GROUND-WATER FLOW AND THE GEOTHERMAL REGIME OF THE FLORIDIAN PLATEAU

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ABSTRACT

Temperature surveys in oil-exploratory wells indicate an anomalous geothermal profile for the Floridian Plateau. The geothermal gradient is negative (the ground water becomes colder) to a depth of about 3,000 feet below sea level. The anomaly is related to cold ocean water below the thermocline in the Gulf of Mexico and the Florida Straits. At 3,000 feet below sea level the ground water has a temperature of about 70°F near the edge of the deep sea water bodies and warms to more than 108°F toward the central axis of the Floridian Plateau. The horizontal and vertical temperature distributions suggest the possibility that cold, dense sea water flows inland through the cavernous dolomite in the deep part of the aquifer, where it becomes progressively heated by upward geothermal heat flow. The reduction in density produces an upward convective circulation which brings the sea water into contact with fresh water recharged through sinkholes in the karst region of central Florida. The mixing with fresh water further reduces the density. The diluted salt water then flows seaward and discharges by upward leakage through confining beds into shallow aquifers and thence back to the sea, or discharges through submarine springs on the Continental Shelf and Slope.

INTRODUCTION

This paper adds five temperature profiles to the single profile first shown in a paper hypothesizing a cyclic flow of salt water related to geothermal heating in the Floridan aquifer (Kohout, 1965, Figs. 9 and 10). The new temperature data tend to support the hypothesis and confirm that vertical and horizontal temperature gradients underlying the Floridian Plateau are affected by the cold ocean water that sweeps around the plateau from the Gulf of Mexico through the Florida Straits. Cavernous limestone in the deep part of the Floridian aquifer permits ground-water flow to anomalously affect the geothermal profile to a depth of 3,300 feet, whereas more normal temperature gradients are present below that depth extending to the oil horizons at about 11,500 feet below sea level. This paper describes the anomalies and attempts to formulate the few observations that now exist into a consistent pattern.

GEOLOGIC AND GEOMORPHIC SETTING

The State of Florida is the above-sea-level part of a much larger peninsular landmass called the Floridian Plateau (Fig. 1). On the west this platform is flanked by abyssal depths of about 12,000 feet in the Gulf of Mexico, roughly equivalent to the depths of oil-producing wells in southern Florida at Felda, Sunniland, and Forty Mile Bend (Fig. 2).

The dominant structural control of the deep sediments is an anticline called the Peninsular Arch, which crests in northern Florida (Puri and Vernon, 1964). Sea water in the Gulf of Mexico sweeps southward around the southern end of the Florida Peninsula and then eastward and northward through the Straits of Florida. The water depth decreases from about -5,000 feet between Key West and Cuba to about -1,800 feet between the Floridian Plateau and the Bahama Banks.

The Gulf of Mexico and the Straits of Florida form the hydraulic boundaries for several aquifer systems that underlie the Floridian Plateau.

THE FLORIDIAN AQUIFER

The Floridan aquifer is a regionally developed artesian aquifer that supplies water to thousands of municipal, industrial, and irrigation wells. The aquifer system is composed of Tertiary limestone underlying Florida and parts of South Carolina, Georgia, and Alabama. In Florida recharge to the system occurs through sinkhole lakes and by direct infiltration of rainfall where the aquifer crops out or lies near the surface in the karst region of north-central Florida (shaded area in Figure 1). After moving downward into the aquifer the fresh water then moves laterally seaward under moderate hydraulic gradients. The piezometric surface — the height to which water will rise in tightly cased wells that tap the aquifer — was first mapped by Stringfield (1936, pl. 13). His work of nearly 40 years culminated recently in his important summary, published as Geological Survey Professional Paper 517 (Stringfield, 1966). Over the years he used the name "principal artesian aquifer." Parker and others (1955, p. 199)

1Publication authorized by the Director, U.S. Geological Survey.
used the name “ Floridan aquifer.” Stringfield (1964, p. C164) described it as follows:

In Florida, it is known as the Floridan aquifer . . . . The aquifer includes as many as seven geologic formations, ranging in age from middle Eocene to middle Miocene. In Florida the basal unit of the aquifer is the Lake City Limestone of middle Eocene age.

From temperature and hydraulic evidence to be presented later, it now appears that the lower Eocene Ocala Limestone also is a participating unit of the aquifer in southern Florida, at least as far north as Ocala (Fig. 1). This has more than doubled the thickness of the aquifer, from about 1,000 feet to about 2,300 feet in southern Florida. Conforming with Stringfield's definition, the upper part of the Floridan aquifer (900 to 1,900 feet below sea level in southern Florida) is referred to as the Principal Artesian Zone (Figs. 9 and 10). The lower part of the aquifer system (about -1,900 to -3,300 feet) is referred to as the Boulder Zone because of distinctive hydrologic properties. Although confining beds may separate the zones in certain areas, water movement in the entire thickness of about 2,300 feet is apparently controlled by recharge in the karst region of central Florida and by the discharge hydraulic boundaries formed by the deep sea-water bodies along the perimeter of the Floridan Plateau (Fig. 1). The geologic column in Table 1 gives formation tops and hydrologic properties observed at Forty Mile Bend. (See Fig. 2 for location.)

Mainly because of expense, water wells are infrequently drilled deeper than about -1,200 feet, and ground-water studies to date have been confined primarily to the upper part of the Floridan aquifer. This is especially true of southern Florida, because the top of the aquifer ranges from 900 to 1,200 feet below sea level and the water is brackish.

Because of the lack of water-well information, oil exploratory wells were investigated as a possible source of information for the deep part of the artesian aquifer.
This investigation showed that highly permeable zones occur at depths ranging from about 1,900 feet to as much as 4,000 feet in southern Florida. The geologist's lithologic and paleontologic log usually omitted the desired information, but frequently the driller's log contained statements such as "strong salty sulfur water flow at 2,690 feet." These brief words were very illuminating from a hydrological standpoint. Because of the large scale of oil-drilling operations, the term "strong" is somewhat of an understatement; by personal observation the writer can state that frequently the flows range from 2,000 to 5,000 gpm (gallons per minute), and special ditching is required to keep the drilling pad from being awash with water.

The Principal Artesian Zone

The piezometric surface of an artesian aquifer is the imaginary surface that coincides with the height to which water will rise in tightly cased wells that tap the aquifer. The map of this surface for peninsular Florida (Fig. 3) shows that the highest altitude of the piezometric surface is about 120 feet above mean sea level (msl) in an area of about 250 square miles in central Florida. This head is sufficient to produce theoretical hydrostatic balance between fresh water and sea water at a depth of 4,800 feet below sea level and to produce seaward hydraulic flow at shallower depths. This depth must be considered as the maximum depth to which fresh-water recharge in central Florida might induce a circulation of fresh water in the aquifer.

During the drilling of an oil exploratory well a "zone of lost circulation" is usually encountered from about 1,000 to about 3,300 feet below sea level (see Table 1). The term "lost circulation" refers to the loss of return drilling fluid and cuttings in hydraulic-rotary drilling operations. In southern Florida the piezometric surface may be more than 40 feet above the land surface, and a fresh- or brackish-water flow is usually encountered 1,000 to 1,300 feet below sea level. This flow zone correlates with the Ocala and Avon Park limestones at the top of the Principal Artesian Zone; the piezometric surface representing the pressure head of this part of the aquifer is shown in Figure 3.

The Boulder Zone

Distinct zones (Table 1) in the deeper part of the aquifer are recognized and defined mainly from drilling experiences in about 15 wildcat wells spread throughout southern Florida and Florida Bay. Generalizations concerning the average drilling times for most wells are as follows:

<table>
<thead>
<tr>
<th>Depth (feet)</th>
<th>Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1,900</td>
<td>About 4 days</td>
</tr>
<tr>
<td>1,900-3,500</td>
<td>Variable as little as 3 days to as much as 3 months, according to the amount of trouble; in the average wildcat well, a month has been required to overcome drilling difficulty in the &quot;Boulder Zone.&quot;</td>
</tr>
</tbody>
</table>
| 3,500-11,500| Discounting coring and testing time, the brine aquifer (oil zone) at about 11,500 feet can be reached 10 to 14 days after the 9-5/8-inch casing is cemented in place at about 4,000 feet.

The Boulder Zone in southern Florida is defined as the deep part of the Floridan aquifer (1,900-3,300 feet below msl), consisting of cavernous dolomite and limestone (Kohout, 1965, p. 260). The term originated from the drilling action of the bit and is a misnomer because the rock does not consist of boulders. Fractured dolomite breaks off from the roofs and sides of caverns and these chunks fall under and around the bit to produce very rough drilling conditions. The difficult drilling conditions gained such notoriety in the oil industry that the name has taken on quasi-official status (Burke, 1967) and is appropriated to identify the lower part of the Floridan aquifer.

The top of the Boulder Zone can be recognized frequently in the driller's log by the reports of an increase of flow or loss of circulation—both of which imply a significant increase of permeability. The hydrologic change occurs about 900 feet below the top of the Floridan aquifer at an average depth of 1,900 feet below sea level in southern Florida. "Boulders" are usually reported at an average depth of about 2,300 feet below sea level. At 2,700 feet large cavities, "boulders", and a "strong salt-water flow" form an identifiable hydrologic marker. The 1,200- and 2,700-foot flow zones are consistent enough to be marked by heavy dashed lines on the Geologic section (Fig. 4).
Figure 3. Map showing the piezometric surface of the Principal Artesian Zone as of 1960. After Stringfield (1964, p. C166) based on maps by Healy (1962), Stewart and Counts (1958), and Stewart and Croft (1960).
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>SERIES</th>
<th>FORMATION</th>
<th>LITHOLOGY</th>
<th>HYDROLOGIC CHARACTER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Name</td>
<td>Top (ft.)</td>
<td>Thickness (ft.)</td>
</tr>
<tr>
<td>Quaternary</td>
<td>Pleistocene</td>
<td>Pleistocene and Pliocene</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pliocene</td>
<td>Tamiami</td>
<td>20</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hawthorn</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tampa Limestone</td>
<td>600</td>
<td>250</td>
</tr>
<tr>
<td>Oligocene</td>
<td>Suwannee</td>
<td>Limestone</td>
<td>850</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>Ocala Limestone</td>
<td></td>
<td>1,200</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Avon Park Limestone</td>
<td></td>
<td>1,300</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Lake City Limestone</td>
<td></td>
<td>1,800</td>
<td>250 *</td>
</tr>
<tr>
<td></td>
<td>Oldsmar Limestone</td>
<td></td>
<td>2,050</td>
<td>1,250 *</td>
</tr>
<tr>
<td>Paleocene</td>
<td>Cedar Keys Limestone</td>
<td></td>
<td>3,300</td>
<td>1,950 *</td>
</tr>
<tr>
<td>Upper</td>
<td>Lawson Limestone</td>
<td></td>
<td>5,250</td>
<td>150 ‡</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Unnamed</td>
<td></td>
<td>5,400</td>
<td>2,300 ‡</td>
</tr>
<tr>
<td></td>
<td>Atkinson</td>
<td></td>
<td>7,700</td>
<td>100 ‡</td>
</tr>
<tr>
<td></td>
<td>Undifferentiated units</td>
<td></td>
<td>7,800</td>
<td>4,000 ‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11,800</td>
<td></td>
</tr>
</tbody>
</table>

*Applin and Applin, 1944, Figure 22.
†Banks, Joseph E., 1960, p. 1739.
Figure 4. West-east geologic section through southern Florida from the Gulf of Mexico to the Atlantic Ocean. Adapted from Banks (Ginsburg et al., 1964, Figure 1).
 Depths at which strong salt-water flows have been reported in the small number of wells so far inspected are mapped in Figure 5. From these and other less tangible data the following impressions have emerged in the writer's mind:

1. The depth of most of the reported flows seems to center between -2,600 and -2,700 feet.

2. In the area southwest of Lake Okeechobee the reports of heavy flows tend to center around 2,300 feet below sea level.

3. Along the east coast flows are reported at depths 1,000 to 1,500 feet deeper than over the remainder of Florida.

4. No flows have been reported in the westernmost Keys near Key West, but “300% to 500% returns” — that is, return of drilling fluid — were reported in the Marquesas Key drilling tract. These excessive returns may be evidence of artesian flow under heads too low to rise to the derrick floor, 30 to 50 feet above sea level.

Until recently the lithologic character of the Boulder Zone was poorly known because of lost circulation. However, the Gulf Oil Corp. recovered boulders as large as 8 inches in diameter with a Globe junk basket as it drilled through the Boulder Zone at Gulf State Lease 826-G in Florida Bay (Fig. 6). The rock consisted of black to brown vuggy, finely to coarsely crystalline dolomite. After losing several sets of drill collars and pipes in well Red Cattle 32-2 at its new oil-field discovery at Felda (Fig. 2), the Sun Oil Co. obtained three-dimensional borehole photographs. I am grateful to Sun for the privilege of publishing the photographic stereo pair taken at a depth of -2,442 feet (Fig. 7).

By viewing the pair stereoscopically, one can obtain a most fascinating geological and hydrological insight into the nature of the Boulder Zone. Toward the
Figure 6. Index map showing locations of oil exploratory wells that provided data for this report.
upper right two dark boulders can be seen hanging at the top of a cavern. Fracturing and breaking-out of such boulders during drilling allows the boulders to fall under and around the bit. This would account for the wallowing drill action and twist-off of the drilling pipe. In this same well (Red Cattle 32-2) a 90-foot cavern was encountered from 2,522 to 2,612 feet below land surface. The twisted-off and bent-over remnants of the drill pipe could be recognized in the clear water of the cavern. After the problems were identified in the photos, new drilling techniques were devised (Burke, 1967) to cope with the Boulder Zone; subsequently, drilling time through the zone averaged about 4 days.

The Boulder Zone caverns are developed through a vertical range of at least 1,000 feet, from -1,900 feet to -2,900 feet, and temperature data presented later suggest that they extend to about -3,300 feet. Sinks formed by the collapse of underlying caverns continue to develop at fairly frequent intervals in the karst region of central Florida. For example, recently in the Barrow area slumping-in of the surface resulted in the abandonment and destruction of several homes. Giving recognition to the fact that many sink lakes in the karst region of central Florida are 50 to 100 feet deep and more than a mile in diameter, collapse of caverns at least this large must have been involved in their formation. A question arises: Is the development of such caverns related to great solutinal activity in the Oldsmar Limestone, which appears to be the host geologic horizon for the Boulder Zone caverns of southern Florida? Such a possibility cannot be discounted in investigations of the cause of present-day cavern collapse in central Florida.

Also, one may wonder if a correlation exists between the Boulder Zone caverns of southern Florida and the 2,800-foot trench in the Florida Straits east of Miami. Figure 8 shows a caliper log taken in the Coastal-Williams well on Key Largo. Mr. J. E. Banks of the Coastal Petroleum Co. reports that a 2,000-gpm water flow commenced shortly after the cavity from -3,490 to -3,540 feet was penetrated. Also, he points out that from -3,510 to -3,540 feet, the cavity may be much larger than indicated because the caliper becomes fully extended and loses calibration at a hole diameter of 32 inches.)

The depths of reported flows (Fig. 5) and the existence of caverns at depths only slightly greater than the 2,880-foot trench in the Florida Straits suggest that there may be a direct correlation between the subsurface and surface observations. This trench, as well as many others that exist in the Florida Straits, would seem to be logical places to look for discharge from the Floridan aquifer. Mr. Art Markel of the Reynolds Submarine Services Corp. (oral communication, July, 1967) reports that the Aluminaut deep-sea submarine lost buoyancy while investigating a smaller hole off the northern Florida coast and was forced to jettison 2,000 pounds of ballast. This loss of buoyancy might be explained by passage of Aluminaut from sea water into the less-dense relatively fresh water associated with discharge from a submarine spring (Kohout, 1966).

**THE GEOTHERMAL REGIME OF THE FLORIDIAN PLATEAU**

Desalination and waste disposal represent possible new economic uses of saline zones in the Floridan aquifer. Therefore, the following specific problems concerning the Floridan aquifer need investigation:

1. Is most of the salt water in the aquifer system a remnant of Pleistocene inundation, or is it in the form of a massive zone of diffusion that has not been recognized as such?

2. Is the salt water in all parts of the aquifer under sufficient head for continuous seaward flushing, or is it a state of dynamic equilibrium between fresh water and sea water already in existence?

3. Is there a continuous cyclic flow within the system whereby sea water from the straits of Florida enters the deep part of the aquifer and, after becoming mixed and diluted with fresh water, flows upward and seaward through the upper part of the aquifer?
Gulf - Florida State Lease 340-1 at Forty Mile Bend. This curve and five additional temperature profiles are plotted in Figure 9. (See locations in Fig. 6.)

Because of the great difficulty in drilling through the Boulder Zone, this section of the aquifer is invariably cased off. Customarily 13 3/8-inch casing is cemented in place at 1,000 to 1,300 feet and 9 5/8-inch casing at a depth of 3,500 to 4,500 feet below sea level. Cement is pumped through the lower end of the 9 5/8-inch casing and forced upward in the outside annulus, where it raises until the cavernous rock of the aquifer permits it to spread laterally, at a depth of about 3,300 feet below sea level. After a setting-up period, a temperature survey is run in the dead-water column inside the 9 5/8-inch casing to determine the position of the cement outside the casing, as indicated by the reaction heat of the hardening cement. The dead casing water quickly takes up the temperature of the water and rock outside the casing and provides the temperature profiles of Figure 9. Unfortunately, such temperature surveys are made infrequently, and only a few have been uncovered. Of the wells shown in Figure 9, No. 46-1 had only 200 feet of surface casing and Stevens #1 was uncased from -557 feet to the bottom of the hole. This would permit flow in the well bore that would affect the temperature profile. For example, Stevens #1 was discharging 700 gpm at the surface when the log was made; the temperature profile must be analyzed with this factor in mind.

Hypothesis of Cyclic Flow by Geothermal Heating

Geothermal gradients of about 1°F increase per 50- to 100-foot increase in depth below 1,000 feet are frequently observed and can be considered "normal." However, Schneider (1964, p. 210) attributes observations of very flat gradients in Texas, Maryland, and Idaho and a negative gradient in the Union of South Africa to ground-water circulation. Starting with 78° at a depth of -1,000 feet at Gulf 340-1 at Forty Mile Bend (Fig. 9), the theoretical temperature at a depth of 3,300 feet below sea level, at the base of the permeable zone, should be between 101° and 124°—if a "normal" geothermal gradient were in existence. In contrast, the upper part of the temperature profile of Gulf 340-1 showed a slight increase to 78°F at -1,000 feet, the contact between the upper confining bed and the top of the aquifer. Below that, the temperature profile remains at 78° to a depth of -1,600 feet, and below that it decreases to 74° at -3,100 feet. This negative temperature gradient is abnormal on two counts: (1) it is contrary to the adiabatic compression heating effect of water percolating to this depth from the recharge area in central Florida, and (2) it is contrary to the increase of temperature that would be expected from upward heat flow from the interior of the Earth. Furthermore, the water at -3,000 feet is known to be nearly as salty as sea water; because salt beds are not present at these depths, its entrance into the aquifer as cool fresh water in the recharge area and conversion to salt water during movement through the aquifer would be quite unlikely.

The temperature curve for Gulf 340-1 has been re-plotted in the idealized cross-section of Figure 10 at...
Figure 9. Graph showing temperature profiles in oil exploratory wells.

NOTE: TEMPERATURES BELOW 76°F WERE NOT RECORDED FOR 826Y BECAUSE OF LIMITED INSTRUMENT RANGE.

EXPLANATION

BOTTOM HOLE TEMPERATURE IN °F
DEPTH OF MEASUREMENT IN FEET

190°
13,080'

164°
15,290'

236°
11,352'

201°
11,400'

238°
13,971'

198°
12,442'

826Y

COLLIER #1

STEVENS #1

FLORIDAN AQUIFER

PRINCIPAL ARTESIAN ZONE

BOULDER ZONE

ANHYDRITE CONFINING BEDS

CLAY CONFINING BEDS

DEPT IN FEET, BELOW M.S.L
Figure 10. Idealized section through Miami showing concept of cyclic flow of sea water induced by geothermal heating.
its proper geographical position at Forty Mile Bend, 40 miles west of Miami (after Kohout, 1965, Fig 10). The isotherms in the Florida Straits (adapted from Sverdrup and others, 1942) show that sea water having a temperature of about 44°F is present where the Floridan aquifer (in theory) is truncated by the channel of the Straits. The inference was made in 1963 that this negative temperature gradient at Forty Mile Bend was related to the cold water in the Florida Straits east and south of the Florida Peninsula. As dolomite and anhydrite rock have about the same ability to conduct heat, the contrasting thermal gradients above and below the base of the Floridan aquifer (Fig. 9) are believed to relate to relatively rapid water movement in the aquifer as opposed to very slow water movement in the low-permeability anhydrite underlyng the aquifer.

Inland movement of cold sea water from the Florida Straits might explain the negative gradient, but we have no direct hydraulic evidence at this time. Figure 10 is merely an idealized section which presents a hypothesis showing how such a flow might occur. The low permeability anhydrite can be compared to a hotplate. Geothermal heat raises the temperature of the aquifer water just above the anhydrite, and cold sea water from the Florida Straits becomes progressively warmed and less dense as it flows horizontally inland through the cavernous dolomitic limestone in the deep part of the aquifer.

The loss in density eventually produces a thermal convection cell not unlike the familiar circulation in a teapot being heated on a hotplate. The convective circulation in the deep part of the aquifer should be eastward from the Gulf of Mexico, northward from the southern Florida Straits, and westward from the eastern Straits. The focal point for this deep sea-water flow, and the hottest water, should occur along the axis of the Floridan Plateau farthest from the cold sea-water bodies.

Analysis of Temperature Profiles

The data for the other curves in Figure 9 support the hypothesis. Unfortunately, we are not dealing with temperature data taken for a scientific purpose, and we must examine critically what few data are now available. The temperature curves for wells 340-1, 826Y, Collier #1, and 224B-1 were taken inside the deadwater column of a casing cemented at the bottom. California No. 46-1 had only 200 feet of surface casing when the temperature profile was measured. Gulf-Stevens #1 had only 557 feet of casing and was flowing at the land surface at a rate of 700 gpm.

Nevertheless, it is clear that the wells near the axis of the Floridan Plateau, Stevens #1, and 224B-1, have the highest average temperature at about 99°F and 108°F near the aquifer base; whereas wells 340-1 and 826Y, closer to the edge of the Plateau, not only have much lower average temperatures, but demonstrate negative temperature gradients. Gulf 826Y was measured with a temperature instrument that could not read below 76°F. Consequently, although the curve started to demonstrate a strong negative gradient at about 1,400 feet below mean sea level, the limited range of the instrument prevented observation of the true temperature profile.

The temperature profile for California 46-1 is probably not completely valid. The driller's depth at the time of measurement was -7,871 feet and the hole was open from the surface casing at -200 feet to -5,500 feet, where the hole was bridged over preventing deeper measurements. The sharp negative wiggle of the temperature curve at -1,750 feet probably reflects a cool-water anomaly. However, it is the writer's opinion that the temperature over the entire length of the water column is elevated because of the large amount of open hole and because drilling operations extended into warmer rock at the bottom of the hole.

Geographic Distribution of Temperature in the Floridan Aquifer

The geographic distribution of temperature near the bottom of the Floridan aquifer is illustrated in Figure 11, in which all temperature data now available are plotted in relation to the depth of measurement.

Summer #1 (well 1, Fig. 6) was cased to -1,950 feet; the total depth was -2,650 feet when the well was abandoned. At the time of completion the driller reported a temperature of 155°F but this seems somewhat high compared to other temperatures in Figure 11. Later, W. S. Wetterhall of the U. S. Geological Survey measured the temperature of the water at 99°F after the well had been flowing 2 hours at 100 gpm from a hose on the well. At this rate, it would take nearly 2 hours for water at the bottom of the well to rise upward through the 12-inch casing to the discharge point. The water would be considerably cooled during its slow rise, but Wetterhall's measurement is plotted in Figure 11 although it may be somewhat low for this geographic position. Remeasurement at a high discharge rate probably would show the temperature to be considerably higher than 99°F.

The temperatures and depths of other wells shown in Figure 11 were obtained from Figure 9.

The sharp decrease in temperature from about 102.5°F to 99°F at a depth of -3,200 feet in Gulf-Stevens #1 was recognized and labeled "cooling anomaly" by the Schlumberger logging team at the time of measurement (Fig. 9). This cool water did not contribute greatly to the observed surface flow of 700 gpm, or the anomaly would have been smoothed by blending of the cool water with the overlying warmer water. Nevertheless, the anomaly is important to the hypothesis of convective cyclic circulation of cold sea water. Negative temperature anomalies occur in 340-1, 826Y, Stevens #1, and even 224B-1 at the same time that the overall temperature of water in the Boulder Zone increases from about 70°F near the edge to more than 108°F near the axis of the Floridan Plateau. The anomalies and horizontal temperature gradients support the hypothesis that a geothermal convection cell is cycling sea water through the cavernous dolomite in the deep part of the Floridan aquifer.
Salinity of Water in the Deep Boulder Zone

Data on the salinity of water in the deep Boulder Zone are extremely scarce. The blended water discharging from Sumner #1 contained 3,100 ppm (parts per million) of chloride. A sample collected at a depth of 2,600 feet by the Sun Oil Co. in the cavern of Red Cattle 32-2 is reported to have contained 15,590 ppm of chloride. A 2,000 gpm natural flow at Forty Mile Bend, representing a blend of water coming from the open-hole section between -1,360 and -3,300 feet, was observed by the writer to contain 10,300 ppm of chloride.

Figure 12 shows Humble-Lowndes-Treadwell #1 (well 3, Fig. 6) flowing at a reported rate of about 7,000 gpm in August, 1966.

The well has been flowing in this manner since its plug was corroded out more than five years ago. It is now being developed into a spa by Hot Springs, Inc. A sample collected and analyzed by D. H. Boggess of the U. S. Geological Survey on August 1, 1966, gave a chloride content of 18,700 ppm. The temperature of the water was 96°F. Though not plotted in Figure 11 because depth information is lacking, this temperature correlates reasonably well with other temperatures in the deep part of the Floridan aquifer near the central axis of the plateau (Fig. 11). The circumstances associated with this relatively hot water of sea-water concentration discharging at the rate of about 7,000 gpm for years on end are so astonishing that additional data and study will be required to find complete explanations for the observed phenomena. Nevertheless, the cavernous Boulder Zone in the deep part of the Floridan aquifer probably is involved.

Geothermal Gradients Below the Floridan Aquifer

There is some evidence that the geothermal temperature distribution at the foot of the Floridan Plateau is affected by cold sea-water circulation. In Figure 9,
adjacent to the bottom of each temperature curve, the bottom-hole temperature as shown on Schlumberger electric logs is correlated with the depth of measurement. These temperature data are in no way connected with the temperature curve except that they represent the end point for the temperature profile in the relatively low permeability rock below the Floridian aquifer. The data suggest that the heat sink formed by cold water in the Gulf of Mexico at depths of about 12,000 feet (about 40°F) affects the horizontal temperature distribution even at the roots of the Plateau. For example, a temperature of 164°F at 15,290 feet in California 46-1, nearest to the Gulf of Mexico, is about 74°F cooler than the 238°F temperature in well 224B-1 near the central axis of the Floridian Plateau. Although many inconsistencies can develop in measurement of bottom-hole temperatures because of the circulation of mud in the borehole before measurement, it appears that the large temperature differentials between wells 46-1 and 826Y, near the edge of the cold sea-water bodies, and those in the interior of the Plateau are too large to be explained by such inconsistencies. Rather, the data suggest that there exists under the Plateau a three-dimensional temperature regime that is consistent with upward heat flow from the interior of the Earth, modified by lateral heat flow to the cold sea water in the adjacent ocean trenches.

SUMMARY

This paper presents a hypothesis that the geothermal regime of the Floridian Plateau is modified by the presence of cold sea water (40-45°F) in the Gulf of Mexico and the Florida Straits.

From about 1,500 to 3,000 feet below sea level the ground water in the Floridian aquifer near the Straits becomes colder with depth. In the horizontal direction, the average temperature increases from about 70°F near the cold sea-water bodies to more than 108°F along the central axis of the Floridian Plateau. The data suggest that a geothermal convection cell might cause sea water to flow inland through cavernous dolomite near the bottom of the aquifer. After becoming warmed the water flows upward where it mixes with fresh water recharged through sinkholes in the karst region of central Florida, and thence seaward through the upper part of the aquifer to discharge by upward leakage through confining beds or through submarine springs on the Continental Shelf and Slope.

In the low-permeability rock below the Floridian aquifer, geothermal gradients are more "normal"—that is, the temperature increases with depth in a manner consistent with upward heat flow from the interior of the Earth. However, bottom-hole temperatures recorded in Schlumberger electric logs indicate that even at the foot
of the Floridian Plateau, as deep as 15,000 feet below sea level, the temperature regime is modified by lateral heat flow to cold sea water circulating through the adjacent ocean trenches.

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REFERENCES


