Summary of Hydrologic Testing in Tertiary Limestone Aquifer, Tenneco Offshore Exploratory Well—Atlantic OCS, Lease-Block 427 (Jacksonville NH 17–5)

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By RICHARD H. JOHNSTON, PETER W. BUSH, RICHARD E. KRAUSE, JAMES A. MILLER, and CRAIG L. SPRINKLE

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Summary of Hydrologic Testing in Tertiary Limestone Aquifer, Tenneco Offshore Exploratory Well—Atlantic OCS, Lease-Block 427, (Jacksonville NH 17−5)

By Richard H. Johnston, Peter W. Bush, Richard E. Krause, James A. Miller, *and* Craig L. Sprinkle

Abstract

A summary of hydrologic testing in an offshore oil-test well (LB-427) drilled for Tenneco, Inc., 55 miles east of Fernandina Beach, Florida, is presented. The interval tested (1,050 to 1,070 feet below sea level) is in a calcarenite that is equivalent to the Ocala Limestone (late Eocene) of onshore Florida and South Georgia. At this site the Ocala forms the highly productive Tertiary limestone aquifer system of the southeastern United States. Pressure-head measurements indicate an equivalent freshwater head of 24 to 29 feet above sea level. These pressure-head measurements and an earlier one made in the nearby JOIDES J−1 hole are the only hydraulic head determinations to date in the offshore extensions of any of the aquifers underlying the Atlantic coastal plain.

A drill-stem test recovered water samples containing about 7,000 milligrams per liter chloride. However, seawater used in the drilling process apparently contaminated the samples and the formation water is considered slightly fresher.

The head and salinity data from the Tenneco well suggest that the sampled interval lies in the transition zone between fresh and seawater in the limestone aquifer. These data, when viewed with similar data from JOIDES J−1, show the transition zone to slope very slightly landward. The interface position is probably intermediate between a position compatible with present-day heads and a position compatible with predevelopment heads.

INTRODUCTION

The Tertiary limestone aquifer system of the southeastern United States is a major source of water supply with current pumpage exceeding 3 billion gallons per day. The aquifer system underlies all of Florida, southeastern Georgia, small parts of adjoining Alabama and South Carolina, and adjacent areas of the Atlantic continental shelf and Gulf of Mexico. A current (1978−1982) study of the aquifer system involves computer modeling to simulate the regional flow system and to provide predictive capability for assessing the effects of future water withdrawal (Johnston, 1978). In the coastal areas, simulation requires knowledge of heads and salinities in the aquifer and especially the position of the saltwater-freshwater interface in the upper (heavily pumped) part of the limestone system. The primary purpose of the testing described in this report was to obtain information on heads and water chemistry in the offshore segments of the aquifer and to use these data to estimate the present interface position.

Geologic knowledge in the offshore area has been increased greatly in recent years by various drilling programs. On the continental shelf and slope adjacent to coastal Georgia and northeast Florida the following offshore test holes were drilled prior to 1979: JOIDES J−1, J−2, and J−5, COST GE−1, and AMCOR 6002 (fig. 1). However, hydrologic knowledge, particularly data on pressure heads and permeability, is scanty. Only one pressure-head measurement was made prior to this study. A measurement in the first JOIDES core hole (J−1, about 20 mi offshore as shown in fig. 1) indicated a pressure head of 30 to 38 ft above sea level (Wait and Leve, 1967). Some data on intrinsic permeability exist, but no realistic estimate of aquifer transmissivity has been made. The chemistry of formation water has been inferred at several exploratory holes from interstitial water obtained by hydraulic squeezing of cores (Manheim and Horn, 1968). However, at JOIDES sites 1 and 2, formation water was directly obtained by flow up the drill pipe.

Squeezing cores is described by Manheim (1967) as an effective method for obtaining formation water from fine-grained sediments, but ground water in the southeast limestone aquifer system occurs principally in joints, fractures, solution cavities, coquinas, and locally in large karstic openings. Squeezing limestone cores from this aquifer system is difficult and questionable because of possible mud invasion. Representative formation-water samples are best obtained by direct sampling of produced fluid from flowing wells or drill-stem tests.

The construction of water wells specifically for hydrologic testing in the offshore areas is not feasible because of the prohibitively high cost of leasing offshore

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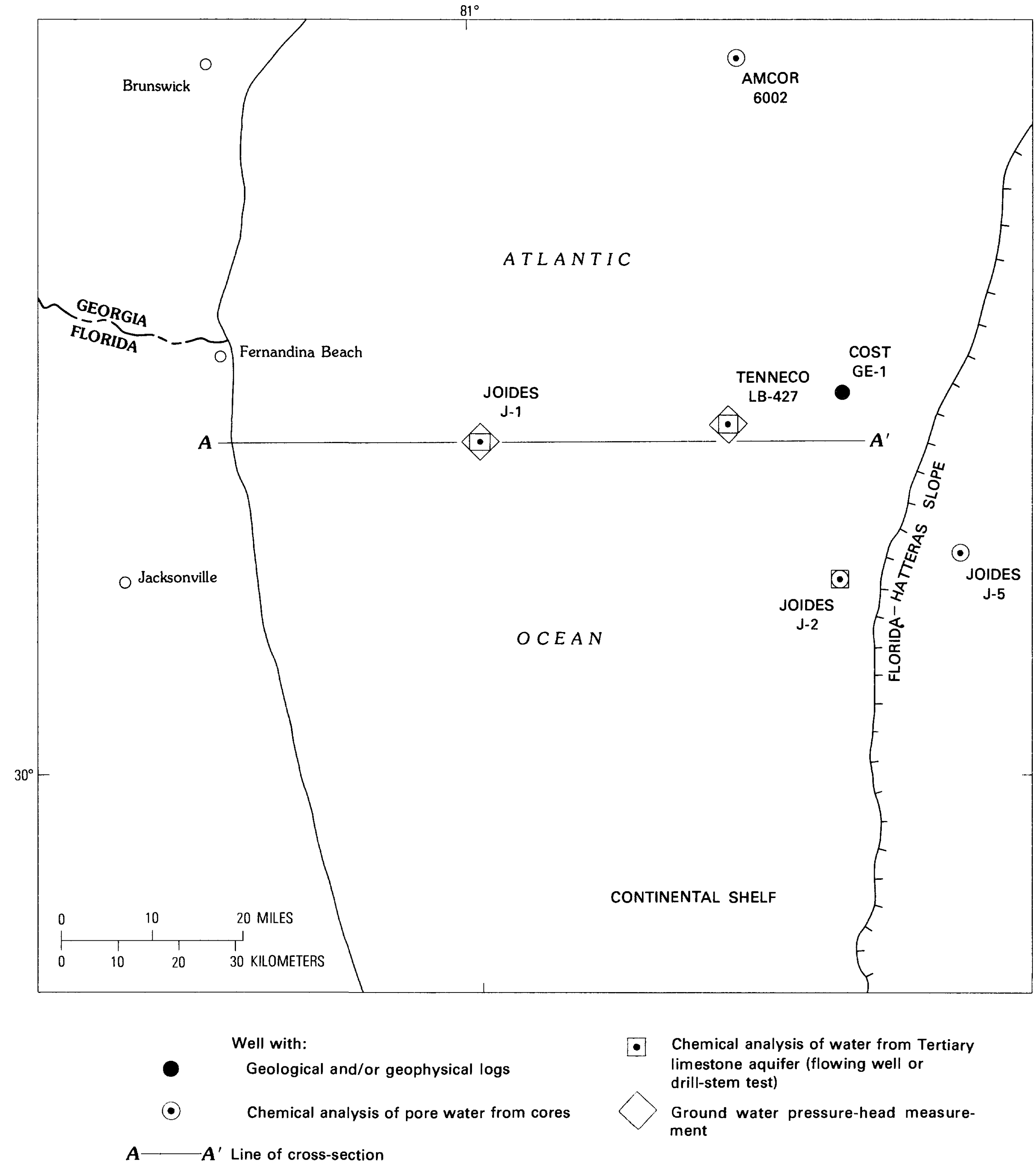

Figure 1. Location of Tenneco exploratory lease-block 427 well and nearby test wells.

drill rigs. An alternative is to take advantage of the presence of a drill rig at a desired location to obtain testing services. During the summer and fall of 1979, the *Offshore Mercury* (a jack-up type offshore drill rig) was under contract to Tenneco, Inc., Getty Oil Co., and Transco Corp. to drill four "wildcat" oil-test wells offshore from southeast Georgia and northeast Florida. Two of these holes were to be drilled by Tenneco; the second hole to be about 55 mi east of Fernandina Beach, Fla. on OCS lease-block 427 (reported position:

30°34.57′ lat. N and 80°32.05′ long. W). This site was believed to be near the seaward limit of freshwater in the limestone aquifer. Tenneco agreed to permit the U.S. Geological Survey to conduct hydrologic testing in this hole prior to its abandonment. The work to be done involved conducting a drill-stem test after gun-perforating the existing well casing at an interval in the upper part of the limestone aquifer system.

GEOLOGIC SETTING

In order to select an interval for perforation and testing in the lease-block 427 well, field prints of geophysical logs and a commercial sample logging service's description of cuttings from the well were examined. These data showed that, except for thickness variations, the sequence of Cenozoic sediments penetrated by the Tenneco well closely resembles that found in the nearby COST GE−1 well. Accordingly, correlations of the geology and water-bearing properties of the rocks at the Tenneco site rely heavily on published descriptions of the COST well (Scholle, 1979). Geologic and hydrologic interpretations of the geophysical logs from the upper part of the Tenneco well are shown in figure 2. Lithologic descriptions on the "mud log" were used to supplement the geophysical log picks, particularly for the base of the aquifer system.

The major water-bearing unit in the limestone aquifer system in both the COST and Tenneco wells is a calcarenite that is recrystallized and dolomitized in part, and is equivalent to the Ocala Limestone (late Eocene) of onshore Florida and south Georgia. The calcarenite is somewhat chalky in the COST well, but is less so in the Tenneco well, where it is composed in large part of the tests of nummulitic and discoid foraminifera. The base of the limestone aquifer system in the Tenneco well is a fossiliferous calcilutite of late middle Eocene age that occurs at 1,690 ft below sea level. In the COST well a corresponding calcilutite is present at a lower altitude (1,980 ft below sea level) but is stratigraphically higher (early late Eocene). The top of the aquifer system coincides with the top of the Ocala limestone that occurs at 650 ft below mean sea level. Total thickness of the Tertiary limestone aquifer system at the Tenneco well is thus 1,040 ft.

Circulation was lost in the COST well between 1,050 and 1,230 ft below mean sea level. In the Tenneco well, walnut shells were logged in the cuttings just below 1,000 ft, indicating that drilling-mud additives were needed to prevent circulation problems. In both cases, the drilling difficulty suggests high permeability, possibly related to fracturing or solution channeling, in the calcarenite unit of the upper Eocene limestones. The interval selected for drill-stem testing (1,050 to 1,070 ft below sea level) was in this unit.

Overlying the upper Eocene calcarenite is a calcilutite of Oligocene age that is 200 ft thick in the Tenneco well and about 500 ft thick in the COST well. This fine-grained Oligocene unit is in turn overlain by sands, clays, and beds of coquina of Miocene to Holocene age, that are about 350 ft thick in the Tenneco well and about 500 ft thick in the COST well. Together with the Oligocene calcilutite, these beds form the upper confining unit of the limestone aquifer system.

DRILL-STEM TEST

Drill-stem testing has long been the standard method used by the petroleum industry to obtain information about the characteristics of subsurface formations. Characteristics important to petroleum geologists and engineers that may be calculated from the test data include formation pressure, permeability, well-bore damage (formation damage due to the drilling process), and formation-fluid chemistry. Drill-stem testing can provide similar useful information to ground-water hydrologists. This technique was selected for the Tenneco site because conversion of the exploratory hole to a water well and conducting a standard aquifer test was prohibited by high rig costs. The objectives of the drill-stem test at the Tenneco site were to obtain undisturbed formation pressure (for conversion to equivalent formation-water and freshwater heads) and samples of formation water. Transmissivity was to be estimated from the test data if possible.

Procedures

In a typical drill-stem test, the well casing, and cement grout if present, adjacent to the stratigraphic interval of interest is perforated. The test tool is lowered into the hole opposite the perforated interval and isolated by expandable packers. The tool contains one or more pressure recorders and an operator-controlled valve that, when open, allows formation fluid to enter the tool column. After first allowing fluid to flow into the tool for a period of time, the operator closes the valve to shut in the formation and cause the formation pressure to recover. The pressure recorders, operating throughout the test, provide a continuous record of the pressure changes; these are the data of interest.

A drill-stem test commonly consists of two or three flow periods, each followed by a shut-in period. The length of a flow period is somewhat arbitrary. The duration of the shut-in period following a flow period is a matter of judgment; but it should be long enough relative to the time of flow to allow the formation pressure to approach its undisturbed, or static, pressure. After the drill-stem test is completed, the drill pipe is pulled out of the well and broken down. Fluid samples may be collected from individual stands of pipe.

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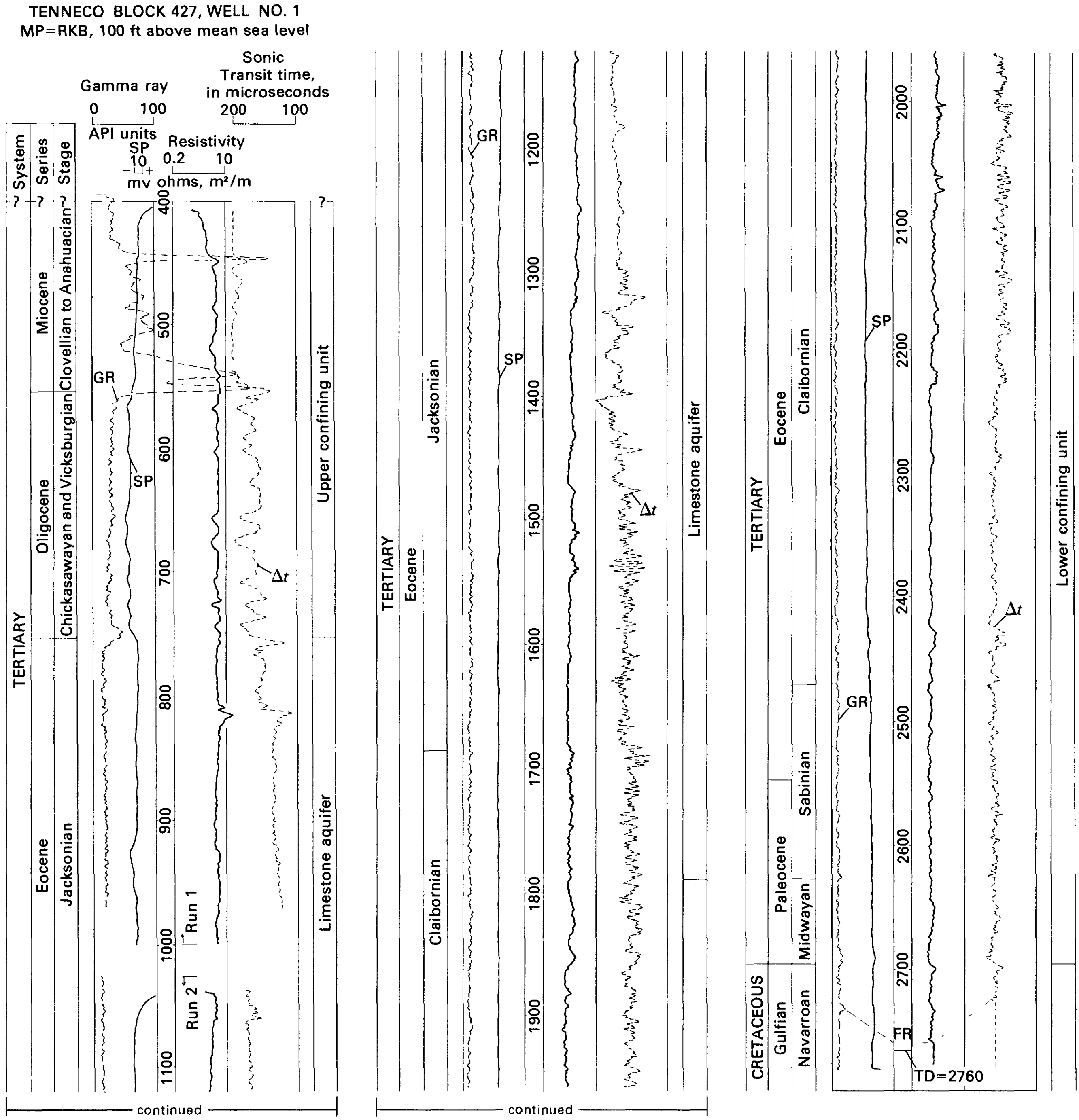

Figure 2. Geophysical logs of Tenneco lease-block 427 well, showing geological and hydrologic correlations.

The testing at the Tenneco site was done in an interval of the upper part of the limestone aquifer where the occurrence of freshwater was considered likely. Pertinent features of well construction and the drill-stem tool (in position for testing) are shown in figure 3. Note that the rig datum (top of the rotary kelly bushing) is about 100 ft above mean sea level. Actual field measurements as listed in tables and shown on the geophysical log (fig. 2) are referred to rig datum. However, all discussions in the text refer to sea level for ease in making comparisons with other wells and in drawing regional conclusions.

The base of freshwater was estimated to be 1,400 ft below sea level before testing. The existence of double casing precluded perforating intervals higher than 940 ft below sea level. Two intervals, 1,050 to 1,090 ft and 1,140 to 1,160 ft below sea level, were proposed for testing based on the probable existence of permeable limestone as inferred from electric and gamma-ray log patterns,

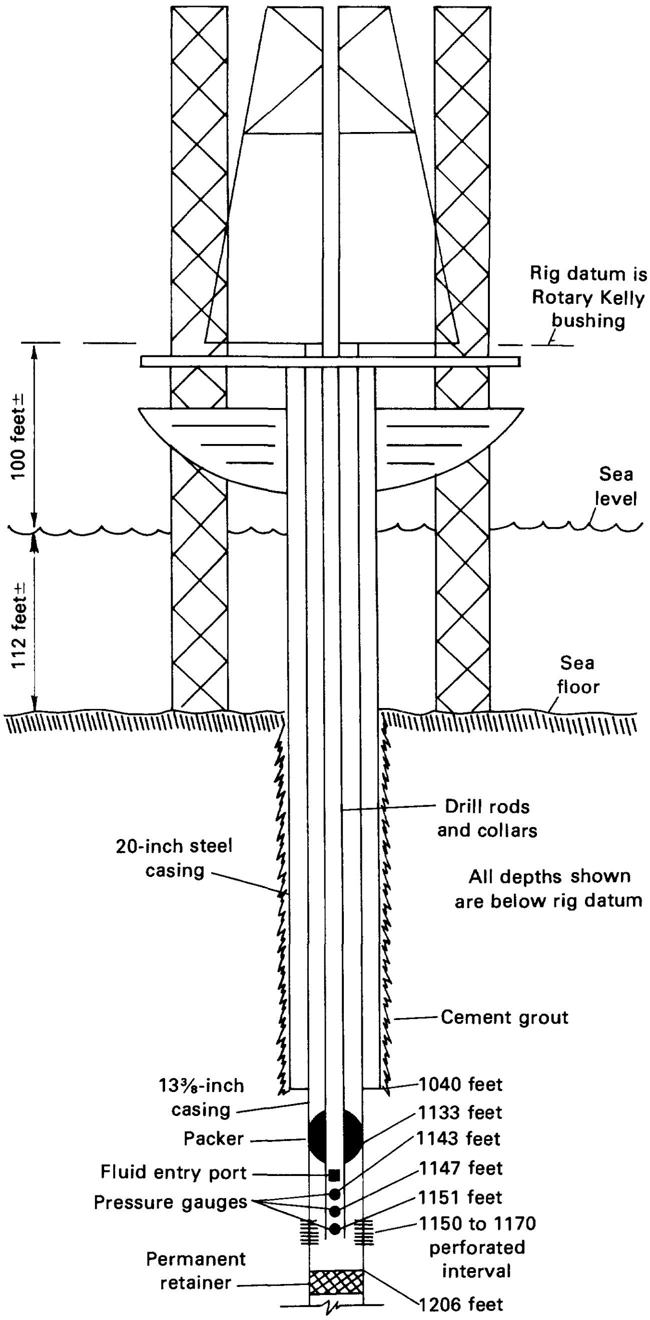

Figure 3. Pertinent features of rig setup, well construction, drill-stem tool, and measurement datum.

lithologic logs, and drilling-time characteristics. The interval 1,050 to 1,070 ft below sea level was selected because a cement-bond log run prior to perforating indicated the presence of a uniform continuous cement bond that would minimize the potential for vertical leakage of water from other strata. A cement retainer plug was set 1,106 ft below sea level to isolate the test interval from the deeper part of the hole. The casing and grout in the interval (1,050 to 1,070 ft below sea level) were then perforated with 80 shots (4 shots per foot) from a perforating gun. A packer attached to the drill-stem tool isolated the uphole side of the interval after the tool was lowered into position. Three pressure recorders were in the tool near its lower end (fig. 3).

The test provided hydrologic data; however, the relatively short flow periods yielded fluid samples that were obviously contaminated with drilling mud. An attempt was made to pump out all the seawater and mud from the well casing using a standard submersible pump, but mechanical problems caused this effort to be abandoned after pumping out 500 to 700 gal of fluid. Finally the drill-stem tool was used with one long flow period (8 hours) to obtain samples more representative of the formation water.

Theoretical Analysis

Drill-stem test data may be analyzed using a method devised by Horner (1951) for petroleum-reservoir evaluation and applied to aquifer evaluation by Bredehoeft (1965). Horner's equation describing pressure recovery is analogous to Theis' formula for analyzing water-level recovery in wells (Theis, 1935, *in* Ferris and others, 1962, p. 100).

Horner's equation is:

$$p_f = P^* - \frac{2.3q\mu}{4\pi kh} \log\left[\frac{t_0 + \Delta t}{\Delta t}\right]$$

where:

p_f = formation pressure during recovery (F/L^2)
P^* = undisturbed formation pressure (F/L^2)
q = average fluid-production rate during periods of flow (L^3/T)
μ = fluid viscosity (FT/L^2)
k = Intrinsic permeability of the formation (L^2)
h = thickness of the formation being tested (L)
t_0 = time of flow (T)
Δt = time of shut-in (T).

The equation assumes radial, single-phase flow, a homogenous infinite formation, a reasonably constant rate of flow (q), and a time of recovery (shut-in time) sufficiently long so that the logarithmic approximation for the exponential integral (Horner, 1951) is acceptable.

Horner's equation is solved graphically by plotting recorded shut-in pressure recovery as a function of the dimensionless time factor log $\left[\frac{t_0 + \Delta t}{\Delta t}\right]$. If the assumptions inherent in the method are met, then the plot should be a straight line with slope $M = \frac{-2.3\, q\mu}{4\pi kh}$. However, Horner plots of recovery data usually do not approximate straight lines until the latter stages of the shut-in period (Johnston-Schlumberger, 1976, p. 4). Therefore, the latter part of the curve is used for analysis. Undisturbed formation pressure, P^*, can thus be estimated by extrapolating the plot of shut-in pressure recovery to the point where $\log \left[\frac{t_0 + \Delta t}{\Delta t}\right] = 0$; that is, to the point where t_0 becomes very small relative to Δt.

As in solving for transmissivity with the Theis recovery formula, the slope from the Horner equation can be equated to the actual slope of the Horner plot for later times over one log cycle, and the quantity $\frac{kh}{\mu}$ obtained:

$$\frac{kh}{\mu} = \frac{2.3\,q}{4\pi\Delta p}$$

where:

Δp = pressure change over one log cycle (F/L^2).

$\frac{kh}{\mu}$ is referred to as transmissibility in the petroleum industry, and has the units millidarcy-feet per centipoise. Multiplying $\frac{kh}{\mu}$ by the specific weight of water at the prevailing temperature and appropriate conversion factors yields transmissivity in ground-water units (commonly feet squared per day).

Results

An example of pressure changes with time as recorded by the lowermost pressure recorder (Johnston-Schlumberger, 1976, number T−383, 1,151 ft below rig datum or about 1,050 ft below sea level) throughout the drill-stem test is shown graphically in figure 4. Initially, with the tool in place but before the upper packer was set, seawater used to clean the inside of the well casing caused

FIELD REPORT NO. 14309D (Prepared for U.S. Geological Survey by Johnston-Schlumberger)

INSTRUMENT:
Number: T-383
Capacity: 1700 psi
Depth: 1151 ft. below rig datum
Port opening: Outside

EXPLANATION	LABELED POINT	PRESSURE (PSIG)	ELAPSED TIME (MIN)
Hydrostatic mud	1	507	−27.8
Start flow	2	40	0.0
End flow and start shut-in	3	53	2.9
End shut-in	4	464	65.6
Start flow	5	55	65.2
End flow and start shut-in	6	55	73.3
End shut-in	7	92	75.2
Start flow	8	56	75.2
End flow and start shut-in	9	56	81.8
End shut-in	10	73	83.0
Start flow	11	56	83.0
End flow and start shut-in	12	57	93.2
End shut-in	13	466	184.9
Hydrostatic mud	14	497	188.6

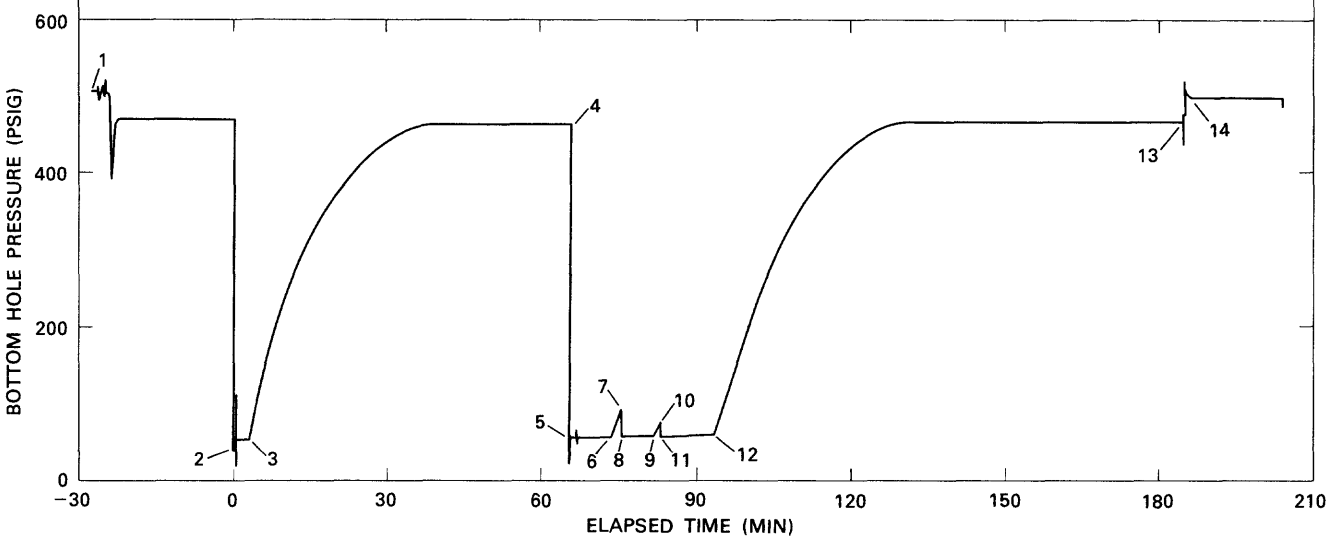

Figure 4. Shut-in pressure versus time during drill-stem test.

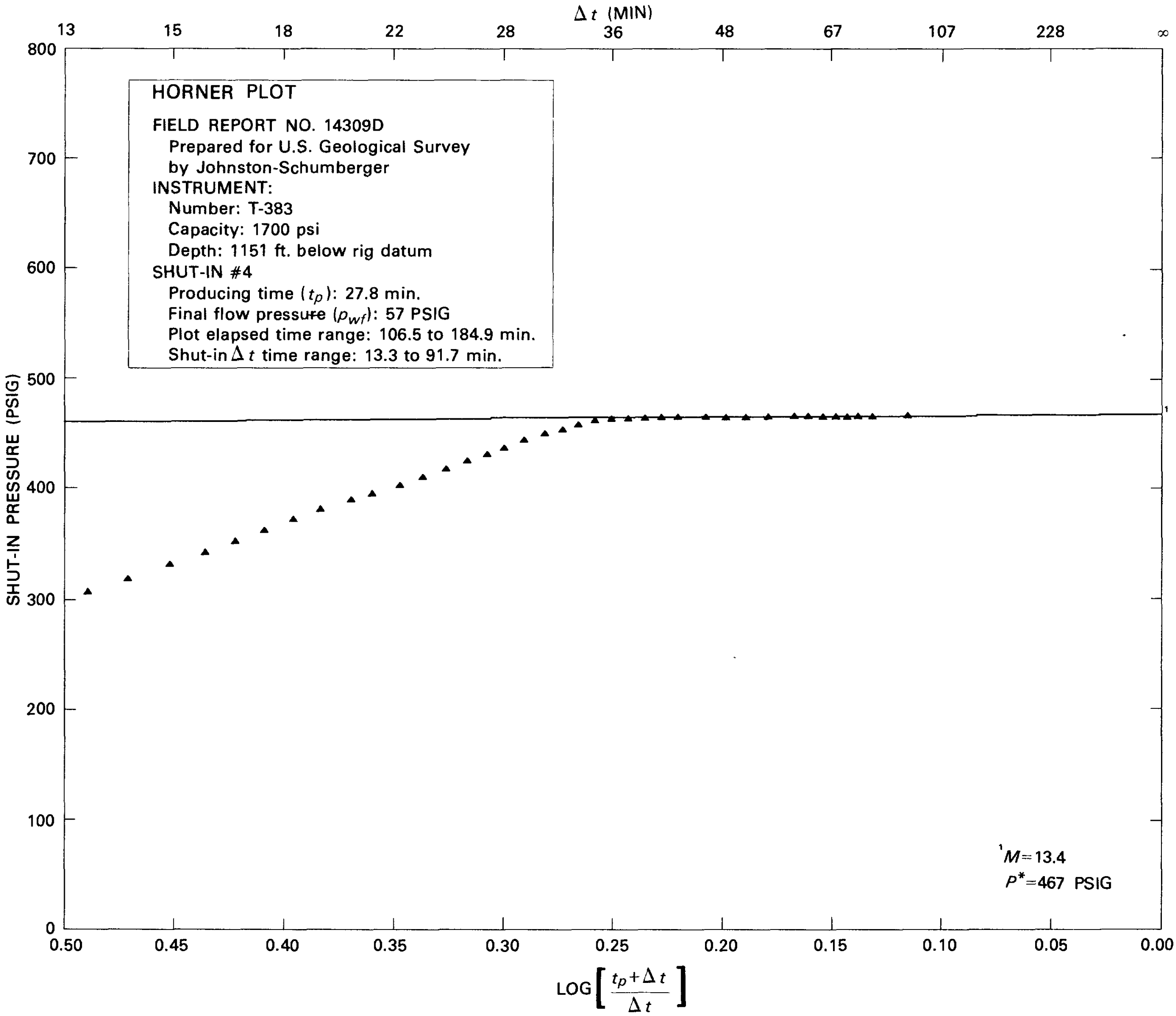

Figure 5. Shut-in pressure recovery versus dimensionless time factor during latter part of final shut-in period.

hydrostatic pressure on the recorder (labled point 1, fig. 4). (A sufficient quantity of wash water was removed from the well so that displacement during tool insertion would not cause reverse flow from the well into the formation.) The first blip past labeled point 1 (fig. 4) represents the isolation of the test interval caused by the setting of the upper packer. Shut-in period 1 (62.7-min duration, from labeled point 3 to 4) and shut-in period 4 (91.7-min duration, from labeled point 12 to 13) produced the data for analysis. The short shut-in periods 2 and 3 (labeled points 6 to 7 and 9 to 10, respectively) were the results of operator testing when a tool malfunction was suspected.

The pressure-recovery data from recorder T−383 for the last part of the final shut-in period, plotted in expanded format for ease of evaluation, are shown in figure 5. Extrapolating the straight-line part of the data plot to its theoretical limit produced an undisturbed formation pressure, *P**, of 467 lb/in², 1 lb/in² more than the pressure recorded at the end of the shut-in period. Horner plots were also made from the data obtained from recorder T−383 during the first shut-in period, and from data obtained from the two other recorders (4 ft and 8 ft above recorder T−383; fig. 3), during both shut-in periods. As in the example of figure 5, extrapolated undisturbed formation pressures from each of the five ad-

Table 1. Undisturbed formation pressures and equivalent hydraulic heads from drill-stem test of August 11, 1979

Johnston-Schlumberger recorder number	Depth to recorder		First shut-in			Final Shut-in		
	Below rig datum[1] (ft)	Below sea level[2] (ft)	Undisturbed formation pressure (psig)	Altitude of equivalent freshwater head[3] (ft)	Altitude of equivalent formation-water head[4] (ft)	Undisturbed formation pressure (psig)	Altitude of equivalent freshwater head[3] (ft)	Altitude of equivalent formation-water head[4] (ft)
T−86	1,143	1,043	462	26	16	462	26	16
T−307	1,147	1,047	463	24	15	463	24	15
T−383	1,151	1,051	466	27	18	467	29	20

[1]Rig datum is rotary kelly bushing.

[2]Sea level at time of test was 97.5 to 103.5 ft below rig datum depending upon tide; sea level is considered to be 100 ft below rig datum.

[3]Altitude to which freshwater at 25°C would rise in a tightly cased well open to the interval 1,150 to 1,170 ft below rig datum.

[4]Altitude to which formation water (relative density 1.006 at 25°C) would rise in a tightly cased well open to the interval 1,150−1,170 ft below rig datum.

ditional plots were the same as, or very close to, the pressure recorded at the end of the shut-in period.

Results of extrapolating the six Horner plots to obtain undisturbed formation pressure are summarized in table 1. In the table, pressures have been converted to equivalent formation-water and freshwater heads. The conversion to equivalent freshwater heads assumes that the column of freshwater would be uniformly 25°C, the measured temperature of six formation-water samples from the interval 395 to 850 ft below sea level in JOIDES J−1 (written commun., R. L. Wait, Jan. 1980). An actual temperature of 41°C was recorded in the drill-stem tool during the test, but this relatively high temperature probably resulted from heat generated by the curing of the cement around the well casing. The equivalent formation-water heads listed in the table also assume a uniform water-column temperature of 25°C. Laboratory-determined relative density of a water sample collected from the drill-stem tool was 1.007 at 20°C. In making the temperature correction to obtain equivalent formation-water head, it was assumed that the decrease in density per unit increase in temperature of formation water is the same as that for freshwater.

The pressure recorders used in the test are accurate to within 0.25 percent of the recorded values of the instruments (oral commun., Johnston-Schlumberger, 1979). Since the range of measurements among the three instruments used was 461 to 466 lb/in², accuracy was within ±1.17 lb/in² (.0025×466), which converts to ±2.71 ft of freshwater, or ±2.68 ft of formation water, both at 25°C. Thus, potential error in the equivalent heads is not appreciable. The fact that the equivalent heads from three independent instruments in two separate shut-in periods were within a 5-ft range implies that the pressure recorders worked well; they were consistent. The estimate of equivalent freshwater head of 24 to 29 ft above sea level is judged to be good. The estimate of equivalent formation-water head of 15 to 20 ft above sea level is also good, if the water sample from which the density calculation was made is truly representative of the formation water.

A hydraulic conductivity of 4.89×10^{-2} ft/d was calculated using a computed average flow rate of 0.85 gal/min into the tool during the test, formation water at 25°C, a Horner-plot slope of -13.4 lb/in², and a tested-formation thickness of 20 ft. Based on knowledge of the limestone section tested, as well as the fact that considerable mud invasion occurred when drilling this zone, 4.89×10^{-2} ft/d is too low to be realistic. Along the adjacent Florida−Georgia coast, transmissivities are 25,000 to 50,000 ft²/d for 500-ft sections of aquifer; thus, hydraulic conductivity there is about 50 to 100 ft/d. Apparently, formation damage combined with limited flow into the well (due to an uncertain number of finger-sized holes completely through the casing and cement) eliminated the chance to obtain a reasonable estimate of transmissivity at the site.

GROUND-WATER CHEMISTRY

The collection of water samples that are representative of formation water from an abandoned oil-test well presents special problems. The relatively small perforations through thick-walled casing and cement yield small water flows to the well. High hourly rig charges do not permit extended pumping periods or time for well development. As previously stated, the drill-stem test was too short to obtain samples of the formation water. An attempt to pump directly from the well was terminated after pumping 500–750 gal of fluid because of mechanical problems. The technique finally selected to obtain water samples utilized a drill string which consisted of nine 90-ft lengths of drill pipe above nine 33-ft drill collars and the drill-stem tool. The drill-stem tool was left open to the perforated interval for about 8 hours. The water level rose to about 500 ft inside the tool, collars, and drill pipe providing approximately 150 gal of fluid for chemical samples.

Sampling Procedures and Analytical Results

The uppermost 120 gal in the drill string were discarded to increase the chances of sampling representative formation water. Water samples were obtained from the lower four drill collars by lowering a ¼-inch silicone rubber tube inside each drill collar. Water was pumped out of the drill collar through the rubber tubing with a small peristaltic pump. In this manner, approximately 30 gal of samples were obtained. An additional gallon was collected from chambers inside the drill-stem testing tool.

Analytical results for the Tenneco samples are listed in table 2. Water temperature, pH, and specific conductance were measured at the well head on samples drawn from the drill-stem test tool. Since the water samples contained an appreciable amount of sediment, an X-ray diffractogram (fig. 6) was made of some of the sediment that settled in the ^{14}C sample container. The odor of H_2S was noticeable at the well head during collection of the water samples. However, the equipment necessary to collect and preserve dissolved H_2S was not available on the drill platform.

Water samples were analyzed according to the methods of Skougstad and others (1979). Stable isotopes of O, H, and C were measured by the techniques of Epstein and Mayeda (1953), Bigeleisen and others (1952), McKinney and others (1950), and Gleason and others (1969). The ^3H measurement was made by the method of Thatcher and others (1977). Unfortunately, there was insufficient total inorganic carbon in the ^{14}C sample for analysis.

Discussion of Analytical Results

The data of table 2 indicate that the samples from the Tenneco lease-block 427 well contained water that is about one-third as saline as seawater. The presence of measureable ^3H in the tool sample indicates that modern-day seawater is the source of some of the salinity in the samples. This ^3H "contamination" in the samples is due to in-situ mixing of ground water from the aquifer and modern-day seawater introduced during the drilling process. If the formation water is assumed to be completely fresh, a maximum of 35 percent seawater "contamination" of the tool sample can be calculated assuming conservative ion (chloride) mixing. We believe the chloride content of the formation water at the Tenneco site is within the range of the 1000 mg/L reported from the same depth of the JOIDES J–1 well (30 mi farther inshore; fig. 1), and the 7,000 mg/L values listed in table 2. The actual salinity of the ground water in the tested interval cannot be determined with the available data.

One interesting feature of the Tenneco sample data is the low levels of Mg ion found. The molal ion ratios of Mg/Ca in the Tenneco samples are 0.43 and 0.41 for the tool and collar samples, respectively. These low ratios cannot be easily explained in terms of simple mixing of fresh gound water and seawater, with or without maintenance of carbonate mineral equilibrium. For non-equilibrium mixtures of fresh ground water and seawater, Hanshaw and others (1971) reported the following ranges of Mg/Ca for wells in this aquifer in Florida:
brackish zone (TDS 1,040-5,760 ppm)—Mg/Ca 1.3-2.8

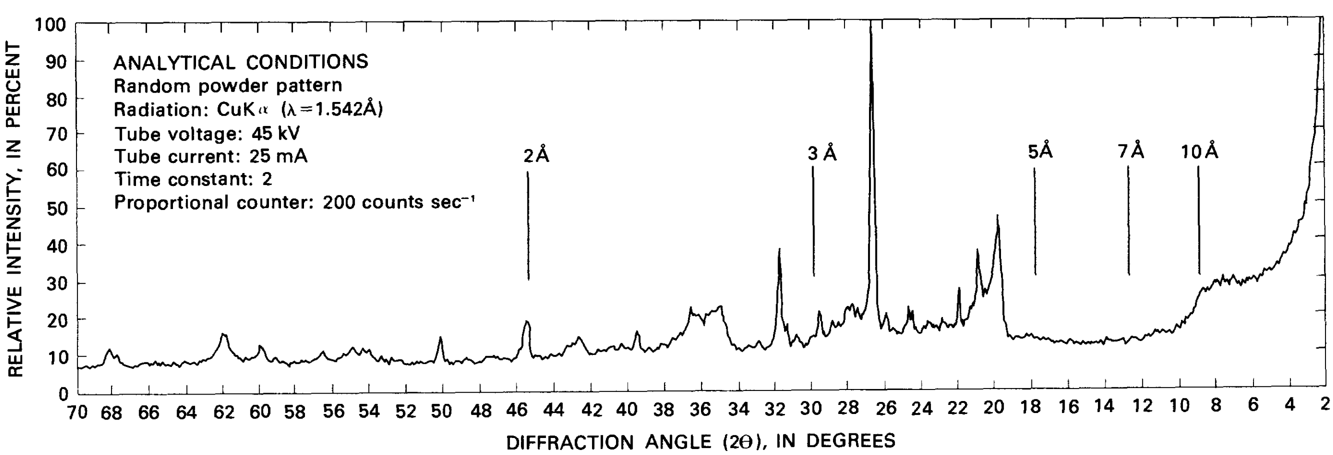

Figure 6. X-ray diffractogram of sediments in a water sample from the Tenneco lease-block 427 oil-test well.

Table 2. Chemical data of water from Tenneco well LB 427 and seawater

Parameter[1]	Sample from drill-stem tool	Composite from drill collars	Seawater[2]
Density (g/cc at 20°C)	1.007	1.007	1.0245[3]
Temperature (°C)	31.5[4]	31.5	25
pH (units)	9.3	9.3	8.22
Specific conductance (micromhos at 25°C)	23,500	23,800	- - -
Ca	200	210	421.9
Mg	52	52	1,322
Na	4,800	4,900	11,020
K	200	200	408.4
Cl	6,900	7,600	19,810
F	1.7	1.2	1.423
SO_4	1,200	1,300	2,775
Alkalinity (as HCO_3)	36.6	32.9	145.0
SiO_2 (total)	15	24	4.380
Br	31	30	68.87
I	0.54	0.50	0.06345
Dissolved solids (residue at 180°C)	14,300	14,400	35,990[5]
^3H (Tritium)	4.2±0.2 Tritium units (TU)		6–7 TU[6]
δD_{SMOW} (Deuterium)[7]	10	11	0.0
$\delta^{18}O_{SMOW}$	-1.92±0.1	-1.85±0.1	0.0
$\delta^{13}C_{PDB}$	-9.3±1.0	-8.7±1.0	- - -

[1]Units are mg/L unless otherwise specified.
[2]Nordstrom and others (1979) seawater test data. Values are rounded to four significant digits, where applicable.
[3]From Handbook of Chemistry and Physics, 55th edition, Chemical Rubber Company, 1974.
[4]Johnston-Schlumberger reported an in-situ temperature of 106°F (41.1°C) during the drill-stem test.
[5]Calculated by sum of constituents.
[6]Values based on range of values of Atlantic surface water reported for stations 29-31, 115-121 in Ostlund and others, 1976.
[7]The δ values are defined as

$$\delta = \left[\frac{R_{sample}}{R_{standard}} - 1\right] \times 1000$$

[where for $\delta^{13}C$, $R = {}^{13}C/{}^{12}C$; for $\delta^{18}O$, $R = {}^{18}O/{}^{16}O$; and for δD, $R = D/H$.] The standard for carbon isotopes is Pee Dee belemnite (PDB); the standard for oxygen and hydrogen isotopes is standard mean ocean water (SMOW).

saline zone (TDS 10,000–43,400 ppm)—Mg/Ca 0.8-5.2 Further, Hanshaw and others (1971) concluded that under equilibrium conditions of calcite, dolomite, and water at 25°C, the Mg/Ca ratio should be near 1.0.

We believe the Mg depletion in the Tenneco samples is a result of reaction of the ground-water/seawater mixture with cement in the vicinity of the well casing. The cement-water reaction produces a strongly alkaline pH which may have induced hydromagnesite $3MgCO_3 \bullet Mg(OH)_2 \bullet 3H_2O$ or brucite ($Mg(OH)_2$) precipitation. However, the X-ray diffractogram (fig. 6) does not show hydromagnesite or brucite peaks.

In summary, we have concluded from the pressure-head data that the sampled interval lies above and shoreward of the freshwater-saltwater interface. The chloride content of the Tenneco samples (6,900 to 7,600 mg/L) is consistent with this conclusion. The formation water is fresher than reported in table 2, but the available data are insufficient to determine the actual salinity of the ground water in the tested interval.

REGIONAL IMPLICATIONS—OFFSHORE LOCATION OF FRESHWATER-SALTWATER INTERFACE AND SALTWATER INTRUSION POTENTIAL

The heads and salinities in the Tenneco hole and JOIDES J–1 and J–2 holes are compatible with the

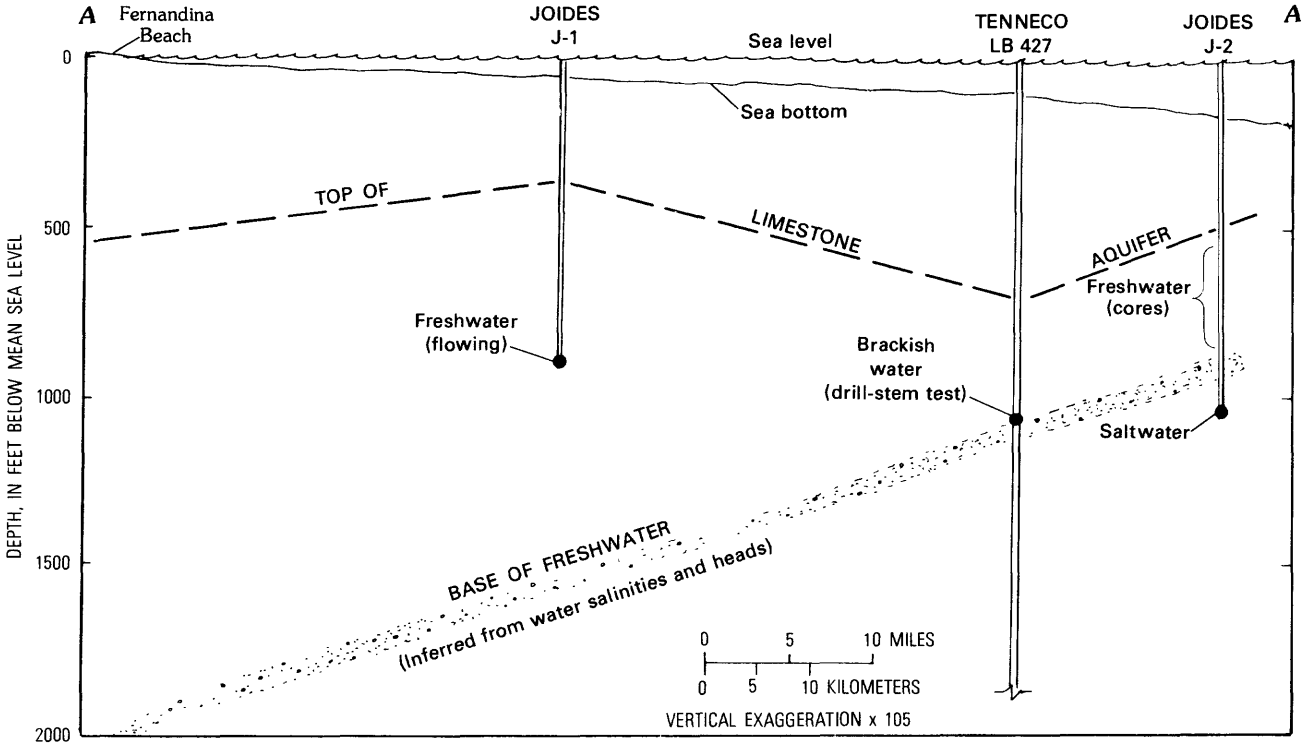

Figure 7. Inferred position of the freshwater-saltwater interface.

modern (post-Pleistocene) onshore flow system. Figure 7 shows the inferred position of the freshwater-saltwater interface based on salinity from the three holes[1] and the commonly used Hubbert interface relation, which states that the depth below sea level to the base of freshwater is about 40 times the altitude of the freshwater head on the interface (altitude of the potentiometric surface of the limestone aquifer as measured directly at the interface). The freshwater heads in figure 7 were all measured at points above the interface, and an assumption was made that the head at the interface was equal to the head of the potentiometric surface as measured vertically above. This condition is not precisely met because freshwater flow above the interface necessitates lines of equal head that are curved, not vertical. However, the interface, which constitutes the limiting flowline of the freshwater system, has a very low slope (without vertical exaggeration figure 7 would show the interface to be nearly flat). Therefore, freshwater flowlines near the interface must be nearly horizontal. This in turn suggests that the lines of equal head near the interface are nearly vertical. Thus an estimate of the interface position based on heads measured higher in the section is probably acceptable.

Several hypotheses could explain what is controlling the present position of the saltwater-freshwater interface:

1. The interface position is compatible with present-day heads. This implies that the interface is being drawn coastward and upward at the maximum possible rate due to pumping.
2. The interface position is compatible with predevelopment heads; thus, although potential for movement exists, none has occurred.
3. The present interface is somewhere between these two positions, implying that some movement from the predevelopment position has occurred.
4. The interface is unrelated to present or predevelopment heads. The freshwater is residual water that entered the aquifer during a low stand of sea level in Pleistocene time. Kohout and others (1977) found fresh ground water below Nantucket Island at much greater depth than would be

[1]Chloride concentrations are as follows: 675 to 1,025 mg/L for JOIDES J–1 (Wait and Leve, 1967), 19,600 mg/L for bottom-hole samples from JOIDES J–2 (G. W. Leve, written commun.), and 1,000 to 7,000 mg/L for Tenneco LB-427 (see above).

predicted from the Hubbert interface relation. Primarily because no hydraulic connection exists between the aquifer containing this freshwater and present-day sources of recharge, they conclude that the freshwater results from recharge when the aquifer was exposed during Pleistocene time.

Consideration of present and predevelopment heads allows inference on these hypotheses. Warren (1944) constructed an estimated predevelopment potentiometric surface map of the limestone aquifer for coastal Georgia and northwest Florida. On Warren's map, potentiometric surface altitudes are about 60 ft at the shoreline to the west of the JOIDES and Tenneco holes. The present base of freshwater along the coast is generally 1,800 to 2,100 ft below sea level (Brunswick to Fernandina Beach), which is below the depth suggested by present-day heads (0 to 30 ft). However, the predevelopment head (60 ft) suggests a greater depth of 2,400 ft to the base. At JOIDES J−1, freshwater occurs to at least 910 ft below sea level. The estimated predevelopment head (45 ft) and recent head (30 to 38 ft) suggest that the base is deeper. At the Tenneco site, the base of freshwater (about 1,100 ft) is nearly compatible with either the predevelopment head or the present head, since they are similar (about 30 ft and 27 ft, respectively). At JOIDES J−2, freshwater was recovered from cores above 900 ft. The present head is probably 15 to 20 ft suggesting a shallower depth to the base of freshwater.

In summary, head and salinity data obtained at the Tenneco test hole, used in conjunction with previous JOIDES data, suggest the existence of a landward-sloping interface as shown in figure 7. Present-day pumping probably has caused small head declines at the JOIDES J−1 and Tenneco sites. The interface appears to be in a transient position between the position that would be compatible with predevelopment heads and the position that would be compatible with present-day heads. This implies that some movement of the interface from the predevelopment position has occurred during the past 100 years. The implied movement is incompatible with the hypothesis that freshwater occurring far offshore is trapped water remaining since the Pleistocene.

SUGGESTIONS FOR CONDUCTING DRILL-STEM TESTS TO OBTAIN HYDROLOGIC DATA IN EXPLORATORY OIL WELLS

An exploratory oil well in the process of being drilled or being abandoned is a poor environment for hydrologic testing. The hydrologist faces various problems: the exploratory well is lined with thick-wall steel casing in the intervals of freshwater aquifers; cement of variable thickness (possibly channeled) separates the casing from the formation of interest; drilling fluids have probably invaded the zone of interest. In order for hydrologic testing to be done, the exploratory oil well must be "temporarily" completed as a water well. Standardized aquifer-test and water sampling procedures are usually too expensive because of the time involved. Compromises can be made and shortcuts taken, however, so that the test, if successful, can provide hydrologic and geochemical data that would otherwise be unobtainable.

The standard drill-stem test (DST) as used by the petroleum industry is the only practical method, from a cost standpoint, of hydrologic testing in an oil well while it is being drilled or being plugged back. The DST can provide head/permeability data and may also provide suitable water samples for chemical analysis. Testing involves the following phases: (1) selection of the interval to be tested, (2) preparation of the hole including perforating the casing, (3) conducting the DST, and (4) water sampling. Pitfalls to avoid during the various phases and suggested techniques are described here.

The selection of preferred intervals for testing is made initially from inspection of geophysical logs, sample logs (lithologic descriptions), and drilling penetration logs. The specific interval to be tested should be a permeable zone of the formation to ensure adequate water flow into the well through the perforated casing. In carbonate rocks, high permeability zones are suggested by fast drilling rates on a drilling penetration log and by indications of lost circulation of the drilling fluid. An interval of lost circulation implies high permeability, but the lost circulation also indicates maximum invasion of drilling fluid into the formation—thus representative samples of the formation water will be harder to obtain.

Cement-bond and casing-collar logs should be run prior to final selection of the interval for testing. The interval selected for perforating should have a continuous uniform cement bond and no collars. A cement bond with voids and channels may permit migration of fluids or transmission of pressure effects from zones other than the perforated interval. If the cement bond is bad, squeeze cementing will have to be done. Squeeze cementing involves perforating the casing just above and below the test interval. Cement is pressure-injected through the perforations into the formation. After the cement is set (usually 24 hours), the cement plug is drilled out of the casing. Squeeze cementing is an expensive procedure requiring 1 to 2 days of rig time and should be avoided.

We recommend that preparation of the hole and perforation of the casing prior to drill-stem testing be performed in the following sequence:

1. Set a cement retainer or bridge plug in the casing below the interval to be perforated. This plug will act as a lower packer during testing.

2. Run the drill bit and scraper to the cement plug. Circulate clean water until the returning fluid is clear; this probably will require several hours.
3. Remove enough water from the casing to prevent water in the casing from entering the formation during the DST. Calculate the volume of the drill-stem tool and associated drill rods and the volume of water inside the casing. Calculate the volume of water that must be removed from the casing in order that the estimated formation head will exceed the fluid level in the hole after the drill-stem tool is lowered to the perforated interval. Use an air compressor or bailer to lower the water level in the casing; or displace the casing water with a closed drill bit and rods.
4. Select the number of shots for perforating the casing. The perforating tool at the Tenneco site used four shots per foot—arranged 90° apart in spiral fashion. The tool will always lie against one side of the casing, and thus one-fourth of the shots will be fired directly into the casing wall; three-fourths of the shots must travel through water before entering the casing. The small, finger-sized holes must penetrate the casing and the cement into porous rock or fractures to obtain water flows. In oil-test wells lined with standard 13⅜- or 17½-inch steel casing, not all of the shots will penetrate the casing and the cement bond into the formation. We perforated 20 feet of casing (80 shots) in the Tenneco well and achieved only a low rate of flow. Therefore, we suggest a greater interval of perforation (perhaps 40 to 100 ft) or a higher shot density.
5. Before firing the casing perforating gun, it is advisable to measure the water level in the annular space (between drill rods and casing) to ensure that the annular water level is below the estimated head in the formation.

The objective of the DST is to determine the static formation pressure and possibly to estimate the formation permeability (see section entitled "Theroetical Analysis"). The tool is lowered into the hole with fluid-entry ports closed; however, the pressure recorders have sensors outside the tool and thus continuously record pressure changes, including the increase associated with the down-hole descent of the tool. When the tool is in position, the upper packer is expanded, the fluid entry port is opened, and the test begins.

The key to a successful DST is to select suitable times for flow and shut-in periods. It should be noted that one is testing a "temporarily completed" well with extremely large well losses. Although the aquifer transmissivity may be high, flow into the well through a few finger-sized holes will be slow. Recovery will also be slow, so that flow periods should be short and shut-in periods long. Based on a study of several thousand drill-stem tests, Johnston-Schlumberger (1976) state that "not having any other information, it is recommended that a minimum of 60 minutes be given to the initial shut-in period." Our suggested times are:

Initial flow period	2 to 3 minutes
Initial shut-in period	60 minutes
Second flow period	15 to 30 minutes
Second shut-in period	90 minutes

During the test, a pressure manifold is connected to the upper end of the drill rods. This manifold prevents water-level measurements inside the drill pipe during the DST. However, it is possible to use a pressure gage (attached to the manifold) to record the rise of water inside the drill rods. If the recovery of the water level is very slow, small diameter tubing may be attached to the manifold with the free end of the tubing immersed in a bucket of water. Air bubbles in the bucket will show that the recovery is progressing.

When collecting water samples from an exploratory oil well, the best method is to remove as much fluid as possible from the formation before taking the samples. Drilling-fluid invasion of the formation and cement-water reactions can radically change the water chemistry in the vicinity of the well (see "Discussion of Analytical Results"). If flow from the perforated interval is adequate, use of a deep-well pump is the preferred sampling technique because a large volume of water can be withdrawn from the formation prior to sampling. If pumping is possible, the hydrologist should have his equipment onsite before the DST begins. The minimum equipment we recommend would be two deep-well submersible pumps (10 to 20 horsepower), electric cable, transformer panel and breaker box, tubing for the pump column, slips designed to handle the tubing, and a flow meter. Pumping should be continued until the water is clear and the pH and conductance are stable.

If the well will not yield sufficient water to sustain a pumping rate of at least 5 to 10 gal/min for several hours, then the drill-stem tool and drill rods should be used to collect the water samples. The drill-stem tool as sample collector has an advantage over other possible methods in that a very large hydraulic gradient can be established between the empty tool and the formation. At the Tenneco site, a head difference of 1,050 ft was developed when the tool was positioned opposite the perforated interval. This large head difference sufficiently overcame the large well losses so that the water level inside the tool and pipe rose about 500 feet by the end of one 8-hour flow period.

Water sampling with the drill-stem tool and drill rods has disadvantages, however, including the possibility of contamination of the water samples by the dirty drill rods. Also, our single 8-hour flow period did not remove enough formation water from the well to get water samples uncontaminated by drilling fluid. A second or third flow period of 8 hours would have removed a larger volume of water and increased the probability of obtaining a representative sample of formation water. Of course, if money is available, three 8-hour flow periods are preferable to one 24-hour flow period, because of the higher head differences maintained during the shorter flow periods.

When conducting drill-stem tests in exploratory oil wells, the high cost of testing forces the hydrologist to consider tradeoffs. Spending additional time and money to perforate a longer interval of casing must be weighed against the possibility of unacceptably long flow periods to obtain water samples. At the Tenneco site, we believe that perforating a longer interval of casing would probably have produced better results.

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