with a resistivity of 0.05 ohm-meter on the right-hand log. Using the appropriate chart in Schlumberger (1958), a resistivity of 0.05 ohm-meter at 71°F gives a sodium chloride concentration of approximately 180,000 ppm, and a resistivity at standard temperature (77°F) of 0.046 ohm-meter.

In addition to data on dissolved-solids contents, these logs afforded information on the circulation of the ground-water system. Several of the temperature logs made in February of 1965 showed a steeper geothermal gradient below than above the interface. A slight change in gradient was observed on earlier logs of the same holes. The change in temperature gradient with time and after the drilling of the test holes has been completed points out the need for a longer period prior to logging to allow thermal equilibrium to become established.

Test well T–18 provides the best example of change in gradient. The temperature was 68.5°F at 60 feet, 69°F at 220 feet, and 71.5°F at 490 feet. The increase in temperature with depth is only 0.5°F in 160 feet in the fresh-water zone and approaches the normal 1°F per hundred feet in the brine. Because hydraulic conductivities and pumping rates in the area do not indicate rapid ground-water circulation above the interface, the flattened temperature gradient may indicate vertical movement of ground water in the vicinity of the well, either within or outside the casing. A temperature anomaly indicative of a zone of rapid circulation was found in only one hole. The temperature log of hole T–5 shows a normal gradient below 200 feet; however, the lack of gradient above 200 feet (the temperature distribution was erratic) indicates upward movement of fluid within the borehole.

The change in temperature gradient warrants more study to determine if it can be used as a tool for location of the interface. It may be true that the change is more closely related to hole construction and the availability of new routes for vertical move-

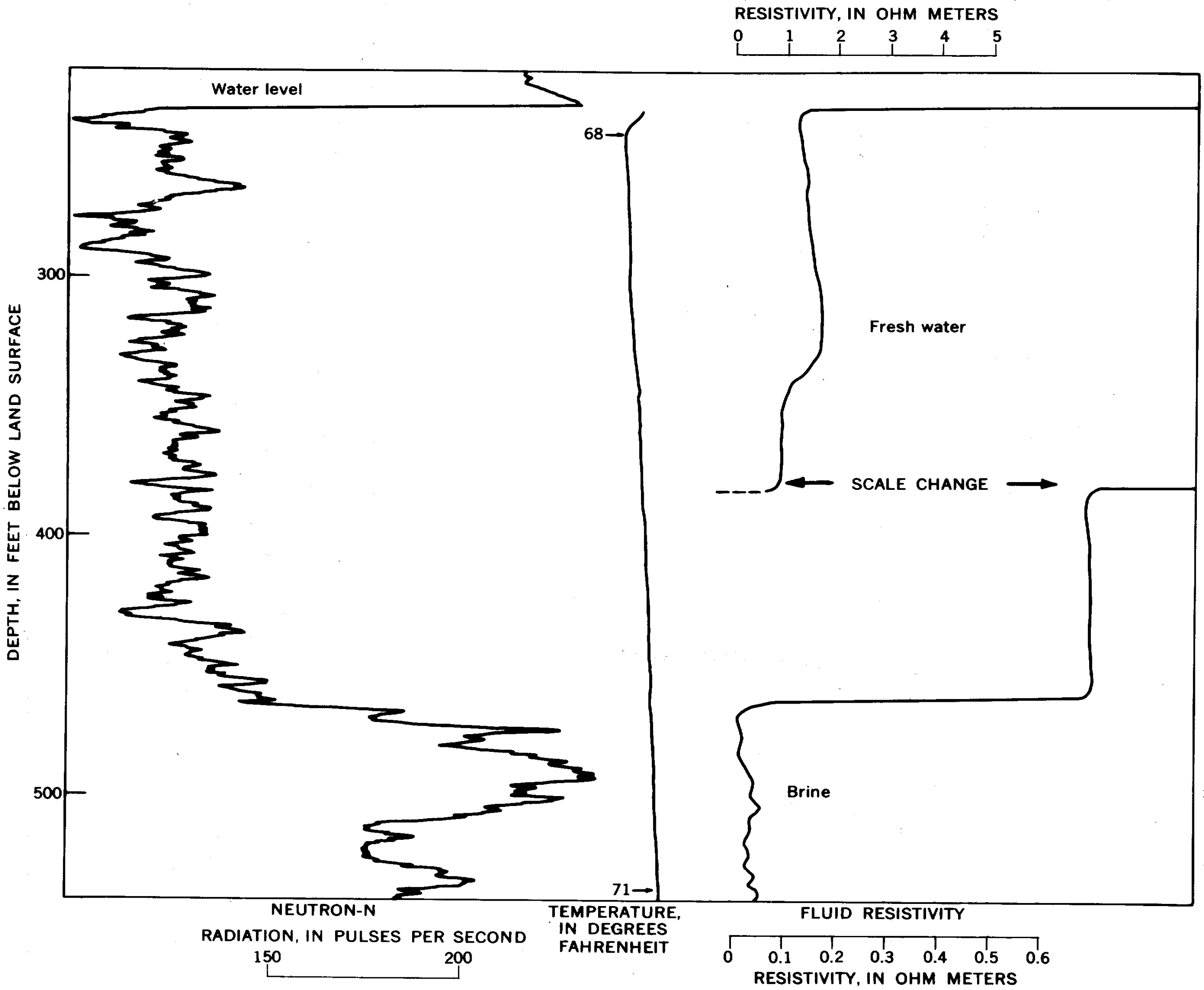

FIGURE 4.—The brine–fresh-water interface on neutron and fluid-resistivity logs, hole T–19.

ment than to natural ground-water conditions before the well was drilled.

DATA FROM CALIPER LOGS

The caliper log is a record of the changes in average diameter of a drill hole. Its major uses are (1) to evaluate the environment in which other logs are made in order to correct them for hole-diameter effects and (2) to provide information on lithology.

In figure 5 the general similarity in the character of the caliper logs of holes T–14 and C–1 is due to the same lithology and the differences in amplitude are due to a change in drilling technique. Hole C–1 was cored slowly with a diamond bit, and nearby hole T–14 was drilled rapidly with a tricone rotary bit. The obvious effect of hole diameter on the gamma-gamma logs of these two holes is discussed in the section on gamma-gamma logs. Caliper logs were also useful for stratigraphic correlation and for the identification of fracture zones. They were also used extensively in the study area to determine the best depth for packer settings. These logs made it possible to select a depth for setting with a bed thickness and hole diameter within the limitations of the packer and hole wall smooth enough that there was no danger of rupturing the packer elements.

The relationship of lithology and fracture zones to the response of caliper and resistance logs is shown in figure 6. Halite is very soluble in water and is dissolved from the periphery of the hole by circulating drilling fluid. The halite-filled fractures or veins

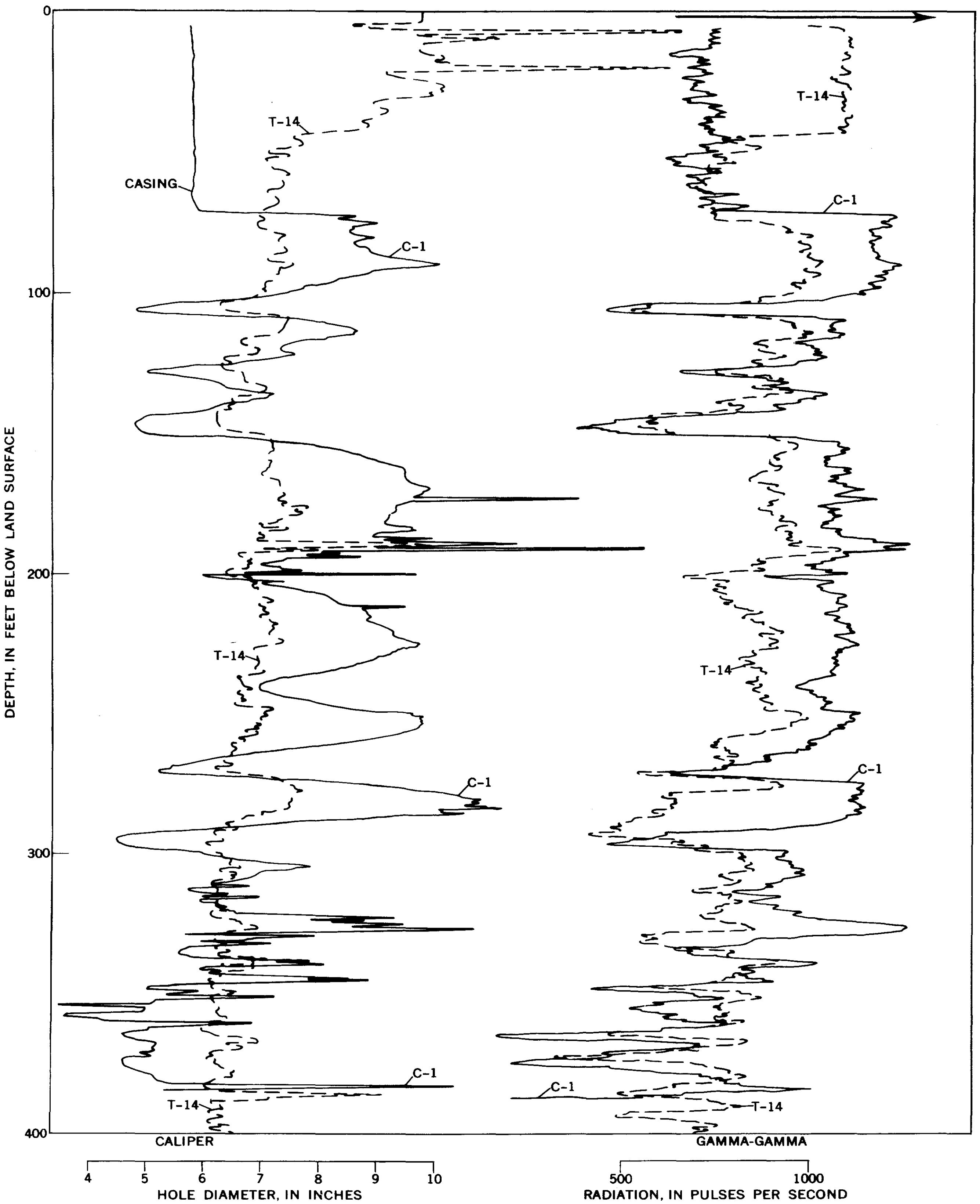

FIGURE 5.—The effect of drilling technique on hole diameter and the effect of hole diameter on gamma-gamma logs.

therefore appear as low-resistance deflections on the point-resistance logs and as enlarged hole diameter on the caliper logs. Note that caliper logs repeated after 3 months do not show continued solution of halite after drilling was finished. Apparently the brine in the hole was in chemical equilibrium with the halite-bearing rocks.

Holes C–1 and T–14 are close enough together that they can be considered to penetrate nearly identical lithologic units. The small solution openings or fractures found by the caliper at a depth of 190 feet in these holes can be correlated with similar openings at 180 feet in hole T–5, which is nearly 3 miles distant from C–1 and T–14 (fig. 6). The openings in T–5 yielded gas and brine; but the fractures at this depth in C–1 were filled with halite, so the zone was relatively impermeable. The single-point logs indicate that the fracture zones in C–1 and T–5 are in the same stratigraphic position.

The following tabulation shows the main solution openings or fracture zones determined from caliper logs of the test holes. Smaller openings are indicated by question marks.

Test hole	*Approximate depth of openings (feet)*
T–3	247
T–4	200
T–5	180, 340
T–7	195
T–10	205?
T–11	226
T–13	200, 238, 454
T–14	190, 386
T–16	200, 240–260
T–17	200
T–18	196?, 306
T–21	268?
T–24	200
T–25	187
T–27	304, 426

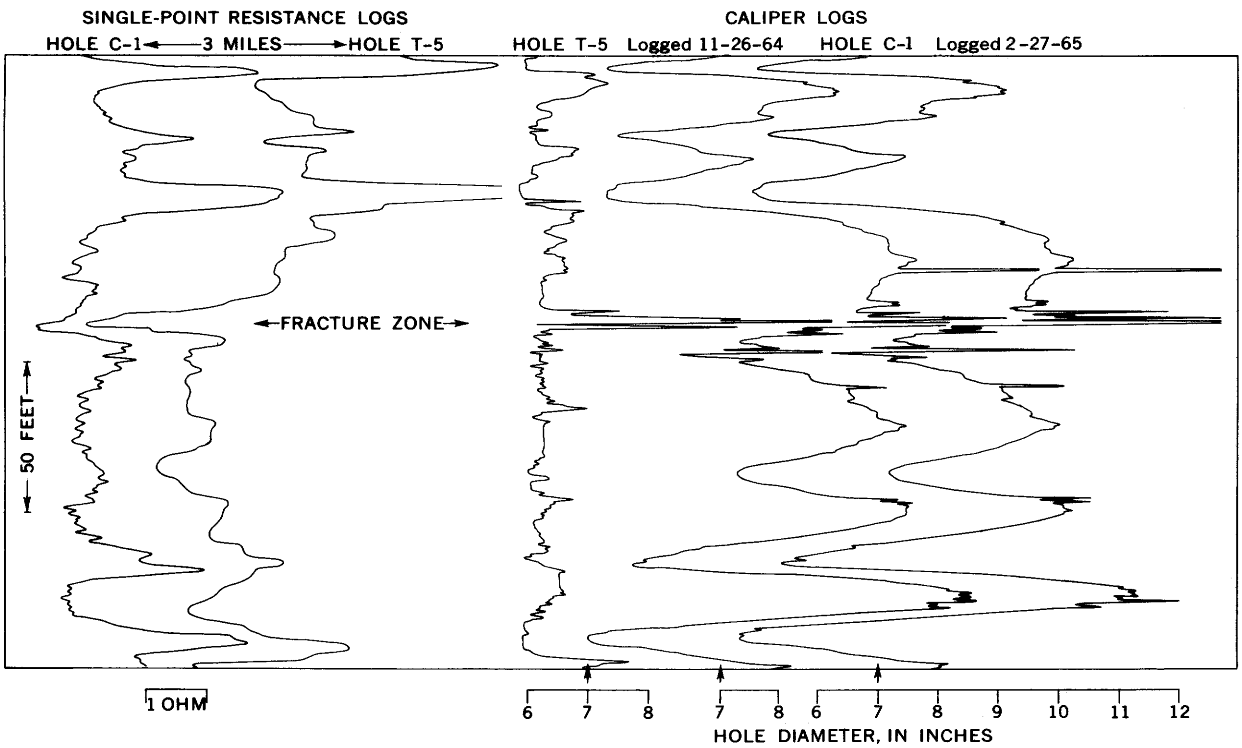

FIGURE 6.—The correlation of fracture zones between rotary hole T–5 and core hole C–1 utilizing caliper logs.

DATA FROM NUCLEAR LOGS

NATURAL GAMMA

Natural-gamma logs are records of natural-gamma photons that are emitted by the rocks penetrated by a borehole. The chief uses of natural-gamma logs are for the identification of lithology and for stratigraphic correlation. The gamma log has an advantage over electric logs in that it can be used in either cased or open holes, and above or below the water table.

Natural-gamma logs can be used with more confidence as a lithologic tool than the SP logs in the study area. In figure 2 the gamma log above 300 feet shows relatively low-intensity radiation, a response which agrees with a lithology dominated by sandstone. Below 300 feet radiation increases in good agreement with that expected for a lithology dominated by rocks of higher clay content. Laboratory analyses of particle-size distribution gave an average of less than 10 percent clay-size (<0.004 mm) particles above 300 feet and an average of more than 20 percent clay-size particles below 300 feet. In two of the samples from below 300 feet, the content of clay-size particles exceeded 50 percent.

An example of one of the possible errors in the identification of lithology from gamma logs is demonstrated by an analysis of the log of well T–33 (fig. 7). The gamma log shows a major deflection to the right that begins near the surface and ends at a depth of about 60 feet. If identification were made without benefit of lithologic logs or cores, this deflection might be correlated with shale; however, the deflection is actually due to uranium minerals present in the rocks intersected by the well bore. Because of the high natural-gamma background, it was impossible to make a meaningful gamma-gamma log in hole T–33.

In addition to stratigraphic correlation and identification of lithology, the natural-gamma log can be used in a semiquantitative manner to estimate the hydrologic properties of rocks.

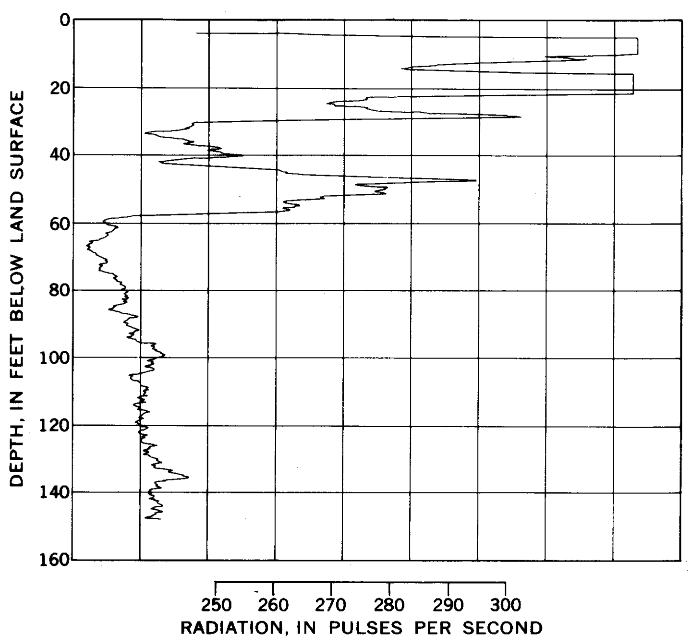

FIGURE 7.—Natural-gamma log of hole T–33.

Raplova (1957) reported studies in Russia that indicate a relationship between specific yield of granular aquifers and natural-gamma values from logs. Gaur and Singh (1965) established a relationship between natural-gamma intensity and hydraulic conductivity of an oil-bearing sand in India. The relation between gamma intensity logged in hole T–14 and clay content measured on cores from the adjacent hole C–1 is shown in figure 8. Natural-gamma intensity, in pulses per second, was taken from depth intervals on the log and was plotted against the percent clay from cores within these intervals. Although many points depart markedly from a linear trend, the general grouping indicates that increasing gamma activity correlates with increasing clay content. The scatter of points is due, in part, to the difficulty of accurately fitting core depths to corresponding depths on the logs. Furthermore, the logs provide an average value for a much larger volume of material than the core samples.

Hydraulic conductivity is related to effective porosity, which is inversely related to clay content. Therefore, hydraulic conductivity should increase with decreasing clay content. In figure 9, natural gamma intensity, in pulses per second, at specific depths in well T–14 is plotted against laboratory hydraulic conductivity data from cores of the same intervals in C–1. The distribution of these points tends to support the correlation of decreasing natural-gamma activity with increasing hydraulic conductivity. A more reliable system would be to planimeter the areas bounded by sector deflections of the gamma log and compare these areas with the average hydraulic conductivity of cores taken from each sector. This method requires complete core hydraulic conductivity studies within each sector, which were not available. In the upper Brazos River basin, the relationship of clay content to hydraulic conductivity is further complicated by the presence of halite and anhydrite cement in some of the sedimentary rocks. Chemical cements of this type will have no appreciable effect on the gamma log, but the reduced porosity will show upon neutron and electric logs. For this reason, the most reliable estimates of hydraulic conductivity in the study area can be made by comparing natural-gamma and neutron logs.

GAMMA-GAMMA

Gamma-gamma logs are records of the intensity of gamma radiation from a gamma source in the probe after it is backscattered and attenuated within the borehole and surrounding rocks. The main uses of gamma-gamma logs are for identification of lithology, measurement of the bulk density and porosity of rocks, and determination of borehole conditions such as hole enlargements, gas-entry points, and changes in fluid density.

The gamma-gamma logs made in the study area display radiation increasing to the right so as to agree with the response of the other nuclear logs. On these gamma-gamma logs bulk-density increase shows as a deflection to the left and increasing porosity or hole diameter shows as a deflection to the right. The gamma-gamma log of hole T–14 (figs. 2, 5) shows good correlation with the caliper log at the hole enlargements just above the 200-, 300-, and 400-foot depths. Some of the strong caliper log deflections to the left approach bit size, and these points mark the positions of anhydrite beds, a resistant rock that usually does not wash or cave during drilling. At these same horizons, the gamma-gamma log shows a strong deflection to the left, a response produced in part by the higher bulk density of the anhydrite and in part by the decreased hole size. The difficulty in actually separating hole-diameter effects from density effects makes the estimation of hydrologic properties from the gamma-gamma log only semiquantitatively correct. Improved gamma-gamma logging equipment now in use reduces, but does not eliminate, extraneous borehole effects.

Gamma-gamma logs are also affected by changes in fluid density. Figure 10 shows the response of the gamma-gamma log of T–5 to the density changes in the drilling mud produced by gas and brine that has entered the well from a fracture zone. Below the gas-entry point, the gamma-gamma baseline is to the left. Above 200 feet the gas-brine mixture is less dense than the drilling mud, and the gamma-gamma baseline is shifted to the right. The neutron log is only slightly affected by the change in density of the borehole fluid.

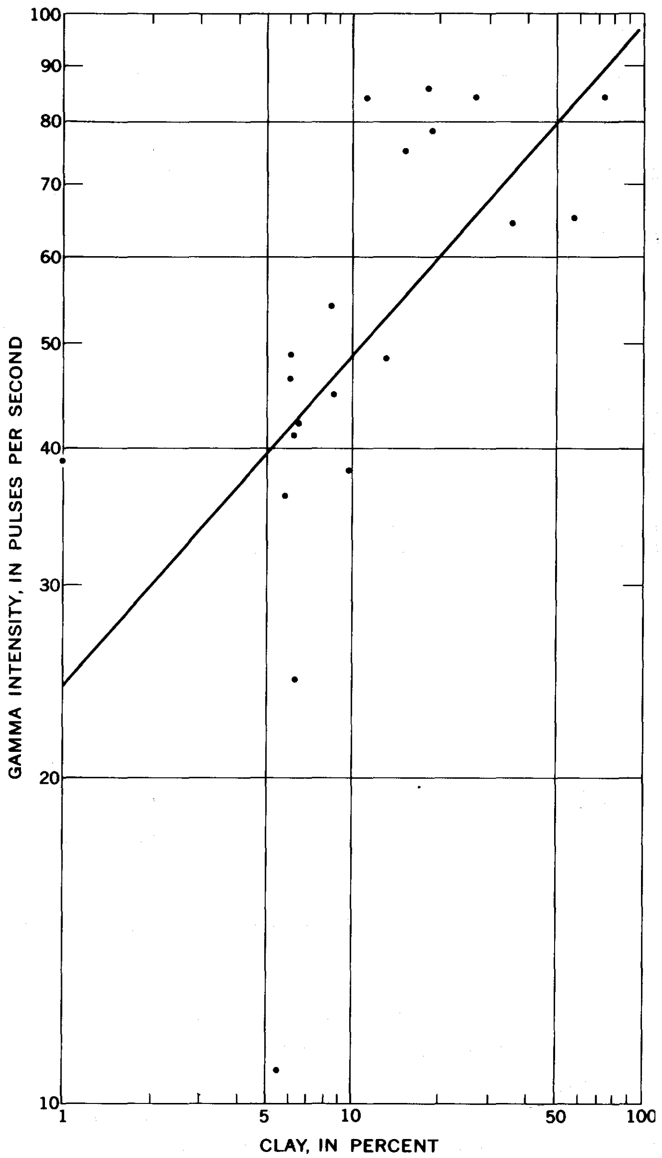

FIGURE 8.—Natural-gamma intensity and percent clay of core material.

NEUTRON

A neutron source and a detector are arranged in a probe so that the output is primarily a function of the hydrogen content of the borehole environment. The neutron logs are chiefly used for the measurement of moisture content above the water table and total porosity below the water table.

Two different methods of neutron logging were used to cope with the great range in salinity of borehole fluids encountered and to investigate the interface between brine and fresh water. The first system is the neutron–epithermal-neutron log (shortened to "neutron-N" on most logs). Epithermal neutrons are those in the energy range from 0.1 to 100 electron volts; that is, they are above thermal energies at which neutron capture and activation are possible. For this reason, measuring epithermal neutrons provides a log which is least affected by the chemical composition of rocks and contained fluids. Therefore, it should provide the most accurate means of measuring total porosity in saturated rocks.

The second method of neutron logging applied in the study area was the neutron-gamma system

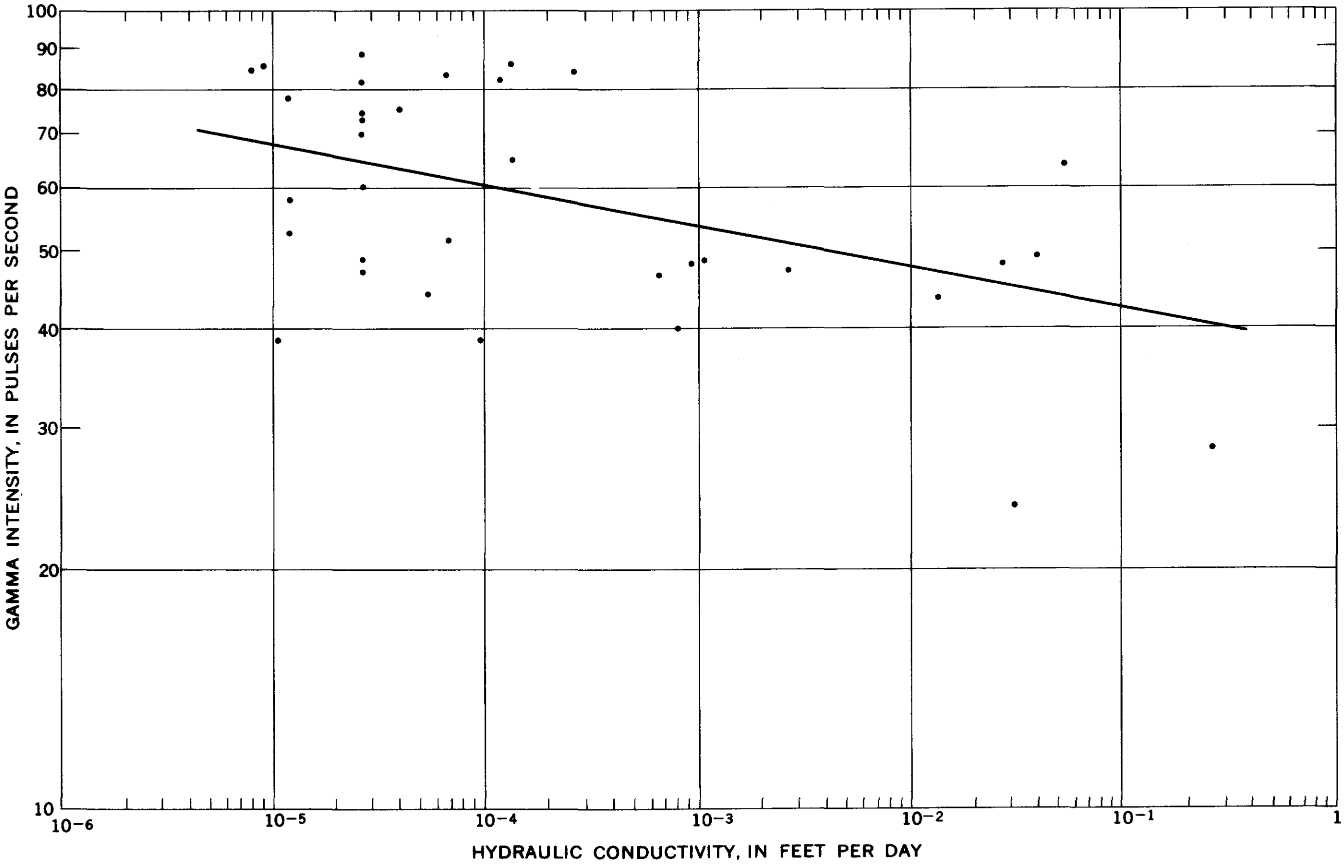

FIGURE 9.—Natural-gamma intensity and hydraulic conductivity of core material.

(shortened to "neutron-γ" on some logs). The neutron-gamma probe is very sensitive to the chloride content of borehole and formation fluids in contrast to the neutron–epithermal-neutron probe, which, as noted, is less sensitive to the chemical constituents of the fluids. The difference between these two logs gives a theoretical basis for measuring the chloride content of the rocks in place and through casing. Of course, most of the chlorine present will be due to common salt, NaCl. Chlorine detection in petroleum logging is done by directly comparing the count rate of the neutron–epithermal-neutron log with that of the neutron-gamma log. Increase of count rate on the neutron-gamma log relative to the neutron–epithermal-neutron log is supposed to be due to chlorine and thus to brine in the rock. During this study, however, it was found that brine produced a shift on both types of neutron logs, though of different magnitude. For the neutron–epithermal-neutron tool, this shift to the right, or increase in count rate, may be due to a reduction in the amount of hydrogen. For example, a sandstone with 25-percent porosity saturated with a brine of 200,000 ppm, common in the upper Brazos River basin, will be logged as a lower porosity because of the replacement of hydrogen atoms by sodium and chlorine atoms. The difference in response of the neutron-N and neutron-γ logs to the presence of chloride is shown in figure 3. Below the brine interface, the count rate on the neutron-gamma log is higher than that on the neutron–epithermal-neutron log, owing to the fact that the decrease in hydrogen and increase in chloride both raise the neutron-gamma count rate. This increase is offset to an unknown degree, however, by the paucity of thermal neutrons available for capture due to the reduction in hydrogen content. Above the interface in figure 3, the neutron-N and neutron-γ had similar responses. Below the interface, the neutron-γ log is displaced to the right of the neutron-N log showing that there is an increase in chloride content. Although the two logs have a similar character below the interface, it is the actual separation between them that indicates the chloride content. At the time of the upper Brazos River basin study, the comparison of a neutron-N and neutron-γ log was the only technique available to locate the interface through well casing. At the present time it is only a qualitative technique for locating major changes in salinity under the proper hole conditions. Inhole neutron activation of sodium may provide a more positive and sensitive means of interface identification through casing (Keys and Boulogne, 1969).

The neutron-N logs were the most accurate for estimating porosity; however, other parameters also cause deflections on these logs. For example, gypsum has a large percentage of water of crystallization, and in response neutron moderation by chemically bound water gives a negative deflection (decreased radiation detected) that is unrelated to high porosity. In the study area it was found that this negative deflection on the neutron log could be used to distinguish gypsum from anhydrite. Since gypsum and anhydrite both emit very little natural-gamma radiation, on natural-gamma logs both appear as deflections to the left. On neutron-N logs, however, gypsum causes deflections to the left; anhydrite, in contrast, causes deflections to the right. The presence of gypsum causes such a dual deflection to the left (fig. 13) at an altitude of about 1,950 feet in well T–22. Because of these relationships, a comparison of neutron-N and natural-gamma logs permits the

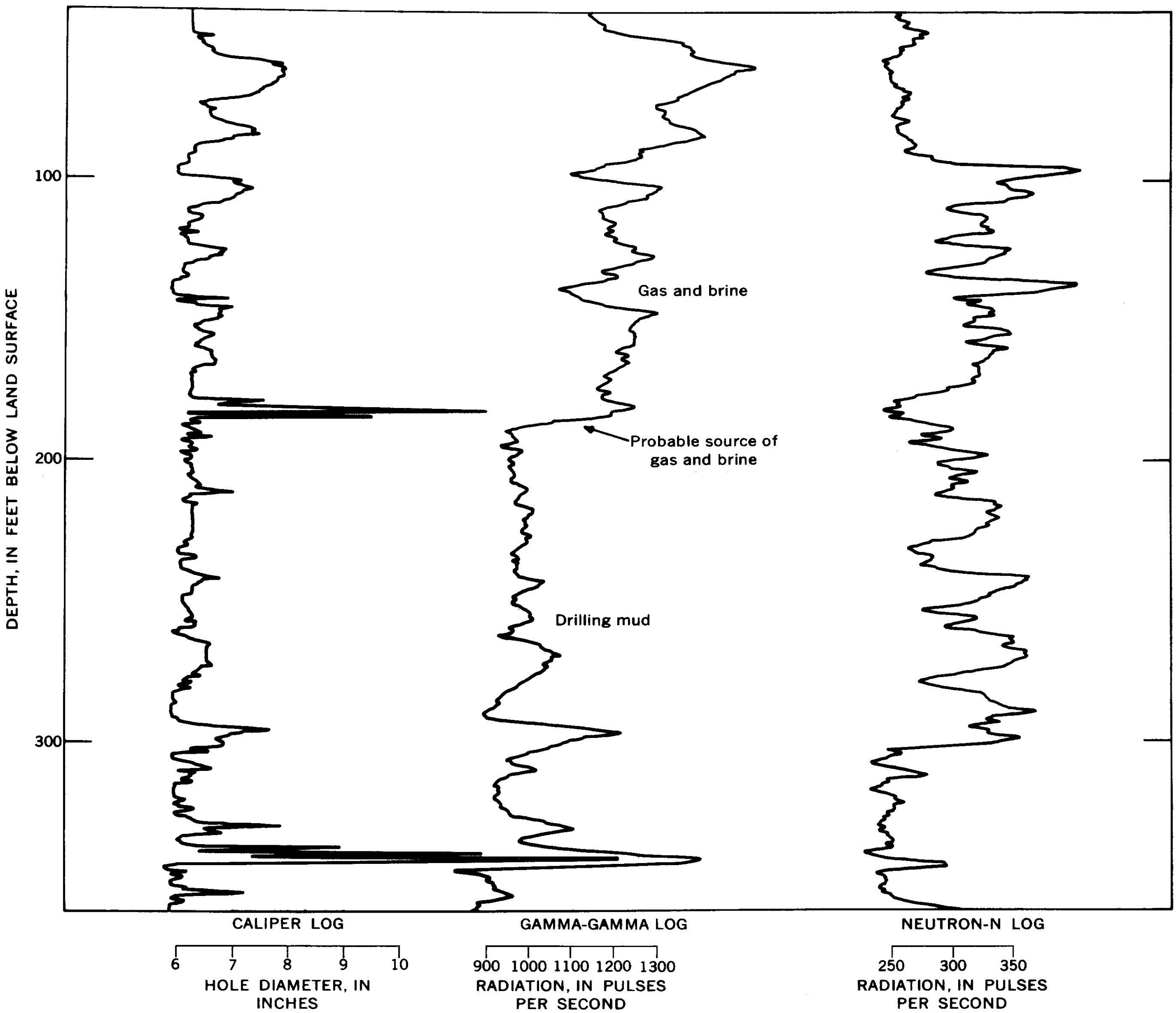

FIGURE 10.—Hole-diameter and fluid effects, hole T–5.

discernment of the depth of transition from gypsum to anhydrite; in the study area, the depth of hydration of gypsum may have a bearing on the hydrologic history of the area and position of the brine.

Changes in the hydrogen content of the borehole fluid will cause baseline shifts in the neutron-N log. The neutron-N log in figure 4 shows a marked baseline shift at the interface at 470 feet. Above this level the fluid in the borehole and in the rocks is fresh water, but below it is brine. Volume for volume the brine contains less hydrogen than the fresh water owing to the large amounts of dissolved sodium chloride. The neutron-N sees this decrease of hydrogen content as a shift toward lower total porosity.

Under controlled borehole diameter and fluid conditions, the neutron-N log can be used for porosity determinations. The laboratory determinations of porosity of cores in hole C–1 were used to calibrate the scale of the neutron-N log of adjacent hole T–14. C–1, the first corehole on the upper Brazos River basin test-drilling project, washed out badly and then part of the hole caved before logging was completed. It was necessary to drill, caliper log, and case an offset hole (T–14) approximately 100 feet from the core hole in order to interpret the hole-diameter effect on logs. Because of the excellent lateral lithologic continuity in the study area, it is relatively certain that lithologic changes within 100 feet are very minor. The offset hole, therefore, provided a unique opportunity to study the problems of hole-diameter effect on geophysical logs run in essentially the same lithologic sequence.

Laboratory analyses of the core were done by Core Laboratories, Inc., of Dallas, Tex., and the U.S. Geological Survey. Formation-resistivity factor, not available from the U.S. Geological Survey, and porosity were measured on 48 samples by Core Laboratories. The Survey measured the porosity of 214 selected samples and determined the horizontal and vertical hydraulic conductivity of 50 representative samples. Some of the samples sent to the two laboratories for porosity measurement were duplicates, and some were duplicated for reanalysis by one laboratory in order to determine the confidence that could be placed in a core as a means of calibrating logs. Some of the analyses of duplicated samples varied by more than 100 percent, while others were exactly the same. Failure to reproduce results does not necessarily indicate a problem in the laboratory. It was obviously impossible to use the same piece of core twice, and closely spaced samples analyzed in some sections indicate that porosity varies more than visual inspection of the core indicates. Recent articles on a gamma-gamma method of making a continuous measurement of core porosity suggest that because variations in porosity are much greater than suspected, the small plug cut from the core for laboratory analysis may not provide a representative sample (Evans, 1965; Harms and Choquette, 1965). Some differences apparently also exist between laboratory techniques, for some analyses show relatively consistent differences in the higher porosity range. A further difficulty in comparing core analyses with logs is caused by footage inaccuracies for zones with lost core.

Figure 11 shows porosities measured in the laboratory on core from C–1 on the right side and the neutron-N log of T–14 on the left. The neutron-N log simulates integrated core analyses compiled from an infinite number of discrete determinations of porosity. Once calibrated against core, the neutron-N log can be used to estimate porosities in the same lithologic units provided hole diameter and borehole fluid composition are known. All the anhydrite beds had a porosity less than 1 percent, so a neutron-log scale estabished with core values can be fitted to other logs in the area provided that hole and fluid conditions are similar.

Neutron logs are affected by changes in borehole parameters to a lesser degree than most other geophysical logs that measure the properties of rocks. Figure 12 shows that there is little difference between neutron-N logs made in an open hole and those made through two different types of casing installed in the same hole. These neutron logs, made under three entirely different hole conditions, can all be calibrated in percent porosity by using known porosities for shale and anhydrite beds. The one major difference between these logs occurs at a depth of 80 feet and is probably due to caving and removal of an anhydrite and shale bed that occurred when the plastic pipe was being reamed out of the hole. Water-filled cavities of sufficient size cause neutron response to approach the value for 100-percent water content. Where such large cavities exist, a porosity scale can be approximated for neutron logs by fitting a logarithmic scale between the 100-percent value and a 1 percent opposite anhydrite or dolomite beds.

Although the chemical quality of the fluid in a drill hole may have an effect on the neutron log, a fresh-water–brine interface or a water-mud interface is likely to cause a shift that is not always readily recognizable. For example, the brine-mud interface at 180 feet in well T–5 (fig. 10) is clearly displayed in the gamma-gamma log, but only a minor shift is shown by the neutron log, a response which alone might not be self evident, although it would have to be considered in any porosity determinations based on this log. Mud invasion also has a minor effect on neutron logs.

RESULTS OF WELL LOGGING

DETERMINING THE INTERFACE BETWEEN BRINE AND FRESH WATER

Locating and characterizing the interface between overlying fresh water and brine was one of the most important objectives of the upper Brazos River basin project. Single-point, nuclear, fluid-resistivity, and temperature tools were used in an attempt to locate the position of the interface in the rock surrounding the hole and in the fluid column in the hole. One of the basic problems in extracting data from a drill hole is that drilling operations disturb the hydrologic and lithologic parameters for which measurements are needed. The position of the interface in the finished hole may be higher or lower than it was in the formation before drilling commenced. Natural fluids may be displaced away from the hole by drilling mud, and the chemical composition of the natural fluids above and below the actual interface in the formations may be changed. It was not possible to locate the interface accurately by sampling the mud returns during the drilling of most holes, for the time lag for mud return from a depth of several hundred feet makes the depth inaccurate. Moreover, because of the low hydraulic conductivity of most of the rocks, only a small amount of brine was added to the mud when the interface was penetrated; as a result, the interface was difficult to detect.

It can be seen that the most accurate information on the depth and character of the interface will be derived from a hole where the casing is relatively well sealed against the wall of the hole and where the rock is not penetrated by drilling mud. Neutron logs provide the only practical means for deriving this information through casing. Table 1 summarizes data on the interface position as interpreted from fluid, electric, and neutron logging devices and interface positions as reported by the driller. The last column presents the altitude of the interface selected from the best data from the various sources. The second and third columns of the table show that the position of the interface as determined by the fluid resistivity (that is, in the borehole) is dependent on the depths of the perforations or the depth of the bottom of the casing and may depart markedly from that reported by the driller or that interpreted from the neutron log. Observations in the fluid column, however, may provide valuable data on variations of water quality with depth in those wells where the construction allows equilibrium to be established between interstitial and borehole fluids.

Recognition of the interface by neutron logging is difficult or impossible where a brine-filled hole occurs in brine-saturated rocks, where the water has a salinity concentration of less than 25,000 ppm, or where the rocks have a porosity of less than 10 percent (Dewan and others, 1961). In several wells, one or more of these conditions were present. In most of the holes, however, the position of the interface was clearly marked by a sharp position deflection, or increase in count rate, on both types of neutron logs. In general, the position thus determined corresponded fairly well with the position determined from the electric logs and the interface data reported by the driller; however, because of lag in return of drilling fluid, the probability that returns were not frequently examined, and the considerable dilution of brine by drilling fluid, drillers tended to place the interface somewhat deeper than it really is.

Test hole T–18 provides an excellent example of the use of neutron logs for the identification of the chlorine content in the fluids and in the rock. (See fig. 3.) A neutron-gamma log made 7 months after drilling shows a higher count rate in the more porous zones below a depth of 252 feet than the neutron–epithermal-neutron log made on the same date. The two logs coincide closely above 252 feet, but the neutron-gamma response is greater than the neutron–epithermal-neutron response below that point. Below 434 feet, where the porosity decreases considerably the coincidence of the two logs is again quite good. This agreement is to be expected for low-porosity rocks saturated with brine, because the percentage of total count due to chlorine will be less than for brine saturated rocks of higher porosities. If the changes in count rate were due only to the changes in chemical quality of the fluid in the hole, no apparent porosity change would be observed on either log. The resistivity log shows the interface at 256 feet but the driller reported brine at 244 feet. Exact correspondence of interface depths derived by the various methods is not likely. Because the anhydrite bed from 238 to 252 feet causes a major increase in the count rate on the neutron logs and because the porosity of the anhydrite is so low, little brine would be detected in that interval by any method.

In uncased holes, the single-point resistance curve of the electric log usually offered the most positive identification of the interface in the adjacent rocks. In most holes these logs were made immediately after

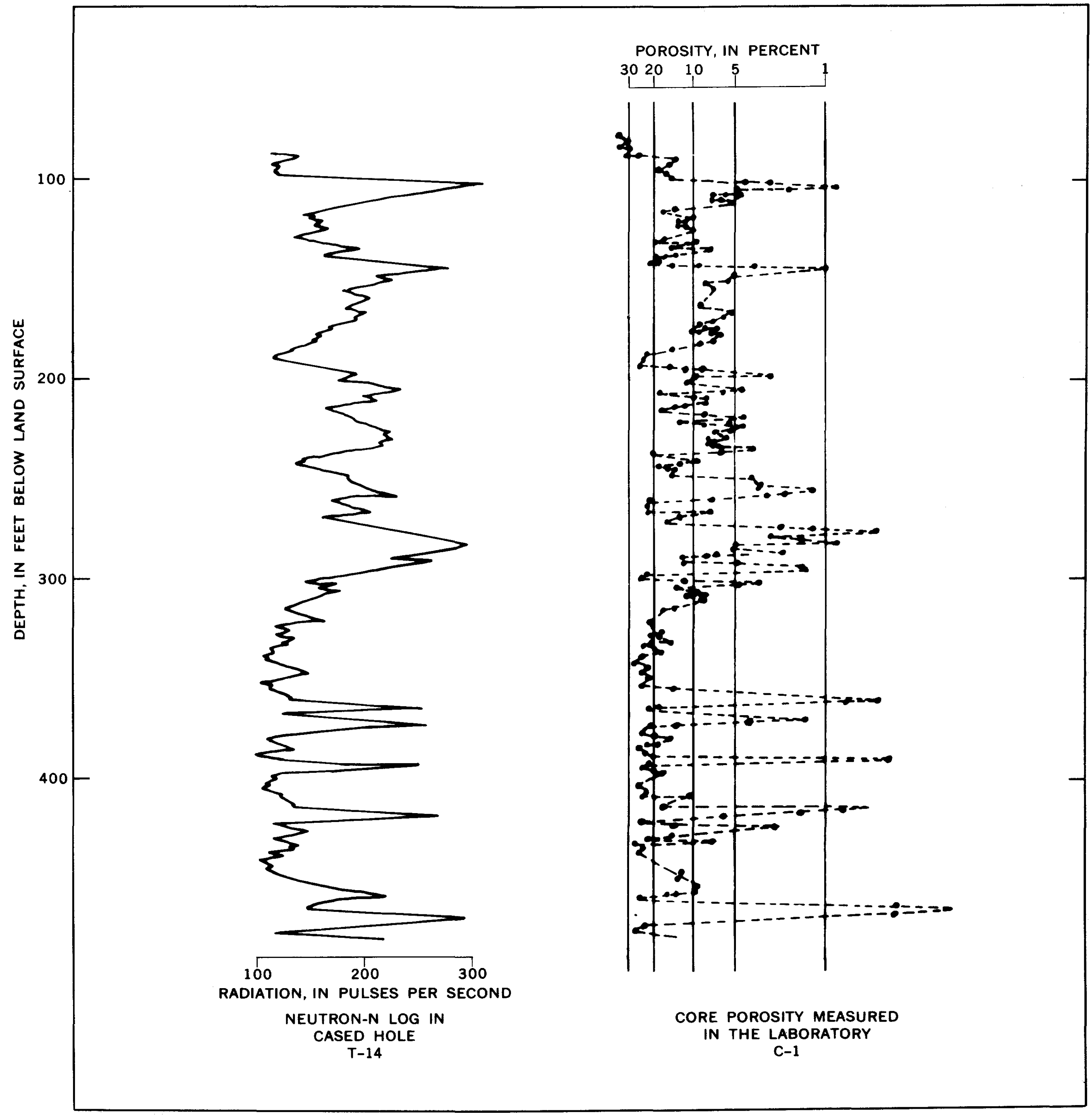

FIGURE 11.—A comparison of a neutron log with porosity of core samples.

termination of circulation so that differences in concentrations in the fluid column would not have time to develop. The interface was indicated most clearly by utilizing a very sensitive scale adjusted to approximately 1 ohm for 10 inches of chart; most of the commercial electric logs used in this study were made on a less sensitive scale of 15 ohm per 2.25 inches of chart. The 65-fold increase in amplitude is most useful for logging in salty holes. Some SP curves were useful for locating the brine because they showed an increase in noise at the interface, and others demonstrated a shift; however, many were of

TABLE 1.—*Data on interface between brine and fresh water*

Hole	Data related to fluid column (depth, in feet)			Depth of interface in the rock (feet)				Consensus altitude of true interface (feet above sea level)
	Bottom casing or top perforations	Water level	Interface in fluid-resistivity log	Driller's report	Electric log	Neutron log	Consensus	
T-3	260	175	265	291	288	280	288	1,752
T-4	309	186	334	310	294	---	294	1,781
T-5	48	33	33	---	---	---	[1]0	1,790
T-6	180	98	180	100	160	160	160	1,720
T-7	26	7	7	---	---	---	25	1,740
T-8	320	168	316	260	274	274	274	1,626
T-9	200	40	?	60	?	60?	60	1,610
T-10	498	168	499	485	488	488	485	1,695
T-11	41	13	29?	30	([2])	30	30	1,675
T-12	100	8	14	<80	([2])	?	30	1,800
T-13	259	49	262	178	230?	168	168	1,622
T-14	---	[1]0	[1]0	---	---	---	[1]0	1,790
T-15	---	+0.8	[1]0	---	---	---	[1]0	1,790
T-16	293	118	320	400	([2])	406	406	1,689
T-17	395	170	394	335	([2])	355	345	1,705
T-18	236	56	247	244	256	252	250	1,655
T-19	372	235	382	410	422	464?	422	1,768
T-21	145	120	145	260	241	250	250	1,690
T-22	190	154	470	325	([2])	325	325	1,665
T-23	234	153	214	240	227	---	227	1,653
T-24	170	35	([2])	94	---	---	113	1,666
T-25	102	76	([2])	110	160	120	120	1,980
T-26	260	29	([2])	145	---	---	140	1,660
T-27	255	180	([2])	225	208	226	225	1,780
T-28	329	34	([2])	270	---	275	270	1,630
T-29	206	34	([2])	145	---	145	150	1,990
T-30	296	24	([2])	135	---	142	135	1,562
T-31	([3])	25	([2])	63	---	76	60	1,720
T-32	([3])	25	([2])	63	90	88	60	1,730
T-33	([3])	33	([2])	([4])	32	33	None	None
T-34	([3])	15	([2])	([5])	---	12?	None	None
T-35	([3])	27	([2])	55	---	58	50	1,746
T-36	([3])	16	([2])	150	---	---	150	1,750
T-37	([3])	12	([2])	108	---	120	110	1,740

[1] At land surface.
[2] No log.
[3] Blank casing, no perforations.
[4] Salty water at 33 feet.
[5] Salty water at 15 feet.

little use for location of the interface or for stratigraphic correlation.

Logs purchased from commercial suppliers or borrowed from oil companies were used to locate the interface where no other information was available. In a few of these logs, identifiable SP shale and sand baselines showed shifts that could be used to estimate the interface position. Where the interface occurred in sand beds, or other more or less homogeneous high porosity zones, it could be recognized in some commercial logs by shifts in average resistivity.

Although contamination of fresh water, dilution of brine, and extraneous borehole effects on logs are problems during interpretation, the general conclusion from logs is that the interface in the rocks is relatively sharp and that the overlying and underlying fluids do not vary much in character within the area studied.

DEPTH OF HYDRATION TO GYPSUM

A second result of the geophysical logging was the detection of the depth of hydration to gypsum. The identification of gypsum and anhydrite was discussed in the section on nuclear logging. If large quantities of gypsum are present in test holes, neutron measurement of porosity will be fallacious; however, MacDonald (1953) pointed out that gypsum is not in equilibrium with a saturated sodium chloride solution (1) at a temperature greater than 50°F at land surface and (2) at a temperature greater than 56.5°F. at a depth of 460 feet. Unless the brine had recently saturated the rocks in the upper Brazos River basin, it would not be chemically possible to have gypsum below the interface, because all the temperatures there are greater than 67° F. Where the rocks are saturated with fresh water, anhydrite is apparently in equilibrium (1) only at a temperature greater than 104°F at land surface and (2) temperatures greater than 102°F at a depth of 460 feet. On the basis of these data, gypsum should not be found below the interface. The amount of anhydrite found above the interface probably depends on the rate and depth of weathering.

Everywhere in the study area, commercially made logs can be used to estimate depth of weathering. For electric logs, the depth of weathering may be estimated by a decrease in amplitude and increase in extraneous noise in the SP log and a lowering of sand-bed resistivities. The depth of the transition from gypsum to anhydrite can be recognized on commercial gamma and neutron logs in the same manner as it was on logs made during the test-hole study.

Although some anhydrite was detected above the interface, no gypsum was found below the interface. The zone of partial hydration is fairly thick, however, so that the interface cannot be located very accurately by this method. The chief use is to substantiate interface locations made by other methods and to approximate the depth to the interface where neutron and gamma logs are available. Furthermore, the complete lack of gypsum below the interface provides indirect evidence that the saturation by brine has not occurred in very recent time.

HYDRAULIC CONDUCTIVITY

Although hydraulic conductivity cannot be measured directly from the geophysical logs described,

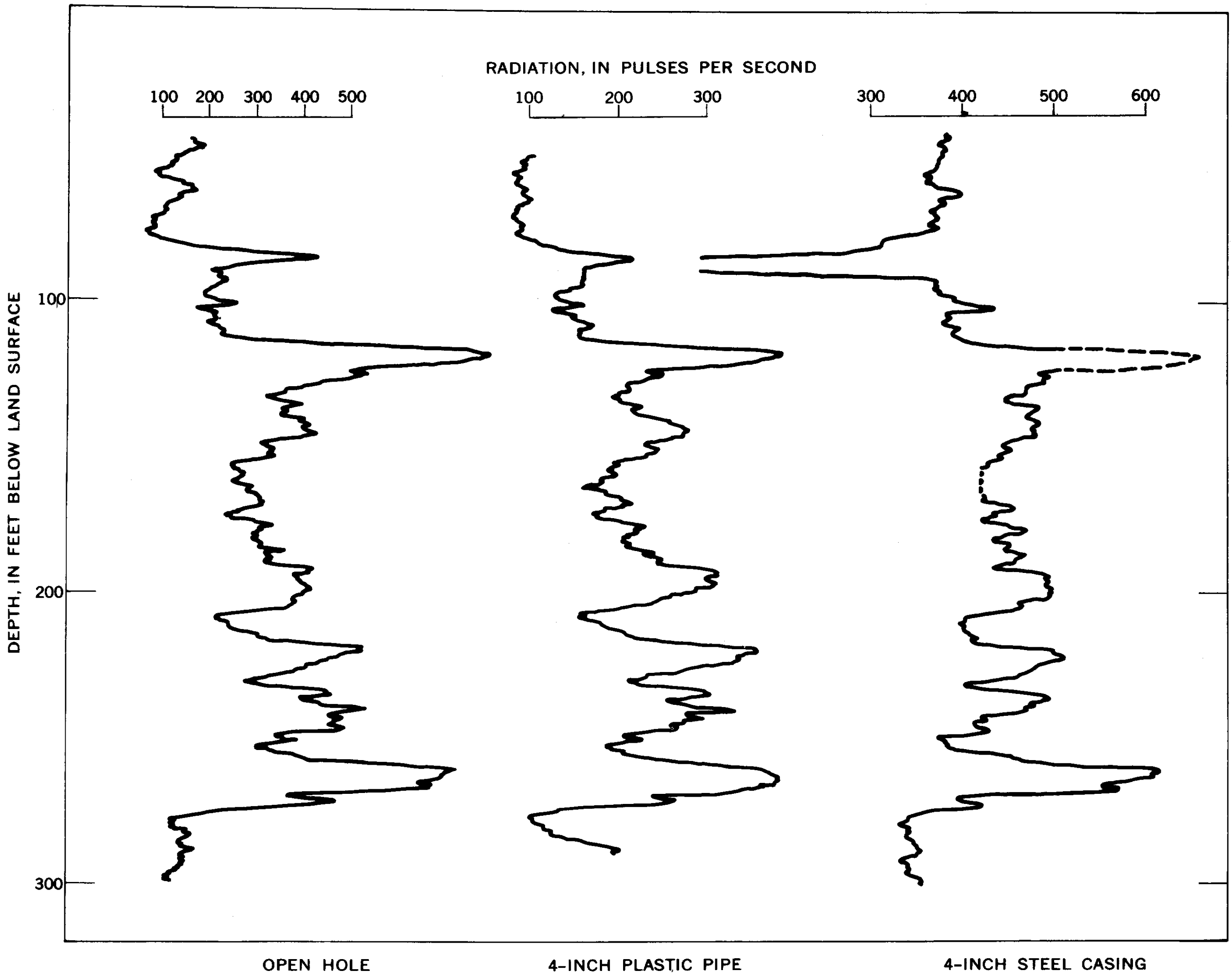

FIGURE 12.—A comparison of neutron-N logs made in the same hole uncased and through plastic and steel casing, hole T–8.

some inferences about it can be drawn. Common empirical relationships between porosity, grain-size distribution, and hydraulic conductivity can be used to select zones of highest water or brine yield from geophysical logs. For example, the natural-gamma log can be used to identify rocks high in clay; these rocks will show a significant apparent porosity on the neutron logs, but a high intensity on the natural-gamma log will identify them as clay. These rocks will probably have a relatively low hydraulic conductivity. Conversely, a zone showing negative deflections on both neutron and natural-gamma logs may be a porous rock such as sandstone. Such rocks would probably produce water. The effects of changes in hole diameter and the presence of hydrogenous materials such as gypsum may also produce negative deflections on the logs. For example, an evaluation of the natural-gamma and neutron logs for T–14 (fig. 2) might lead to the impression that the greatest hydraulic conductivity will be at 190 feet. Actually the caliper logs shows that a hole enlargement at this point is responsible for the anomalously high-neutron porosity and low natural-gamma intensity. Although this opening may produce water, the greatest intergranular hydraulic conductivity indicated by the logs is at several zones that are less than 100 feet deep. Sharp, thin deflections on the caliper log indicate zones where thin masses or veins of salt have washed out, more-rounded thicker deflections indicate places where poorly consolidated granular sediments are washed out, and zones of minimum hole diameter represent horizons where anhydrite beds are found. The fractures and solution openings identified on caliper and single-point logs are probably the zones of highest hydraulic conductivity in the brine-saturated rocks.

In summary (1) zones of low natural-gamma intensity and fairly high neutron porosity and (2) zones of fractured or washed-out sandy sediments indicated by the caliper and single-point logs are likely to have the highest hydraulic conductivity in the area of this study.

LITHOLOGY AND STRATIGRAPHIC CORRELATION

Finally, the geophysical work provided a basis for delineating the stratigraphy. Logs of the test holes and logs obtained from oil companies and commercial suppliers were used to construct stratigraphic cross sections and a stratigraphic fence diagram. Natural-gamma logs were found to give the best results. Very few electric logs of shallow holes were good enough to use in stratigraphic work because borehole fluids are usually too salty to permit indicative resistivity or SP logging.

Halite beds and zones of halite-cemented siltstones can be recognized where gamma, sonic, and focused-resistivity logs are available for the same hole or where these three logs are available for holes very close together. Salt is indicated where the gamma reading is low, where the sonic logs show a velocity of 14,300 to 14,700 feet per second, and where the focused-resistivity log shows extremely high resistivity, usually off scale. None of these criteria is diagnostic alone, but when all three are used together, a high degree of confidence is justified in identifying salt.

When the stratigraphy of a local area is well known and the usual occurrence of salt is fairly well known, the combination of long and short normal or short normal and lateral resistivity logs can be used to estimate the location and thickness of halite deposits. Usually the resistivity logs with short radius of investigation show very low resistivity adjacent to salt beds, for they measure the low resistivity of the more highly saline solution in the hole adjacent to the salt. The logs of long radius of investigation record the resistivity of the rock salt away from the hole, where it is almost entirely nonporous, dry, and nonconductive, and therefore the deeper-looking logs record a higher resistivity than the short normal logs. Other dense rocks, such as some anhydrites and dolomites, may also show this difference in resistivity measurement if the borehole fluid is very salty. A general knowledge of the lithology and the zones where salt may be expected to occur is required for proper log interpretation.

In the test holes drilled in the study area, natural-gamma and neutron logs were found to be most useful for stratigraphic correlation. Correlation with logs also permitted the lateral and vertical extrapolation of laboratory core values such as porosity.

Stratigraphic correlation based on gamma and neutron logs is shown in figure 13. Hole T–14 and the adjacent core hole C–1 are the control or key wells in this figure, and the correlations were extended south to hole T–22 and north to holes T–21 and T–5. The difference in character of both the gamma and neutron logs in hole T–14 above 1,500 feet compared with the character below 1,500 feet is obvious. This change represents the contact between two formations. Above 1,500 feet the holes penetrated very fine grained sandstone and siltstone with a few beds of anhydrite. Below this depth the lithology is mainly mudstone dominated by numerous beds of anhydrite. In the fine-grained clastics above 1,500 feet, the gamma-log baseline is to the

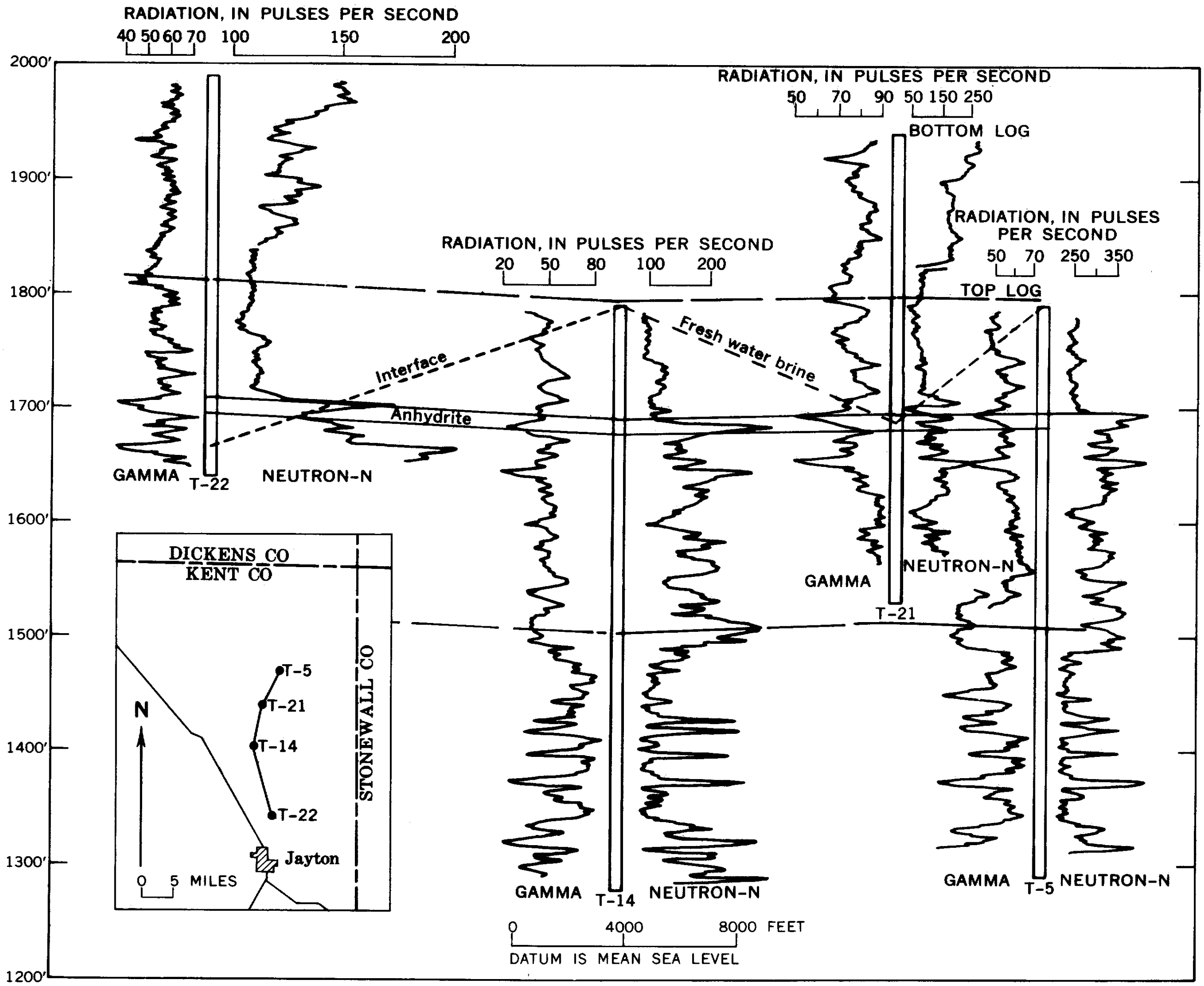

FIGURE 13.—Correlation with gamma and neutron-N logs.

left, but below 1,500 feet the baseline has shifted to the right, toward increasing radiation in the clay-sized sediments. The anhydrite beds show up as strong deflections to the left on all the gamma logs. The same general log characteristic is evident in hole T–5 except that the gamma curve is broken and displaced at 1,550 in order to fit the log within the section as drawn. Figure 13 indicates that the brine interface is independent of lithology on a regional basis though differences in lithology exercise local control.

SUMMARY

Geophysical logs of test holes in the upper Brazos River basin and commercial logs of existing wells were used to establish the position and character of the interface between brine and overlying fresh water. The logs showed that the change in salinity occurs within a vertical interval of several feet and that in places the interface may be controlled by lithology but that regionally it transects lithologic boundaries. Logs were also used to estimate the porosity and hydraulic conductivity of the sedimentary rocks, to locate fracture zones that may transmit brine, and to measure the resistivity and temperature of the brine. Borehole geophysics can be used to identify halite, gypsum, and anhydrite beds and to relate their presence to the interface. Logs made in the study area also permitted the lateral and vertical extrapolation of core data; and commercial logs allow all the data in the study area to be extended to the rest of the upper Brazos River basin.

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