

STATE OF FLORIDA
DEPARTMENT OF NATURAL RESOURCES
Harmon Shields, *Executive Director*

DIVISION OF RESOURCE MANAGEMENT
Charles M. Sanders, *Director*

BUREAU OF GEOLOGY
Charles W. Hendry, Jr., *Chief*

SPECIAL PUBLICATION NO. 21

**THE GEOTHERMAL NATURE
OF THE FLORIDAN PLATEAU**

Editors
Douglas L. Smith and George M. Griffin

Prepared for the
BUREAU OF GEOLOGY
DIVISION OF RESOURCE MANAGEMENT
FLORIDA DEPARTMENT OF NATURAL RESOURCES

TALLAHASSEE, FLORIDA
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**DEPARTMENT
OF
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LETTER OF TRANSMITTAL



Bureau of Geology
Tallahassee
January 23, 1978

Governor Reubin O'D. Askew, Chairman
Florida Department of Natural Resources
Tallahassee, Florida 32304

Dear Governor Askew:

The Bureau of Geology, Division of Resource Management, Department of Natural Resources, is publishing as its Special Publication No. 21, "The Geothermal Nature of the Floridan Plateau."

These selected papers edited by Douglas L. Smith and George M. Griffin represent a broad regional evaluation of geothermal data which should be of substantial interest to agencies and/or persons involved with the assessment of the potential for energy development from the geothermal resource base. 45

Respectfully yours,

Charles W. Hendry, Jr., *Chief*
Bureau of Geology

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THE GEOTHERMAL NATURE OF THE FLORIDAN PLATEAU

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INTRODUCTION

The increased public awareness of the reality of the diminishing hydrocarbon energy base has stimulated inquiry into alternative sources of energy. One of the alternatives receiving considerable attention is the heat from deep inside the earth — geothermal energy.

U. S. Geological Survey Circular 726, 1975, defines the geothermal resource base as heat above 15°C which is stored in the ground to depths of 10 kilometers and geothermal resources are defined as that portion of this stored heat that is recoverable using present technology, regardless of cost. Three categories of geothermal resource base have been recognized:

1. Conduction dominated areas, in which the heat content is indicated by the geothermal gradient.
2. Hot igneous systems, in which heat is produced by magmatic sources.
3. Hydrothermal convection systems, in which sources are found at shallow depths and relatively high temperatures.

There is not available for Florida sufficient data to define geothermal systems or to estimate the geothermal resources. This dearth of information is the stimulus for the Bureau of Geology publishing this collection of papers entitled the "Geothermal Nature of the Floridan Plateau."

The Bureau of Geology has exerted no editorial restrictions on the reports and the conclusions represent the opinion of each individual author. As the State Geologist, however, it is appropriate to offer a preliminary assessment of the future economical and technological feasibility of the contribution of geothermal energy as an alternate energy source to Florida. From the data presented herein and from our general knowledge of the subsurface geology of the State the potential for geothermal energy to provide substantial energy resources appears quite remote.

HYDROGEOLOGY RELATED TO GEOTHERMAL CONDITIONS OF THE FLORIDAN PLATEAU

By

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ABSTRACT

Temperature surveys in oil exploratory and waste-injection wells indicate that geothermal gradients underlying the Floridan Plateau are affected by the presence of cold sea water in the adjacent deeps of the Gulf of Mexico and the Florida Straits. The geothermal gradient is negative (the ground water becomes colder) to a depth of about 3,000 feet near the edge of the Plateau. In the horizontal direction, the temperature increases toward the central axis of the Plateau. The horizontal and vertical temperature distributions suggest that cold, dense sea water flows inland through the cavernous dolomite in the deep part of the aquifer where it becomes progressively warmed by geothermal heat flow. The reduction of density produces upward convective circulation. After mixing with fresh water in the upper part of the aquifer, the diluted salt water flows seaward to discharge by upward leakage through confining beds or through submarine springs on the Continental Shelf.

The focal point for the deep sea-water flow, and the hottest water, should occur along the central axis of the Floridan Plateau, farthest from the cold sea-water bodies. Upwelling of warm saline water at Warm Mineral Springs sinkhole and the Mud Hole submarine spring near the west coast of Florida provides field evidence that a convective flow cell exists. Mathematical and laboratory model studies demonstrate a remarkable similarity to the patterns of salinity and temperature observed in the field.

Below the Floridan aquifer system the permeability of the rock is relatively low and geothermal gradients are more "normal." However, bottom-hole temperatures recorded during geophysical logging of oil exploratory wells indicate that the geothermal regime even as deep as 15,000 feet below sea level is affected by lateral heat flow to adjacent ocean depressions. The circumstances are considered in detail by other papers in this volume.

INTRODUCTION

In 1965 Kohout adopted the term "Boulder Zone" to identify the deep, saline part of the Floridan aquifer system consisting of cavernous limestone and dolomite. Since that time the shallow and deep parts of the Floridan aquifer system have come under practical development for the following uses (Klein and others, 1975; Meyer, 1971; and references therein):

- (1) Storage of industrial and municipal liquid wastes in the Boulder Zone.
- (2) Production and desalination of low salinity brackish water from the Principal Artesian Zone.
- (3) Temporary storage in and recovery of fresh water from, saline parts of the Principal Artesian Zone.
- (4) Possible use of brackish artesian water to promote wildlife survival in Everglades National Park.

Clearly, knowledge of how the system operates must be available in order to predict and avoid conflicting uses.

Additional temperature and water quality data have become available since 1965 as a result of new wells drilled for waste disposal. The data support Kohout's hypothesis (1965) that cyclic flow of salt water related to geothermal heating is occurring in the Floridan Aquifer. The high permeability of the cavernous limestone in the Boulder Zone permits cool ocean water from the Gulf of Mexico and the Florida Straits to move inland, causing a reversal in the normal geothermal gradient at depths of 1,000 to 3,000 ft. or more. Normal gradients are present below 3,000-4,000 ft., extending to the oil producing zones at about 11,500 ft.

This report is a review and extension of earlier studies related to the mechanism of salt-water encroachment in the shallow Biscayne Aquifer of southern Florida. Certain aspects provide background, and the following reports are recommended to the reader: Cooper (1959); Cooper and others (1964); Henry (1959, 1960); Kohout (1960a, 1960b); Pinder and Cooper (1970); Segol and Pinder (1976); and Rubin (1976). It was shown, both mathematically and by field observation, that salt water flows inland from the floor of the sea through the lower part of the Biscayne Aquifer into a zone of diffusion, then upward and back to the sea through the upper part of the aquifer.

In the Biscayne Aquifer this cyclic circulation is caused chiefly by density differences related to hydrodynamic dispersion of salt (Cooper and others, 1964). In the thicker Floridan aquifer system, geothermal heat is believed to be an important additional energy source for the cyclic flow mechanism.

GEOLOGIC AND GEOMORPHIC SETTING

Peninsular Florida is the above-sea-level part of a much larger landmass called the Floridan Plateau or Florida-Bahama Platform (Fig. 1). On the west, this plateau is flanked by abyssal depths of about 12,000 ft. in the Gulf of Mexico, roughly equivalent to the depths of oil-producing wells in southern Florida at the Felda, Sunniland, and Forty Mile Bend oil fields (Fig. 2).

The dominant structural control of the deep sediments in Florida is an anticline in Paleozoic rocks 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 ft. between Key West and Cuba to about 1,800 ft. between the Floridan Plateau and the Bahama Banks, northeast of West Palm Beach. A trench having a maximum depth of about 2,880 ft. occurs in the Florida Straits east of Miami, Florida (Fig. 1). Pratt (1966, p. 62) suggests that this trench was formed by erosion; Ball (1972, p. 65)

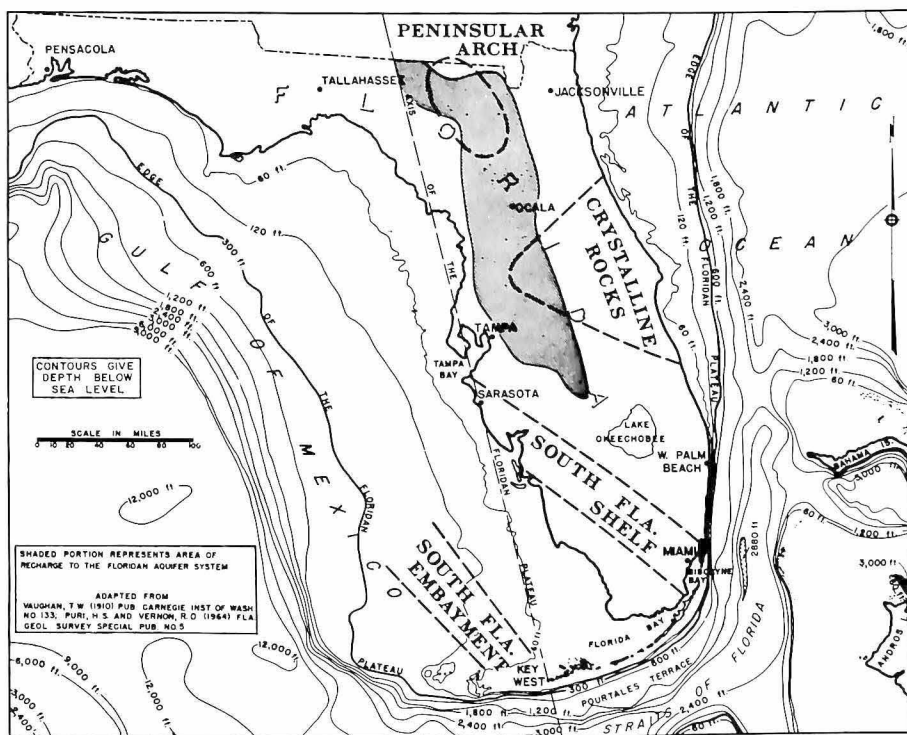


Figure 1. Map showing prominent hydrogeologic features of the Floridan Plateau.

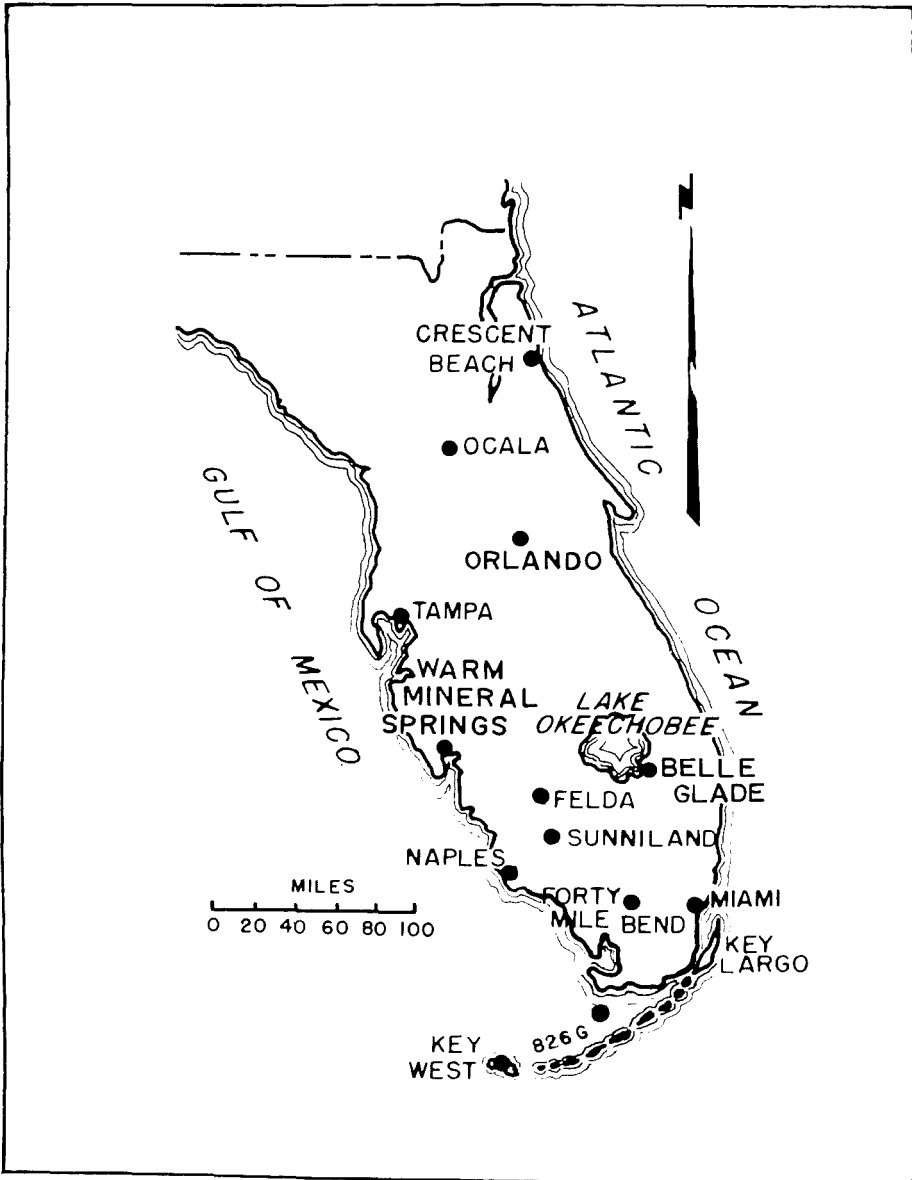


Figure 2. Index map showing localities referred to in report.

suggests that it was formed by tectonic action. A third possibility is that it was formed by solution and collapse of limestone. Caverns and flowing artesian zones deeper than 3,500 ft. occur on the east coast of Florida adjacent to this bathymetric anomaly in the Florida

Straits. Great solutional activity and cavern collapse in the Oldsmar Limestone of central Florida and the Florida Keys supports a conjecture that the anomaly results from submarine development of karst (Puri and Winston, 1974).

Southward from the crystalline rocks (Fig. 1) that occur in central Florida at a shallowest depth of about 6,000 ft., the basement rock deepens to an indicated depth of more than 30,000 ft. below sea level in the Florida Keys, based on seismic, gravity, and magnetic information (Meyerhoff and Hatten, 1974). Only about half of these sediments have been penetrated by the drill. In the oceanic bodies, water below the thermocline (at about 300 ft. below sea level) is relatively cold. Thus, the Gulf of Mexico and the Florida Straits act as hydraulic boundaries where aquifer materials of the Floridan Plateau are partly or completely truncated and exposed to cold sea water (40°-45° F).

THE FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is an extensive group of Tertiary artesian limestone aquifers that supply water to thousands of municipal, industrial, and irrigation wells in 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 limestone crops out or lies near the surface in the karst region of north-central Florida (shaded area in Figure 1). Lake-control and drainage wells, estimated by Vernon (1970, p. 3) to number more than 6,500, also provide recharge to the aquifer. After moving downward into the aquifer, the fresh water then moves laterally seaward beneath clay, silt, and marl confining beds toward discharge points beyond the shoreline. 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. This surface for peninsular Florida was first mapped by Stringfield (1936, Plate 13), whose work of nearly 40 years culminated 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) 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,

the lower Eocene Oldsmar Limestone also is a participating unit of the artesian aquifer system in southern Florida, at least as far north as Ocala (Fig. 1). This has more than doubled the thickness of the aquifer system, from about 1,000 ft. to about 2,300 ft. in southern Florida.

Confirming with Stringfield's original definition, the upper part of the Floridan Aquifer (900 to 1,900 ft. below sea level in southern Florida) is referred to as the Principal Artesian Zone (See Figs. 9 and 10); note that the name is capitalized. The lower part of the aquifer system (about -1,900 to -3,300 ft.) is referred to as the Boulder Zone because of distinctive hydrologic properties. Although confining beds may separate the two zones locally, thermal and water-quality evidence indicates that regionally the aquifer acts as a single hydrologic entity in the region between recharge areas in the karst region of central Florida and the hydraulic boundaries formed by 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 the Forty Mile Bend oil field. (See Fig. 2 for location.)

THE PRINCIPAL ARTESIAN ZONE

In southern Florida the piezometric surface may be more than 40 ft. above the land surface, and a fresh- or brackish-water flow is usually encountered 1,000 to 1,300 ft. below sea level. This flow zone correlates with the Ocala and/or Avon Park limestones at the top of the Principal Artesian Zone. The piezometric map of Figure 3 represents the pressure head for this upper part of the Floridan aquifer system, the Principal Artesian Zone. The inset map shows the approximate depth to the base of potable water as mapped by Klein (1971). In the shaded area the water is salty throughout the aquifer. The altitude of the top of the Principal Artesian Zone ranges from about sea level in central Florida to about 1,000 ft. below sea level in southern Florida. Hydraulic information to map pressure-head gradients in the deep saline (Boulder Zone) parts of the aquifer system is lacking and direction of water movement can only be inferred indirectly from temperature, chemical, and isotopic data.

THE BOULDER ZONE

The Boulder Zone in southern Florida is defined as the lower part of the Floridan Aquifer, consisting of cavernous dolomite and limestone (Kohout, 1965, p. 260). The term originated in the oil industry from the drilling action of the bit and is a misnomer because

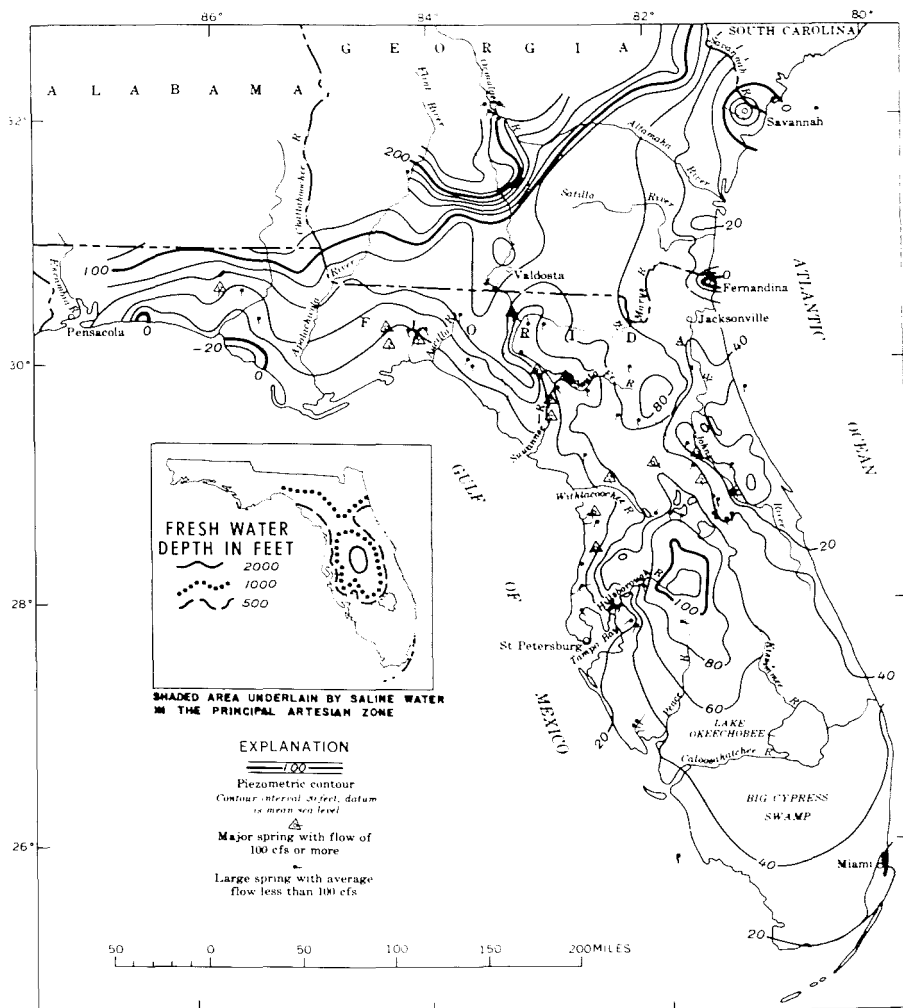


Figure 3. Map showing the piezometric surface of the Principle Artesian Zone as of 1960. After Stringfield (1964, p. C166) based on maps by Healy (1962), Stewart and Counts (1958), and Stewart and Croft (1960), inset after Klein (1971).

the main body of the rock does not consist of boulders, although collapse breccias may be present. Chunks of dolomite break off from the roofs and sides of caverns and these chunks fall under and around the bit to produce very rough drilling conditions. A photo of one of the "boulders" showing two sets of drill-tool marks is given by Puri and Winston (1974, Fig. 23). The difficult drilling conditions gained such notoriety in the oil industry that the name Boulder Zone took on quasi-official status by common usage (Burke, 1967) and was

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TABLE 1
GEOLOGIC AND HYDROLOGIC CHARACTERISTICS NEAR FORTY MILE BEND

SYSTEM	SERIES	FORMATION			LITHOLOGY	HYDROLOGIC CHARACTER
		Name	Top (ft.)	Thickness (ft.)		
Quaternary	Pleistocene	Pleistocene and Pliocene deposits	0	20	Shelly limestone and sand	Water-table aquifer
Tertiary	Miocene	Tamiami Formation	20	180	Marl, clay, sand and limestone	Confining bed, low permeability
		Hawthorn Formation	200	400	Green clay, marl, and sand	Confining bed, low permeability
		Tampa Limestone	600	250	Sandy limestone	Confining bed, fairly low permeability. Wells may flow small amount owing to upward leakage from underlying formations.
		Oligocene	Suwannee Limestone	850	350	Limestone
	Eocene	Ocala Limestone	1,200	100	White limestone	<i>Floridan Aquifer</i> Known as "zone of lost circulation" in the oil industry. Oil-well drillers' comments frequently are as follows: 1,200 ft. - "Fresh-water flow" or "lost circulation" 1,900 ft. - "Lost circulation" 2,300 ft. - "Boulders" 2,700 ft. - "Strong salt-water flow"
		Avon Park Limestone	1,300	500	Chalky limestone	
		Lake City Limestone	1,800	250 *	Tan dolomitic limestone, cavernous	
		Oldsmar Limestone	2,050	1,250 *	Limestone with brown dolomite developed adjacent to large caverns	
	Paleocene	Cedar Keys Limestone	3,300	1,950 *	Dolomite and anhydrite	The "first anhydrite" near top of Cedar Keys Limestone (about 3,300 ft) is the base of the Floridan Aquifer.
	Cretaceous	Upper Cretaceous	Lawson Limestone	5,250	150 †	Porous limestone
Unnamed Deposits			5,400	2,300 †	White chalk and shale	
Atkinson Formation			7,700	100 †	Silty limestone and shale	
Lower Cretaceous		Undifferentiated units	7,800	4,000 †	Limestone, anhydrite, dolomite and shale. Sunniland pay zone.	
				11,800	Deepest well at Forty Mile Bend.	

* Applin and Applin, 1944, Figure 22.

† Banks, Joseph E., 1960, p. 1739.

appropriate to identify the lower part of the Floridan Aquifer by Kohout (1965).

Distinct zones (Table 1) in the deeper part of the aquifer were

recognized and defined mainly from drilling experiences in wildcat wells spread throughout southern Florida. Generalizations concerning the average drilling times for most wells were as follows:

- 0- 1,900 ft. About 4 days
- 1,900- 3,500 ft. 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 was required to overcome drilling difficulty in the "Boulder Zone."
- 3,500-11,500 ft. Discounting coring and testing time, the brine aquifer (oil zone) at about 11,500 ft. could be reached 10 to 14 days after the 9 $\frac{5}{8}$ -inch casing was cemented in place at about 4,000 ft.

The top of the Boulder Zone can be recognized frequently in the oil company driller's log by the reports of an increase of flow or lost circulation — both of which imply a significant increase of permeability. (The term "lost circulation" refers to the loss of return drilling fluid and cuttings in hydraulic-rotary drilling operations and implies very high permeability or caverns.) The hydrologic change occurs about 900 ft. below the top of the Floridan Aquifer at an average depth of about 2,300 ft. below sea level. At -2,700 ft. "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).

Depths at which strong salt-water flows have been reported are mapped in Figure 5. From these and other less tangible data the following generalizations appear to be valid:

1. The depth of most of the reported flows seems to cluster between -2,600 and -2,700 ft.
2. In the area southwest of Lake Okeechobee the reports of heavy flows tend to cluster around 2,300 ft. below sea level.
3. Along the east coast flows as deep as -4,000 ft. are reported.
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 (B. W. Folger, oral commun., 1964). These excessive returns may be evidence of artesian flow under heads too low to rise to the derrick floor, 30 to 50 ft. above sea level.

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

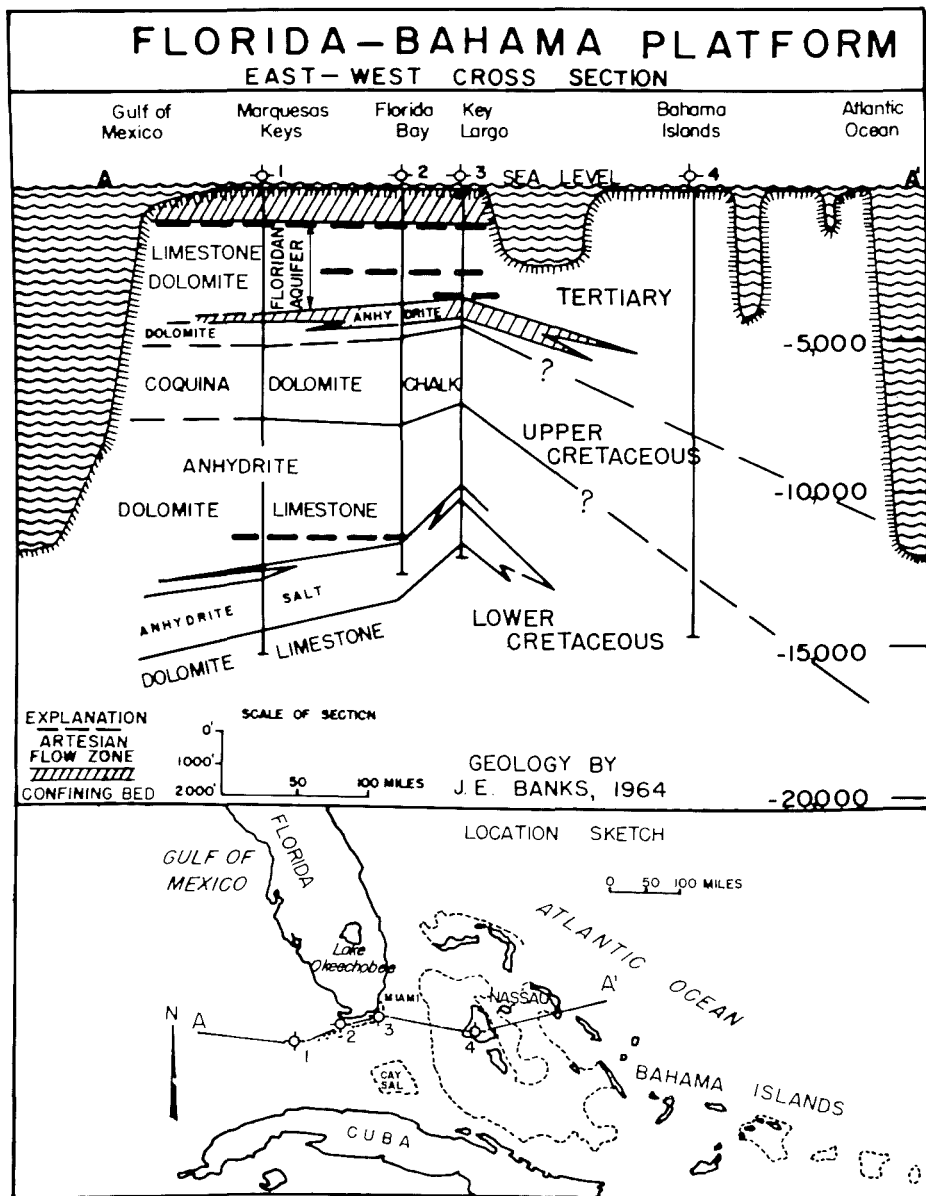


Figure 4. West-east geologic section through southern Florida and the Bahamas from the Gulf of Mexico to the Atlantic Ocean. Adapted from J. E. Banks (Ginsburg, et al., 1964, Figure 1).

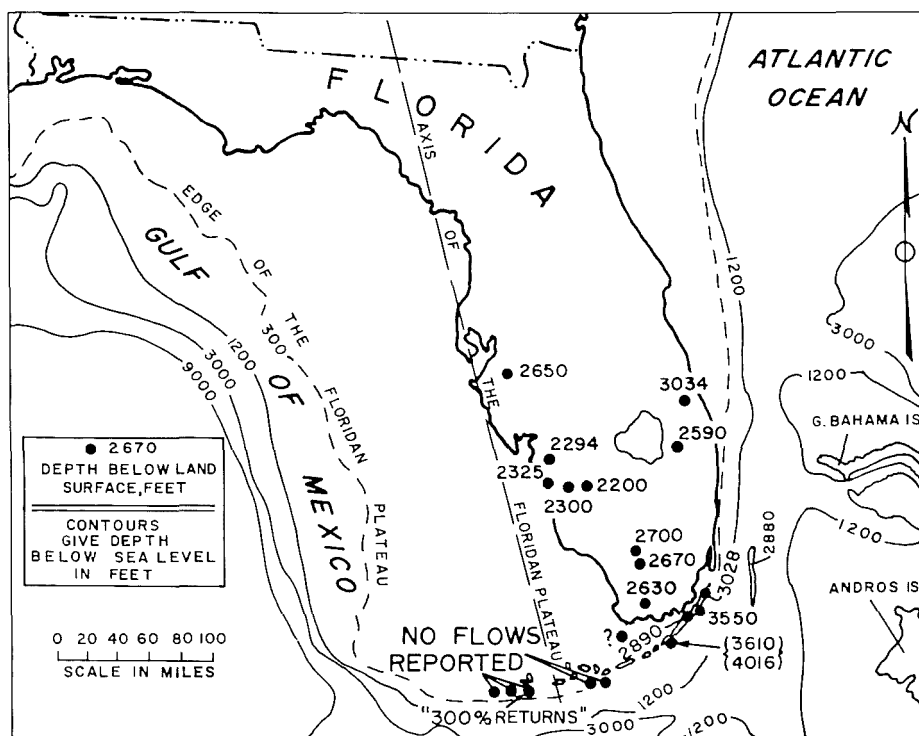
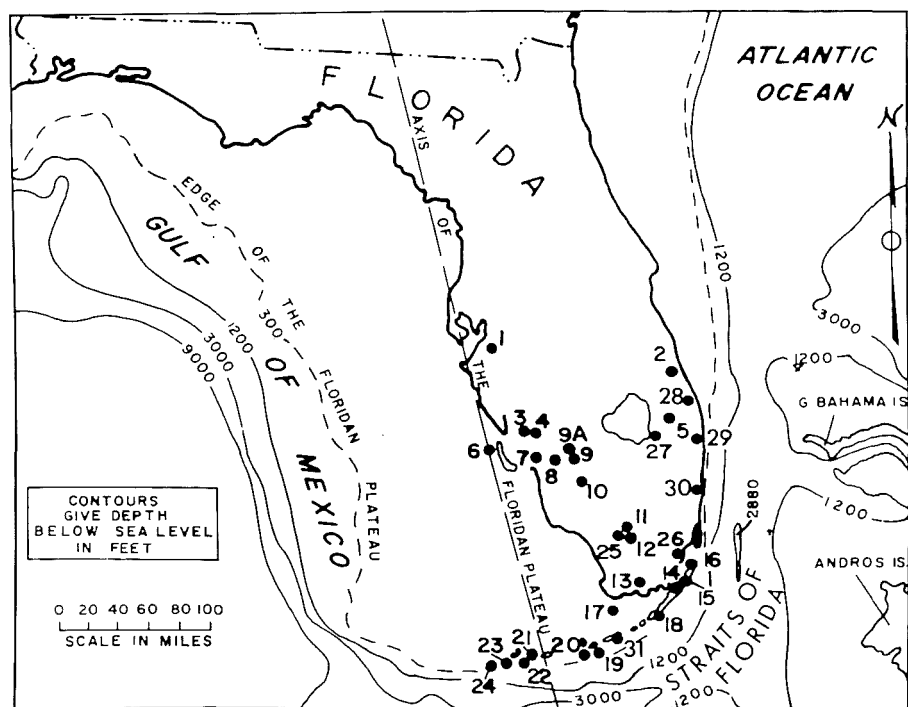


Figure 5. Depth of strong salt-water flows reported in oil exploratory wells.

Florida Bay (Well No. 17 in 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 Red Cattle 32-2 at its oil-field discovery at Felda (Fig 2), the Sun Oil Co. obtained three-dimensional borehole photographs. The photographic stereo pair taken at a depth of -2,442 ft. is shown in Figure 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 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 ft. below land surface. In the photos, the twisted-off and bent-over remnants of the drill pipe could be recognized in the clear water of the cavern. Puri and Winston (1974) describe the cavity occurrences in Red Cattle 32-2 and give additional photos. After the problems were identified



EXPLANATION

• IO

WELL LOCATION AND INDEX NUMBER

- | | |
|--|------------------------------------|
| 1 SUMNER #1 | 16 SINCLAIR—WILLIAMS |
| 2 AMERADA—COWLES MAGAZINES #1 | 17 GULF 826 G |
| 3 HUMBLE—LOWNDES—TREADWELL #1 | 18 COASTAL 363 |
| 4 GULF—STEVENS #1 | 19 CALIFORNIA CO. 1011—1 |
| 5 AMERADA—SOUTHERN STATES #1 | 20 GULF 373 |
| 6 CALIFORNIA CO. 224B—1 | 21 GULF 826Y |
| 7 HUMBLE—KIRCHOFF #1 | 22 CALIFORNIA CO. 1011—3 |
| 8 GULF—CONSOLIDATED NAVAL STORES #1 | 23 CALIFORNIA—GULF 46—1 |
| 9 SUN—COLLIER #1; 9A SUN—RED CATTLE 32—3 | 24 CALIFORNIA—GULF 44—1 |
| 10 HUMBLE—SUNNILAND FIELD | 25 SERIO #1 (S—1463) |
| 11 COMMONWEALTH—COASTAL 1055 | 26 GENERAL WATER WORKS—1 |
| 12 GULF 340—1 | PENINSULA UTILITIES CORP. |
| 13 MODEL LAND CO. 'C' | DISPOSAL WELL (GW—1) |
| 14 ROBINSON | 27 SUGAR CANE GROWERS COOPERATIVE, |
| 15 COASTAL—WILLIAMS | #2 DISPOSAL WELL (SCG—2) |
| 28 STUART, FLORIDA STP | 30 MARGATE UTILITIES AUTH. STP |
| 29 W PALM BEACH STP (PB-782) | 31 FLORIDA KEYS AQUEDUCT AUTH. |
| | DESALINATION SUPPLY (FKAA) |

Figure 6. Index map showing locations of oil exploratory wells that provided data for this report.

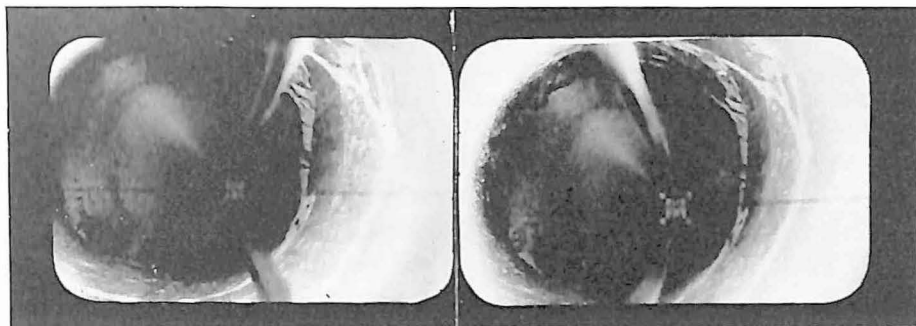


Figure 7. Stereo photograph of Boulder Zone caverns and fractures taken at 2,442 feet below land surface in Red Cattle 32-2. The length of the rods extending from the camera downward to the square light-shield is approximately 4.5 feet. Courtesy of Sun Oil Company. Photo taken by Layne Texas Company.

from the photos, new drilling techniques were devised by Mr. Bennie Franks of Sun Oil Company to cope with the Boulder Zone (Burke, 1967); subsequently, drilling time through the zone averaged about 4 days.

Cavities occur at greater depth in the Florida Keys. During drilling of the Coastal-Williams well on Key Largo (Fig. 6) a 2,000 gpm water-flow commenced shortly after a cavity from -3,490 to -3,540 ft. was penetrated (Joseph E. Banks, personal observation). From -3,510 to -3,540 ft., the cavity may have been much larger than indicated by the caliper log 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 sub-surface and surface features. 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 Mar- kel of the Reynolds Submarine Services Corp. (oral commun., July, 1967) reports that the Aluminaut deep-sea submersible lost buoyancy while investigating a small 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; Manheim, 1967).

Jordan and others, (1964) and Mulloy and Hurley (1970, p. 1970) also suggest that there may be a genetic relationship between discharge from the Floridan Aquifer and karst features (sinkholes) found on Pourtales Terrace and along the Florida Straits east of

Miami (Fig. 1). Meyer (1974) demonstrated by tidal water-level fluctuations and mathematical analysis that a cavity at -2,947 ft. in waste-injection well GW-1 at Miami, Florida, is hydraulically connected to sea water in the Florida Straits east of Miami.

INJECTION SITES IN FLORIDA

The potential beneficial uses of zones of high transmissivity in the Florida subsurface for fresh-water storage and waste disposal were described by Vernon (1970) and Garcia-Bengochea and Vernon (1970). Impetus for the development of the aquifer for these purposes was provided under U. S. Environmental Protection Agency interstate regulatory powers over discharge of industrial pollutants and sewage into surface waters. Much of the recent data about the deep part of the Floridan Aquifer resulted from requirements of several Florida State Agencies for permits to install subsurface liquid-waste disposal facilities and for documentation of disposal activities. The locations of underground waste injection systems drilled prior to late 1976 are shown in Figure 8.

The oldest site is at Sunniland (Fig. 2) where oil-field brine, produced at about 11,500 ft. below sea level, is reinjected into cavernous dolomite at about 3,000 ft. below sea level. Injection of acidic industrial waste has been observed by the U. S. Geological Survey under its Subsurface Waste Storage Program through the cooperation of Monsanto Chemical Company at Pensacola, Florida, since 1964. Papers by Barraclough (1966), Goolsby (1971, 1972), Kaufman (1973), and Faulkner and Pascale (1975) represent one of the most complete, continuing series of studies ever made concerning buildup of pressure and geochemical changes as observed in nearby monitor wells. Vernon (1970) described injection of hot, acidic waste in the Sugar Cane Growers Association well (SCG-2) at Belle Glade on the southeast corner of Lake Okeechobee (Figs. 2, 6, 8). Dissolution of dense limestone overlying the injection horizon and upward migration of the acidic wastes have been described by Kaufman and others, (1973) and Kaufman and McKenzie (1975). The deepest active injection system is at a depth of nearly 5,000 ft., 30 miles east of Tampa, Florida, where acidic, high-chloride waste is injected at the Kaiser Aluminum and Chemical Plant (Wilson, and others, 1973).

Temperature and chlorinity data collected under the supervision of J. I. Garcia-Bengochea (Black, Crow, and Eidsness, 1970, in cooperation with the Florida Bureau of Geology) during the drilling of the General Water Works-Peninsula Utilities Co. injection well

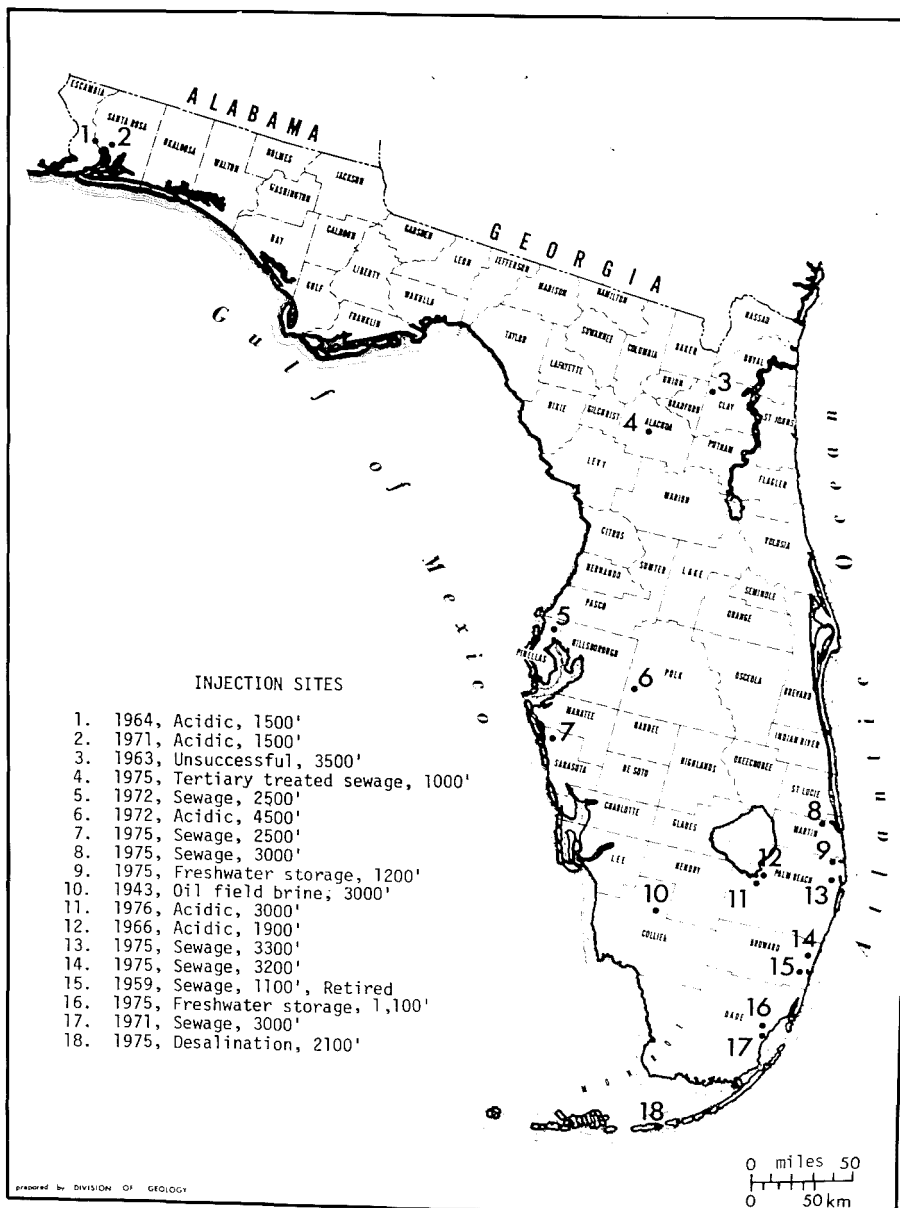


Figure 8. Location of deep injection and desalination production sites showing year of installation, type of waste or use, and approximate depth of well.

(GW-1) at Miami, Florida, are among the best collected to date and are used in a later section of this report. Temperature profiles were obtained from wells recently drilled at the West Palm Beach sewage treatment plant (STP), well PB-782, and at a test well drilled by the Florida Keys Aqueduct Authority (FKAA) for a desalination plant supply well at Marathon in the Florida Keys. These data, along with the bottom-hole temperatures at the Stuart, Florida, STP and the Margate, Florida, STP (wells 28, 29, 30, 31, Fig. 6) are the most recent data to become available (courtesy of F. W. Meyer, U. S. Geological Survey, Miami, Florida), and are used in Figures 10 and 11. Thus, temperature data obtained formerly as an incidental part of cementing casing in oil exploratory wells (see example Gulf 340-1, Fig. 10) are now being obtained as a recognized, important factor in evaluating the Floridan Aquifer for waste disposal.

THE GEOTHERMAL REGIME OF THE FLORIDAN PLATEAU VERTICAL TEMPERATURE PROFILES IN FLORIDAN AQUIFER

The first indication of an abnormal depth-temperature profile underlying the Floridan Plateau was presented by Kohout (1965, p. 264) from a survey made in Gulf-Florida State Lease 340-1 at Forty Mile Bend. The temperature curve for this well is plotted in the idealized cross-section of Figure 9 at its proper geographical position at Forty Mile Bend, 40 miles west of Miami.

Geothermal gradients of about 1°F increase per 50- to 100-foot increase in depth below 1,000 feet are commonly observed and can be considered "normal." It is noted that 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°F at a depth of -1,000 ft. at Gulf 340-1 at Forty Mile Bend (Fig. 9) and assuming the "normal" geothermal gradient, the theoretical temperature at a depth of 3,300-ft. below sea level, at the base of the permeable zone, should be between 101°F and 124°F . In contrast, the upper part of the temperature profile of Gulf 340-1 showed a slight increase to 78°F at -1,000 ft., 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 ft., and below that it decreases to 74° at -3,100 ft. This negative temperature gradient is abnormal on two counts: (1) it is contrary to the adiabatic compressional 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 due to upward heat flow from the interior of

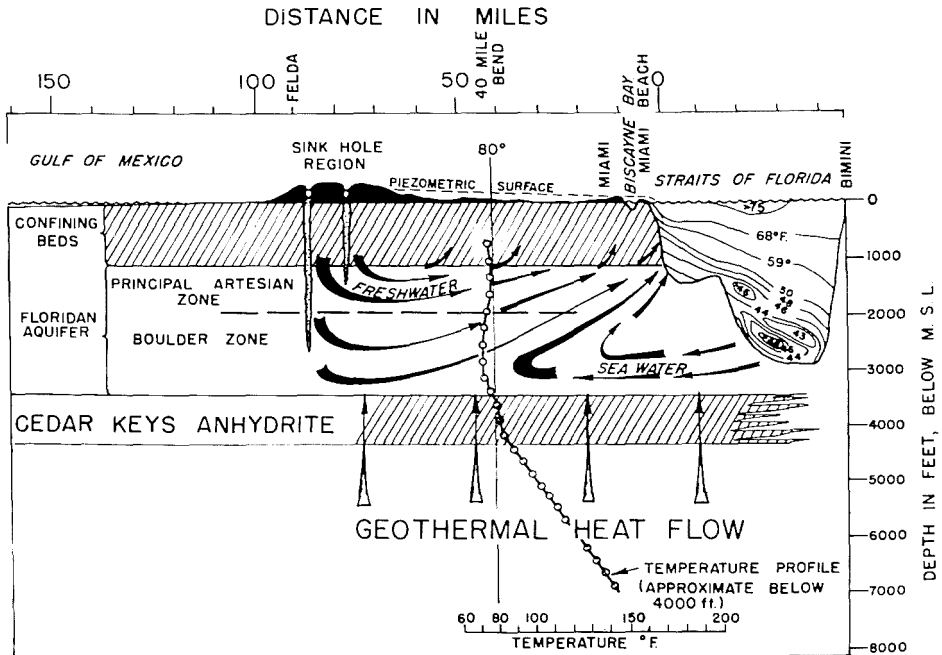


Figure 9. Idealized section through Miami showing concept of cyclic flow of seawater induced by geothermal heating.

the Earth. The isotherms in the Florida Straits (Fig. 9, 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 1965 that the negative temperature gradient at Forty Mile Bend in the Gulf 340-1 hole was related to the cold water in the Florida Straits east and south of the Florida Peninsula.

Because dolomite and anhydrite rock have about the same ability to conduct heat, it was inferred further that the contrasting thermal gradients above and below the base of the Floridan Aquifer (Fig. 10) relate to relatively rapid water movement in the aquifer as opposed to very slow water movement in the low-permeability anhydrite underlying the aquifer. 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 as the water warms eventually produces a

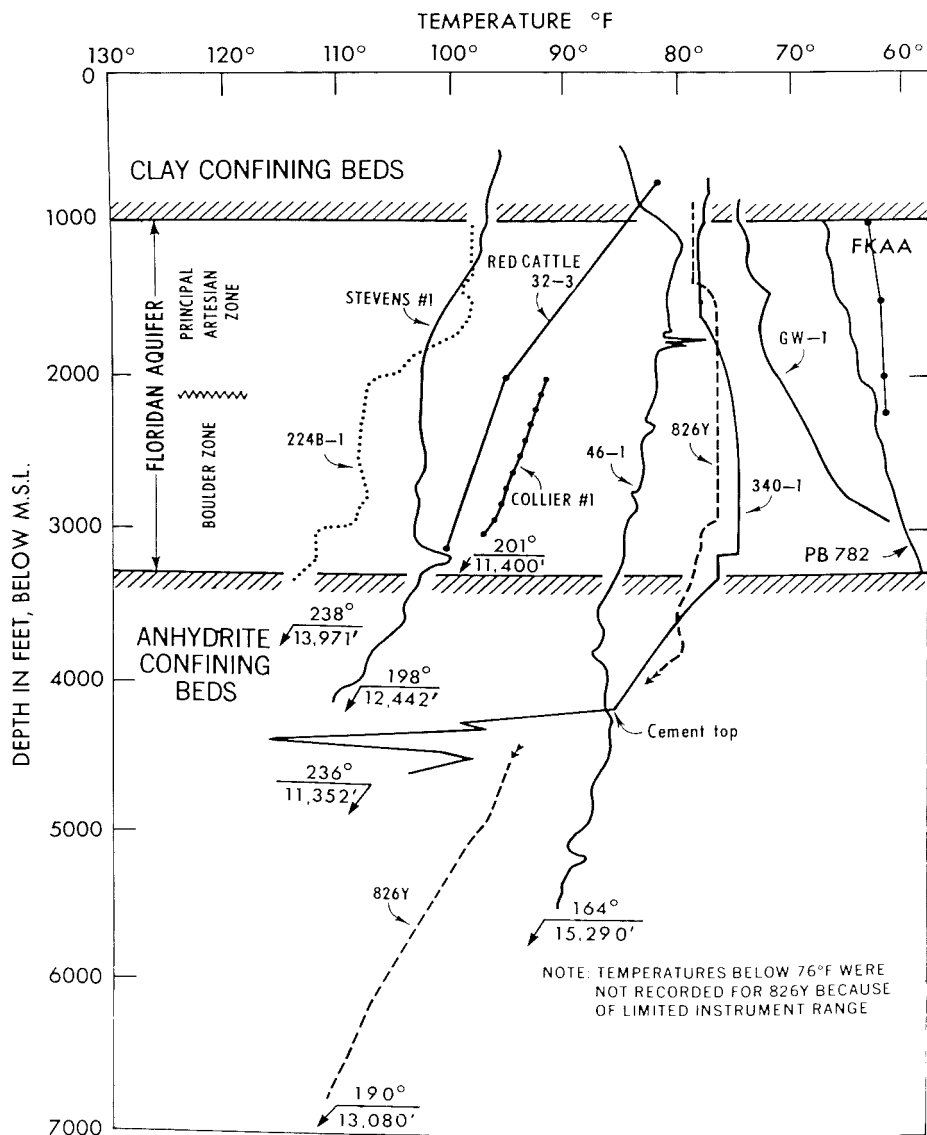


Figure 10. Graph showing temperature profiles in oil-exploratory and waste-disposal wells. See well locations in Figure 6.

thermal convection cell not unlike the familiar circulation in a teapot being heated on a stove. 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.

Vernon (1970) was critical of the temperature data and offered an alternative suggestion related to geochemical reaction whereby the cooling anomaly was involved with intensified solution of limestone and dolomitization in the freshwater-saltwater transition zone. The reader is referred to a rebuttal too extensive to be appropriate in this paper (Henry and Kohout, 1972, p. 207-212).

The curve for Gulf 340-1 is plotted along with nine additional temperature profiles in Figure 10. (See locations, Fig. 6). The temperature data for well GW-1 were collected by the reverse-rotary method of drilling, which permits the continuous collection of rock and native water samples as they are returned to the surface by upward circulation through the drill stem. The temperature decreases from 74°F at 1,000 ft. to 61°F in a cavity encountered at 2,947 ft. below sea level. The difference represents a negative thermal gradient of 13°F in a 2,000-ft. interval — a startling phenomenon in comparison to the normal positive (“textbook”) thermal gradient of about 1°F for each 50- to 100-ft. increase in depth (i.e., an increase of 20°F in 2,000 ft. would be a minimum expectation).

During 1975 additional temperature information was obtained from a test well for sewage injection at the West Palm Beach STP plotted as PB-782 and from a test well for a desalination supply well (FKAA) at Marathon in the Florida Keys. Both sites confirm that a negative thermal gradient approaching 20°F in 2,000 ft. is present in wells close to the Florida Straits. This strong negative thermal gradient (i.e., decrease in temperature with depth) should be expected only for a limited distance inland from the cold sea-water bodies. Beyond this distance, the thermal profile would be expected to become positive (i.e., warmer with depth), because the upward geothermal heat flow continually warms the sea water as it flows inland.

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. The temperature-depth correlations were selected from the profiles of Figure 10 by best judgment related to various conditions of the well when the measurements were made. For example, a temperature of 108°F at -2,800 ft. in well 224B-1 was selected in preference to a temperature of 112°F at 3,000-3,200 ft. (Fig. 10) because of the possibility that the deeper zone might have been affected by heat from the hardening

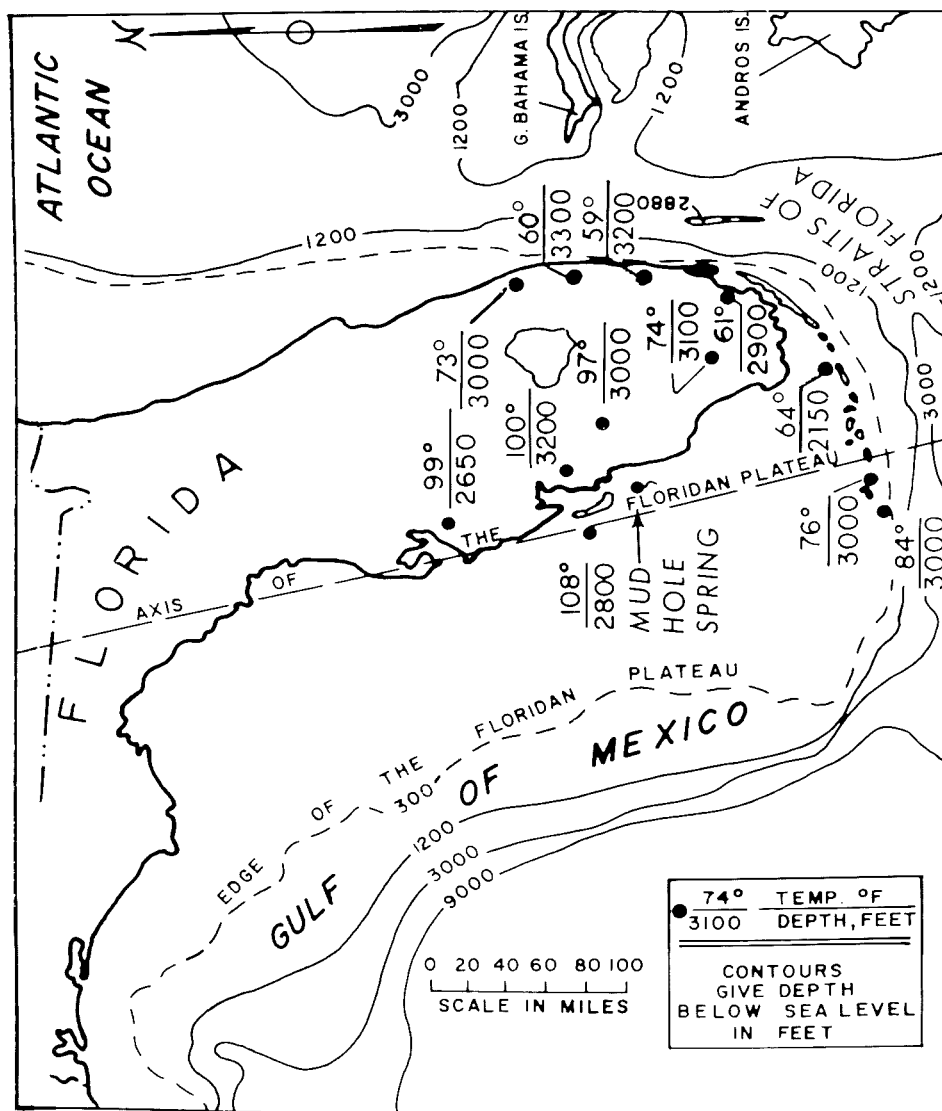


Figure 11. Map showing geographic distribution of temperature related to depth near the bottom of the Floridan Aquifer system (Boulder Zone).

cement below the aquifer base (about -3,300 ft.).

Bottom-hole temperatures obtained for sewage injection test wells at the Stuart STP and the Margate STP are also plotted in Figure 11 (complete temperature profiles not available). The Margate temperature of 59°F is the lowest of all wells and this correlates with a relative location closest to the edge of the sharp dropoff into

the deep water of the Florida Straits (indicated by the dashed edge of the Floridan Plateau, Fig. 11). The temperature at the Stuart site is relatively high and probably correlates with greater distance from the edge of the plateau (edge of Florida Straits). Lichtler (1960, Fig. 21, p. 61-63) has mapped temperatures in relatively shallow artesian wells (900-1,300 ft. deep) in Martin County (Stuart area, Figs. 6, 8), and notes that wells in the eastern part of the county (nearer to the ocean) average about 7° cooler than those in the western part of the county. The relationships are not clear but upwelling of relatively cooler water from the Boulder Zone would be a possible explanation.

The data in Figure 11 show that there is an overall increase of water temperature in the deep part of the Boulder Zone from 59°-61°F at Miami on the southeast, near the edge, to more than 108°F near the axis of the Floridan Plateau south of Tampa.

SURFACE EVIDENCE OF THERMAL UPWELLING HUMBLE-LOWNDES-TREADWELL NO. 1

Several physical examples of increased temperature near the axis of the Floridan Plateau cannot be plotted in Figure 11 because the depth from which the waters rise is not known directly. Figure 12 shows the Humble-Lowndes-Treadwell No. 1, an abandoned oil-exploratory well about 20 miles southeast of Warm Mineral Springs



Figure 12. Photograph of natural flow from Humble-Lowndes-Treadwell No. 1. Photo by D. H. Boggess, August 1966.



Figure 13. Photograph of natural flow from Humble-Lowndes-Treadwell No. 1 after development into a warm-spring spa in 1967.

(Fig. 2), flowing at a reported rate of 7,000 gpm in August 1966. The chloride content of the water was 18,700 mg/l, which is close to the concentration in sea water (about 19,000 mg/l); the temperature of the water was 96°F. In 1967, the well was developed into a warm-spring spa (Fig. 13), demonstrating how quickly a new conceptual application changed the seemingly worthless saline-water flow into commercial value (Kohout, 1970, p. 1446).

The depth from which the water originates is not known, but the temperature of 96°F is close to the 100°F temperature in Stevens No. 1, located about 10 miles to the east (Figs. 10, 11). The high chlorinity suggest that the water originates very deep in the Boulder Zone.

WARM MINERAL SPRINGS SINKHOLE

Warm Mineral Springs (Figs. 2, 14) is a commercially developed spa. The lake is actually a sinkhole about 250 ft. in diameter at the surface and more than 200 ft. deep. The sink was originally named "Warm Salt Springs" or "Big Salt Springs" (Parker and Cooke, 1944, p. 32-35; Ferguson, et al., 1947, p. 148). Discharge through an



Figure 14. Oblique aerial photograph of Warm Mineral Springs sinkhole, a commercially developed spa. White spots in Lake are bathers. Overflow stream is at upper left corner of photo. Photo courtesy of William R. Royal.

outflow creek has been measured periodically over the years by the U. S. Geological Survey at 7 to 11 cfs (cubic feet per second).

Warm Mineral Springs sinkhole is unusual compared to most Florida sinks because warm, hydrogen-sulfide-rich saline water flows upward from depth. Stalactite-hung caves at 20-45 ft. bpwl (below present water level) were occupied by humans during lowered sea level of the glacial Pleistocene Epoch. The high H_2S content (no oxygen) is a probable factor in the excellent preservation of the human bones which have been dated by carbon-14 analysis of surrounding leaf material at about 10,000 years before present (Royal and Clark, 1960, p. 286; Clark, 1969, p. 175-176; Clausen et al., 1975).

The sinkhole has been investigated by SCUBA divers. All walls overhang to form a cathedral-shaped cavity about 400 ft. in diameter near the bottom. In the north wall, at a depth of 215 ft., saline water with a temperature of 90°F discharges from a cave. Flow through the cross-section area shown in Figure 15 was measured by using fluorescein dye as a tracer over a measured distance of 15 linear ft. along the tunnel. The velocity of the water was about 1 fps (foot per

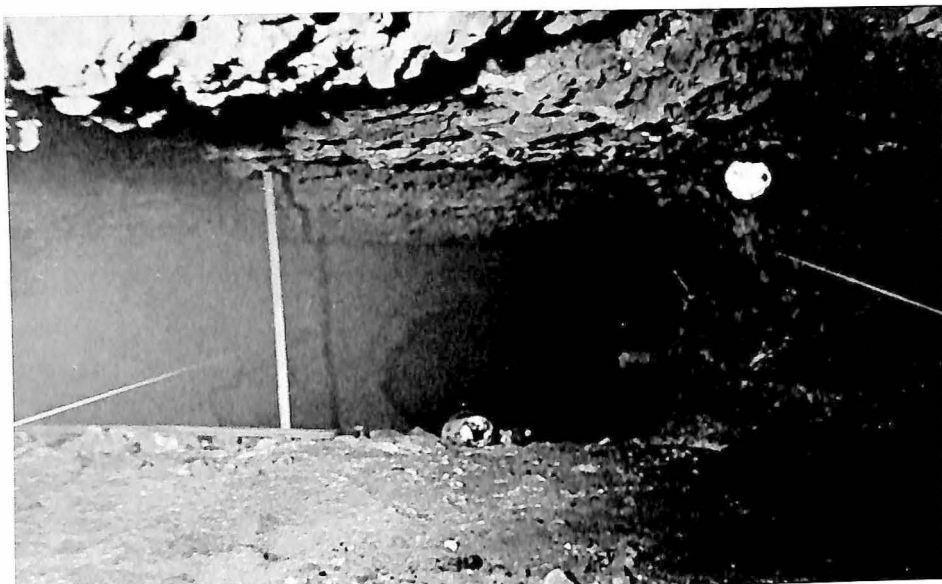


Figure 15. Underwater photograph of cave cross section through which discharge was measured by using fluorescein dye as a tracer. Size of cross section can be judged from a 3-ft measuring stick extending from floor to roof and a 5-ft surveyor's rod extending left from meter stick. Ropes tied off on rock projections enter picture from left and right. White object at right side of photo is a polystyrene ball floating against roof for a marker buoy. Photo by William R. Royal.

second) (W. R. Royal, oral commun., November 22, 1971). Thus, about 30 cfs of warm salt water entered the main sinkhole through this cave. The flow is variable, however; at the end of a very dry season in May, 1974, the discharge from the cave was greatly reduced. A velocity of possibly 0.1 fps at the cave mouth measured with fluorescein by Kohout was inconclusive for determining discharge.

In October, 1973, a sampling hose was carried deep into the cave to minimize contamination from shallow, fresh ground water which enters at various levels in the main sinkhole. A large sample of water was collected for tritium, carbon-14, and uranium-isotope analysis. Tritium concentration was negligible indicating that the discharge emanating from the cave comes primarily from the Floridan Aquifer (i.e., a tritium component would indicate that shallow ground water had been mixed into the warm water rising from the Boulder Zone). The carbon-14 analysis (F. J. Pearson, U. S. Geological Survey, written commun., 1976) indicates that a maximum of 4% of modern water might be present in the blend. The water cannot be age-dated because the end-point source waters that are present

in the blend are not known, either as to original carbon-14 content or salinity. The fact that the water exiting from the cave has a temperature of 90°F strongly suggests that the source is relatively deep in the Boulder Zone (see temperature profile for Gulf-Stevens No. 1 located about 10 miles east of Warm Mineral Springs, Fig. 10). The water undoubtedly cools to some extent during its rise from depth; also, the presence of 4‰ modern water indicates that the blend contains an admixture of ground water (possibly fresh) from the Principle Artesian Zone or possibly a small admixture from shallow aquifers in the 200-500 ft. depth range. In any case, the source-water deep in the Boulder Zone would necessarily have a higher temperature and a higher salinity than the water which we are able to measure in the cave (before its entry into the main sinkhole). We have no way to give better quantitative information but it is clear that warm salt water has sufficient head to flow into the sinkhole where the water level is maintained by an overflow dam at about 5 feet above sea level.

This upwelling of warm saline water appears to be another example of the discharge of geothermally heated water along the central axis of the Floridan Plateau. Also, Kaufman and Dion (1967, Fig. 11) have mapped a zone of high-temperature saline water in wells tapping the relatively shallow part (-1,200 ft.) of the Floridan Aquifer along the Peace River 30 miles northeast of Warm Mineral Springs.

THE MUD HOLE SUBMARINE SPRING

A submarine spring (Kohout, 1966) located about 12 miles off the southwest shore of Florida (Fig. 11) has been an important fishing spot for local fishermen for many years. The spring (Fig. 16) was explored recently by SCUBA diving. It was discovered that the discharge was taking place from a sink-like depression about 200 ft. in diameter at a maximum depth of about 65 ft. below sea level. The bottom consists of grey silt and mud, warm to the touch when the hand is pushed a few inches under the surface. Under the slime and mud, the bottom consists of sand and limestone gravel. When the bottom is disturbed, clouds of mud are thrown into suspension and seepage increases; this probably accounts for the name "Mud Hole" (name used by local fishing captains, Munson, 1961).

Prominent orifices occur at several points. The temperature of the water from each of these orifices was measured with a human fever thermometer at 96.6°F. A birefringent (heat-wave) mixing plume extends about 5 ft. above the orifice. The diver's vision is blurred in this mixing plume but upon penetrating into the orifice,

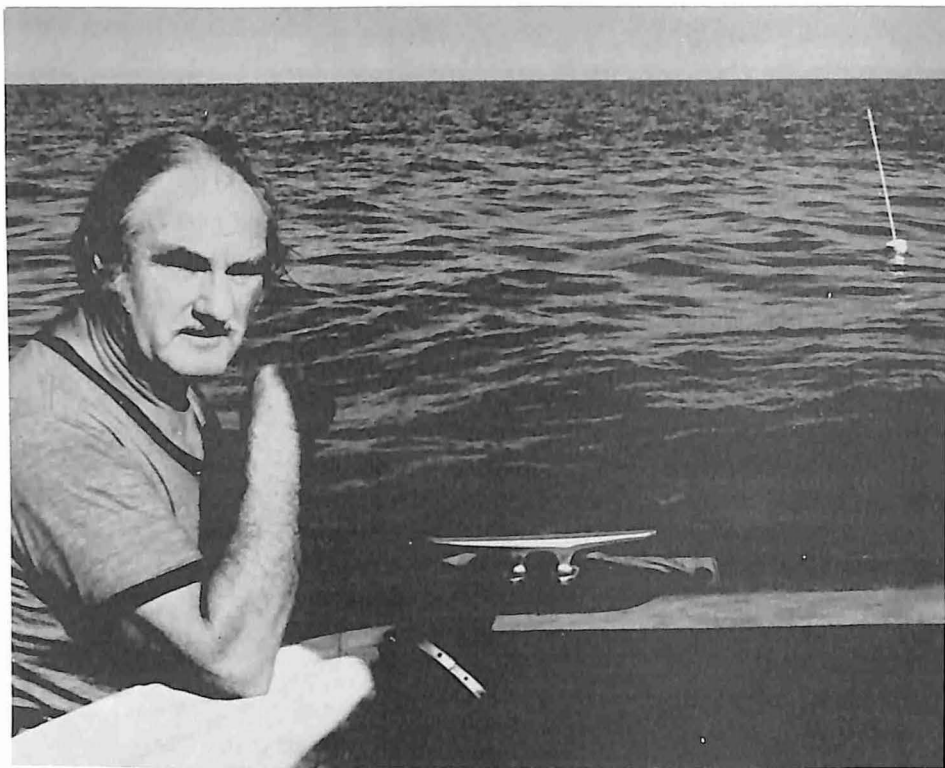


Figure 16. Photograph of surface slick produced by upswelling of warm seawater at the Mud Hole submarine spring, Oct. 26, 1972.

vision becomes dramatically clear; the lower part of Figure 17 demonstrates this observation. In comparison to the cool sea water, the outflowing spring water is sufficiently warm to cause apprehension.

The velocity of the water was estimated at 2 fps from debris moving through the orifice (3 ft. x 1 ft.), half visible in Fig. 17. The discharge is thereby estimated at about 6 cfs. The total discharge from the whole depression is much larger than this but estimates are not possible at this time. However, the Energy Research and Development Administration (ERDA) has provided a grant to further define the discharge, chemistry, and thermal aspects of the spring (Thomas E. Pyle, University of South Florida, Department of Marine Sciences, Oral commun., 1976).

The concentration of major ions is about the same as that of sea water, e.g. chloride 19,000 to 20,000 mg/l on several samplings. A large volume sample was collected by inserting 400 ft. of garden hose



Figure 17. Photograph of one of the orifices in the sink-like depression of the Mud Hole submarine spring. Turbulent mixing zone above changes to clear discharge where water of 96.6°F exits toward reader from orifice. Handheld camera at left indicates scale of photograph.

with taped joints into the orifice and pumping water into three 15-gallon drums on board the anchored survey boat. Tritium content was 0.4 ± 0.2 TU (F. J. Pearson, U. S. Geological Survey, 1976) indicating the possibility of contamination from the surrounding sea water. Carbon-14 analysis indicated that a maximum of 17% of modern sea water might have been mixed into the discharging water.

The temperature represents *prima facie* evidence that the water comes from considerable depth. If 17% of cool sea water (estimated at a maximum of 70°F for bottom water in the area) was mixed with 83% of warm spring water of unknown temperature to yield a 100% blend of water measured at 96.6°F, a simple calculation can be made:

$$\begin{aligned}
 0.17(70) + 0.83T &= 1.00(96.6) \\
 T &\approx \frac{96.6 - 0.17(70)}{0.83} \\
 T &= 102.1^{\circ}\text{F}
 \end{aligned}$$

The calculation suggests that water rising up from depth in the aquifer might be expected to exceed 102°F . The temperature profile in well 224B-1 (Fig. 10, 11), located in the general area of the Mud Hole submarine spring, lends credence to this possibility.

Sea-level head exists along all shorelines of the Florida peninsula. Therefore, although Figure 9 implies complete recycling of the inflowing warmed sea water to the eastern Florida Straits, it would be possible for cold sea water to enter the Floridan Aquifer where it is truncated at depth by the eastern and southern Straits of Florida, and then to flow entirely beneath the above-sea-level part of the Floridan Plateau toward discharge points along the west coast of Florida. Though no wells have been drilled far out on the western part of the plateau, presence of the cavernous Boulder Zone and truncation by deep water in the Gulf of Mexico might also permit eastward flow of sea water toward the central axis of the plateau. The Mud Hole submarine spring may be evidence of upwelling from the western or southern hydraulic boundaries as well as from the eastern boundary in the Straits of Florida.

HYDRAULIC AND MATHEMATICAL MODEL STUDIES

Three sets of gradients control ground-water movement: the hydraulic-pressure gradient, the geothermal gradient, and the salt-concentration gradient. In thick aquifers, interaction of these gradients induces gravity convection currents. Under a grant from the U. S. Geological Survey, the University of Alabama investigated the mechanics of flow in deep saline aquifers affected by geothermal heating (Henry and Kohout, 1972; Henry and Hilleke, 1972). The study was for the purpose of determining theoretically whether patterns of flow or circulation exist in the deep parts of such aquifers which cannot be inferred from the piezometric gradient (as is shown in Figure 3 for the upper Floridan Aquifer), but which might be significant in leading to undesirable movements of liquid wastes injected into these regions. Mathematical prediction of the direction and rate of movement of the native water and the entrained waste is the ultimate goal. However, the results are pertinent to considerations of the influence of ground-water flow on geothermal heat flow and visa versa. The above reports are summarized herein but the reader is referred to the original papers for the mathematical support. The above reports are summarized herein but the reader is referred

to the original papers for the mathematical support.

The investigations consisted of experimental measurements on a hydraulic model of the Floridan Aquifer and theoretical analyses of the system based on solutions of the governing differential equations. The hydraulic model yielded temperature distributions, salinity distributions, and flow patterns which were used for qualitative comparison with field conditions and with theoretical solutions. These comparisons established the validity of solutions of the governing equations which were then utilized for prediction of temperature, salinity, and flow distributions for comparison with field conditions.

The two-dimensional hydraulic model made of sand was built to simulate some aspects of the Floridan Aquifer. Systems were provided for supplying fresh-water recharge at ambient temperature (approximately 70°F) and for maintaining a constant concentration of salt water in the simulated ocean at approximately 43°F. Heating pads were installed on the bottom and fresh-water end of the model to simulate the geothermal heating which occurs in the field. The physical dimensions of the simulated sand aquifer were 6 inches in width, 12 ft. in length, and 3 ft. in depth. The corresponding length and depth of the aquifer in the field are approximately 167 miles and 2,500 ft., respectively.

COMPARISON OF THEORETICAL AND FIELD STUDIES

The kinds of field data of particular interest for comparison with theoretical studies are the temperature and chloride concentrations obtained at various depths from drilling records. Information on pressure-head distribution is only available from wells near the top of the Floridan Aquifer (Fig. 3), and data that would permit determination of flow direction in the deep, Boulder-Zone part of the aquifer are non-existent.

The section line shown in Figure 18 is positioned to take advantage of the largest amount of field data presently available. Figure 19a was obtained by translocating the temperature data of Figure 10 to an appropriate position along the section line of Figure 18. The theoretical isotherms for one set of variables (Henry and Hilleke, 1972, Fig. 28) are plotted for comparison (Fig. 19b). In the deep part of the aquifer, the isotherms in both diagrams are displaced inland and form a concave seaward pattern. This concavity strongly suggests that cold ocean water moves inland in the deeper part of the aquifer. Other evidence related to uranium isotope ratios (Osmond and Cowart, this volume) support this indication of inland flow.

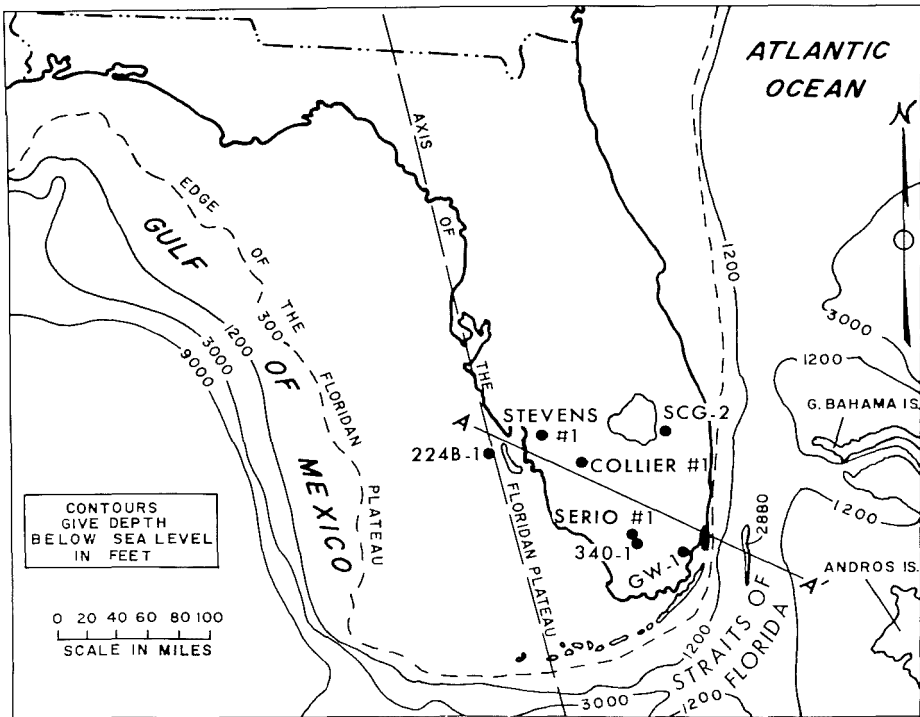


Figure 18. Map showing section line and locations of wells used in Figures 19 and 20.

In Figure 20, the theoretical field isochlor pattern is compared with the few chloride data that have been obtained from wells tapping both shallow and deep parts of the Floridan Aquifer. The sparse data were collected mostly as blends of water from long sections of open hole, rather than as point sources of water from a specific depth. Nevertheless, there is correspondence to the calculated chlorinity pattern of Figure 20b.

As previously noted, sufficient synoptic pressure-head data from wells tapping the deep, saline part of the aquifer are non-existent and direction of water movement in these regions cannot be deduced directly from field measurements. In lieu of this, the hydraulic laboratory model studies and the mathematical solutions applied to the Floridan Aquifer as a field model demonstrate a remarkable similarity of temperature and chloride distribution. Confidence, then, can be placed in solutions of streamline pattern as shown in Figure 21. This model assumes, however, that a hydraulic boundary represented by recharge of fresh water exists at the inland end of the model. The

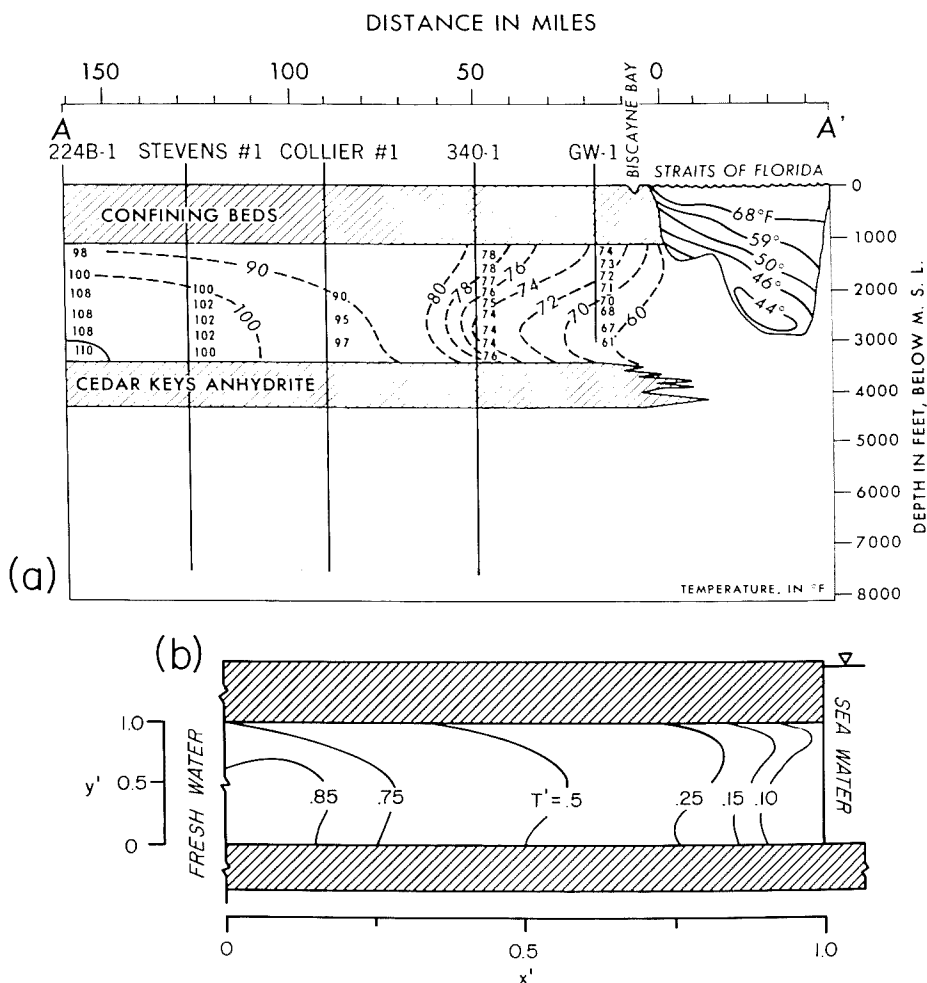


Figure 19. (a) Temperature distribution in Floridan aquifer system.
 (b) Theoretical field isotherms for variables $N_c=10$, $N_\phi=3$, $N_T=1$
 (After Henry and Hilleke, 1972, Fig. 28, for aquifer 167 miles long and 2,500 feet thick).

The dimensionless units for temperature have the following equivalents: 1.00 = 110°F, 0.85 = 100°F, 0.75 = 93°F, 0.5 = 75°F, 0.25 = 58°F, 0.15 = 51°F, 0.1 = 47°F, 0.0 = 40°F.

field situation is more complicated than this because, in fact, sea-level head exists along all shorelines of the Florida peninsula. Cold sea water can enter the Floridan Aquifer at depth where it is truncated by the eastern Straits of Florida, and then flow entirely beneath the peninsula toward shallow discharge points along the west coast of Florida. The warm, saline effluents at Warm Mineral Springs sink-hole and the Mud Hole submarine spring are field evidences that

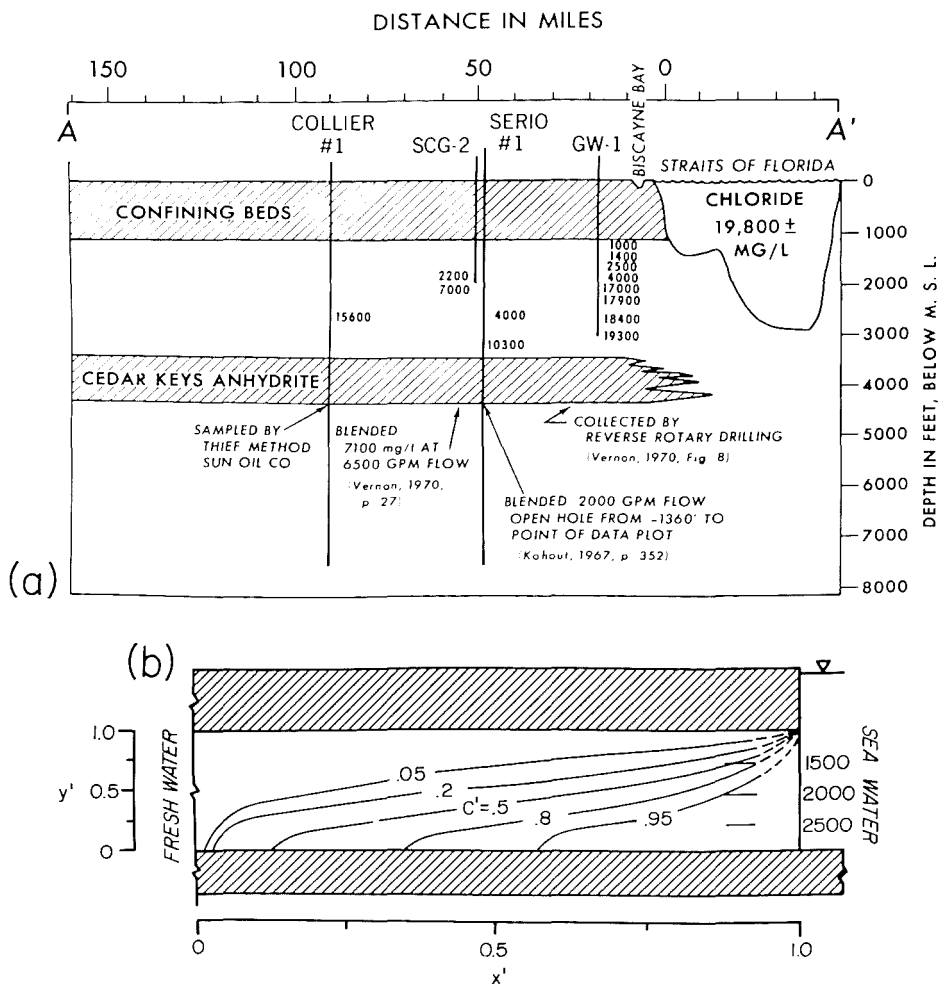


Figure 20. (a) Chloride distribution in the Floridan aquifer system. (b) Theoretical field isochlors for variables $N_c = 10$, $N_\phi = 3$, $N_\tau = 1$ (After Henry and Hilleke, 1972, Fig. 26, for aquifer 167 miles long and 2,500 feet thick).

The dimensionless units for chloride have the following equivalents in mg/l: 0.00 = freshwater, 0.05 = 990, 0.2 = 3,960, 0.5 = 9,900, 0.8 = 15,840, 0.95 = 18,810, 1.00 = 19,800.

such circulation exists.

THE DOLOMITE QUESTION AND CAVITY FORMATION

Though seemingly remote to the subject matter of this volume, continuous chemical diagenesis of the limestone matrix of the Floridan Aquifer may be involved with the geothermally-motivated cyclic

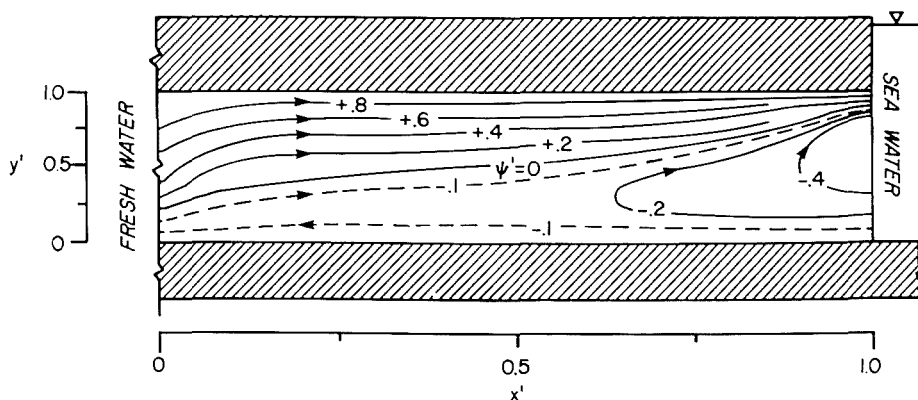


Figure 21. Theoretical streamlines for variables $N_c = 10$, $N_\phi = 3$, $N_r = 1$ (After Henry and Hilleke, 1972, Fig. 27, for aquifer 167 miles long and 2,500 feet thick).

flow of sea water. The amount of dolomite that is present in the geologic column worldwide continues as one of the enigmas of carbonate geochemistry (Fairbridge, 1957; Bathurst, 1971) because dolomite has not yet been synthesized under laboratory conditions that are characteristic of sedimentary environments (Deelman, 1975, p. 471). Hanshaw, Back, and Deike (1971, p. 710) point out that although the oceans are at or beyond saturation with respect to pure calcite and dolomite, modern marine sediments are composed primarily of aragonite, high-magnesium calcite, and low-magnesium calcite. Concerning the source of magnesium ion for dolomite underlying the Florida Platform, they succinctly state:

"Mass balance calculations by Hsu (1963) indicate that simply moving magnesium ions (obtained from high-magnesium calcites) from the recharge area to a downgradient area cannot dolomitize a significant portion of the Floridan Aquifer. Our mineralogic studies concur with this; there is obviously insufficient magnesium from magnesium calcites available today to accomplish widespread dolomitization."

Puri and Winston (1974, p. 56) in discussing the origin of cavities in the Floridan Aquifer state:

"Dolomitization is critical to the formation of the cavities, as all cavities occur in dolostone. All hypotheses stand or fall on the time of dolomitization. So far, there is no evidence to conclusively prove when this took place.

Previously expressed hypotheses include those of Vernon (1947, 1951, 1970) and Kohout (1965), and Hanshaw, Beck and Dieke (1971).

Vernon (1970) proposed a geochemical reaction that follows the mixing of two bodies of water that contrast in concentration of salts. The interface is the locus of dolomitization and of an intensified solution and removal of solids.

Kohout proposes a convection current, generated by geothermal heating of sea water freshly intruded into the high transmissivity zone from the rock outcroppings in the Straits of Florida at the east, south, and west sides of the Floridan Plateau. Dolomitizing magnesium-rich water is thus continuously circulated into the aquifer to provide the magnesium for continuous dolomitization.

A geochemical hypothesis for dolomitization by ground water was offered by Hanshaw, Back, and Deike (1971). Their study was based on chemistry of the Floridan ground water and the mineralogic composition of the artesian aquifer. They observed that there was a systematic change in the magnesium to calcium ratio from 0.5 in the potable water to 1 from the recharge area down-gradient into the deeper part of the aquifer system. They examined stable carbon isotope composition of calcite-dolomite and found that the calcite δC^{13} composition is always that of normal marine limestone; however, the δC^{13} of the associated dolomite was not formed under marine conditions but was formed under the effect of ground water, perhaps saline.

From our incomplete data in this study, we observed that the base and top of cavity zones in cores are usually bounded by peaty partings, or other impediments to vertical migration of fluids. The dolomitizing fluids then were forced to spread laterally, creating the horizontally oriented cavities and zones of cavities."

In contrast to the above references to inadequate supply of magnesium for dolomitization, the cyclic flow mechanism can occur purely by dispersion of salt as in the Biscayne Aquifer of the Miami, Florida area or as postulated here, by dispersion of salt augmented by convection from geothermal heat flow as in the Floridan Aquifer. The possibility therefore exists as noted by Folk and Land (1975) for continuous dolomitization and continuous formation of voids below sea level, as well as by the commonly recognized mode of above-sea-level solution. One may even speculate that the orientation of the cavities may not be completely horizontal as implied in the above quotation from Puri and Winston (1974). Although horizontally oriented in a localized sense, the flow of sea water from the edge of the deep sea-water bodies must also have a vertical upward component because of the convective circulation. Assuming contemporaneous continuing dolomitization to be a valid process, intergranular flow initiated by geothermal heating in a homogeneous, isotropic limestone matrix could be expected to ultimately superimpose a system of dolomite-lined voids and cavities on the original layer of rock. The cavities would form a pattern that would duplicate the original streamline pattern of the hydraulic flow. Indeed, the creation of the first voids would increase the permeability of the matrix, thus increasing the rate of flow of the dolomitizing fluids, and in turn augmenting cavity formation. The diagenetic change should be a self-perpetuating, accelerating phenomenon. In geologic time, changes

of sea level, natural differences in the original sedimentation, structural movement, collapse of caverns, etc., would provide great variability. However, Puri and Winston (1972, p. 3) note that "cavities tend to rise stratigraphically away from the Florida Straits in a northerly direction." Also, it is interesting to note that the deepest flows in Figure 5 occur in the Florida Keys adjacent to the Straits of Florida at depths of 3,500 to 4,000 ft. The occurrence of strong salt-water flows as reported during drilling becomes progressively shallower toward the central axis of the Floridan Plateau to a depth of about 2,300 ft., representing a rise of over 1,000 ft. relative to the Florida Keys. No evidence exists that these cavern systems are interconnected — but can the above hydrologic and geologic evidence be entirely circumstantial and misleading?

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 10, 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 Floridan Aquifer. The data suggest that the heat sink formed by cold water in the Gulf of Mexico at depths of about 12,000 ft. (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 ft. in California 46-1, nearest to the Gulf of Mexico, is about 74° cooler than the 238° temperature in well 224B-1 near the central axis of the Floridan 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 basins. Other papers in this volume give detailed consideration to geothermal gradients and heat-flow in beds underlying the Floridan Aquifer (also see Reel and Griffin, 1971).

SUMMARY

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

From about 1,500 ft. to 3,000 ft. below sea level the ground water in the Floridan Aquifer system becomes colder with depth. In the horizontal direction, the average temperature at -3,000 ft. increases from about 60° near the cold sea-water bodies to more than 108°F along the central axis of the Floridan Plateau. The water at these same depths approximates the salinity of sea water as evidenced by samples obtained during drilling of waste injection wells along the east coast of Florida. Mathematical and laboratory model studies indicate that the anomalies may be caused by a geothermal convection cell which causes 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. The convective circulation in the deep part of the aquifer should be eastward from the Gulf of Mexico and northward and westward from the Straits of Florida. The focal point for this deep sea-water flow, and the hottest water, should occur along the central axis of the Floridan Plateau (Fig. 1), farthest from the cold sea-water bodies. The Mud Hole submarine spring which discharges warm sea water from a sink-like crater about 65 ft. below sea level off the west coast of Florida (Fig. 11) provides field evidence that the convective flow cell exists.

In the low-permeability rock below the Floridan Aquifer system, 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 Floridan Plateau, as deep as 15,000 ft. below sea level, the temperature regime is modified by lateral heat flow to cold sea-water circulating through the adjacent ocean depressions.

The possibility of cyclic circulation of cold sea water into permeable carbonate rocks underlying the Florida-Bahama Plateau has practical importance because the coolness may represent a fundamentally important control on the occurrence of hydrocarbons—i.e., the temperature of the rocks may have been too low except in specific places to convert organic matter to oil and gas (Reel and

Griffin, 1971). Subsequent papers in this volume give consideration to these problems.

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**HEAT FLOW IN FLORIDA OIL TEST HOLES
AND INDICATIONS OF
OCEANIC CRUST BENEATH THE SOUTHERN
FLORIDA-BAHAMAS PLATFORM¹**

By

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¹ Based on research performed in the Geology Departments of the University of Florida and the University of South Florida. The financial assistance of Cities Service Oil Co., Texaco Inc., and Coastal Petroleum Co. is sincerely appreciated as is the personal assistance of Mr. Joseph E. Banks of Coastal Petroleum Co.

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ABSTRACT

Heat-flow was determined for three deep oil-test holes, yielding values of 0.71 and 0.76 HFU for south Florida and 0.92 HFU for north Florida. Both the magnitude and trend of the values are similar to those previously known for the eastern Gulf of Mexico. The very low heat flow of the southern part of the peninsula supports the concept that oceanic crust, with very low heat generating potential, underlies the southern part of the Florida-Bahamas Platform.

INTRODUCTION

By 1968, a moderate number of heat-flow values had been published for the marine areas of the Gulf of Mexico and northwestern Caribbean Sea (Epp et al., 1970; Langseth and Grim, 1964). Four measurements in the deep eastern Gulf averaged 0.88 HFU, indicating below-average heat flow for the region as a whole. Individual values increased from 0.7 in the southeastern Gulf to approximately 1.0 in the northeastern Gulf. If extrapolated across the untested continental shelf and coastal plain of Florida, Georgia, and Alabama, this trend appeared to continue northward into the continent, where values of 0.95, 1.02, 0.97, and 1.00 (avg.=0.99 HFU) had been reported in the Piedmont of Alabama, Georgia, and South Carolina (Lee and Uyeda, 1965; Roy, et al., 1968).

Remarkably, in 1968 no published heat-flow measurements existed for any of the land areas surrounding the eastern Gulf or northwestern Caribbean, including the Florida-Bahamas Platform, Cuba, and Yucatan. Therefore, between 1968 and early 1971, we partially filled this gap with the measurements reported herein for three deep oil-test holes.

The methods used in this study are detailed in the appendix. Generally, thermal gradients were calculated from the "maximum" or "bottom-hole" temperatures recorded on electric log headings. Thermal conductivities of well samples were determined in one hole by the Beck (1957) divided-bar method. In the other two holes, published relationships between lithology, porosity, and thermal conductivity were used to estimate the conductivity parameter of the heat-flow equation.

RESULTS AND DISCUSSION

The heat flow measurements and related data resulting from this project are listed in Table 1 and plotted on Figure 1, where all other heat flow values known to exist for the region at the time of completion of our experimental work are also indicated. The values resulting from this project suggest that heat flow is least in the southern part of the Florida Peninsula (0.71 and 0.76 HFU) and increases toward north Florida (0.92 HFU). The general trend on the land therefore parallels the previously known trend in the offshore part of the region and is similar in magnitude. The principal point of interest is the very low heat flow through south Florida and the adjacent part of the eastern Gulf of Mexico.

As Roy et al., (1968) have pointed out:

$$Q = a + bA \quad (\text{eq. 1})$$

where:

Q = total heat flow,

a = the fraction of heat flow produced by transfer from the lower crust and upper mantle, = 0.79 HFU in the eastern United States,

b = the depth of radiogenic sources of heat in the upper crust, = 7.5 km in the eastern United States, and

A = heat produced by radioactive crustal rocks at a depth of b .

Recalling that the average value for the two boreholes in south Florida is $Q = 0.735$ HFU, the observed heat flow is entirely accounted for by that portion produced by conductive transfer from the lower crust and upper mantle. That is, in south Florida:

$$Q \approx a,$$

and the contribution to heat flow by upper crustal radioactive sources is negligible, i.e.:

$$bA \approx 0$$

The implication from this is that south Florida is underlain by oceanic crust in which the heat-generating potential is quite low when compared to sial (approximately one-sixth). Such an interpretation is consistent with the continual subsidence of the area, which over its approximately 150 million year (age from Khudoley, 1967) history of sedimentation is calculated to average 200 ft. per million years at Cay Sal Bank, its southern tip.

Dietz et al. (1970) have previously postulated from other types of geophysical evidence that the Bahama Platform is underlain by oceanic crust, an hypothesis agreed to by Uchupi et al. (1971).

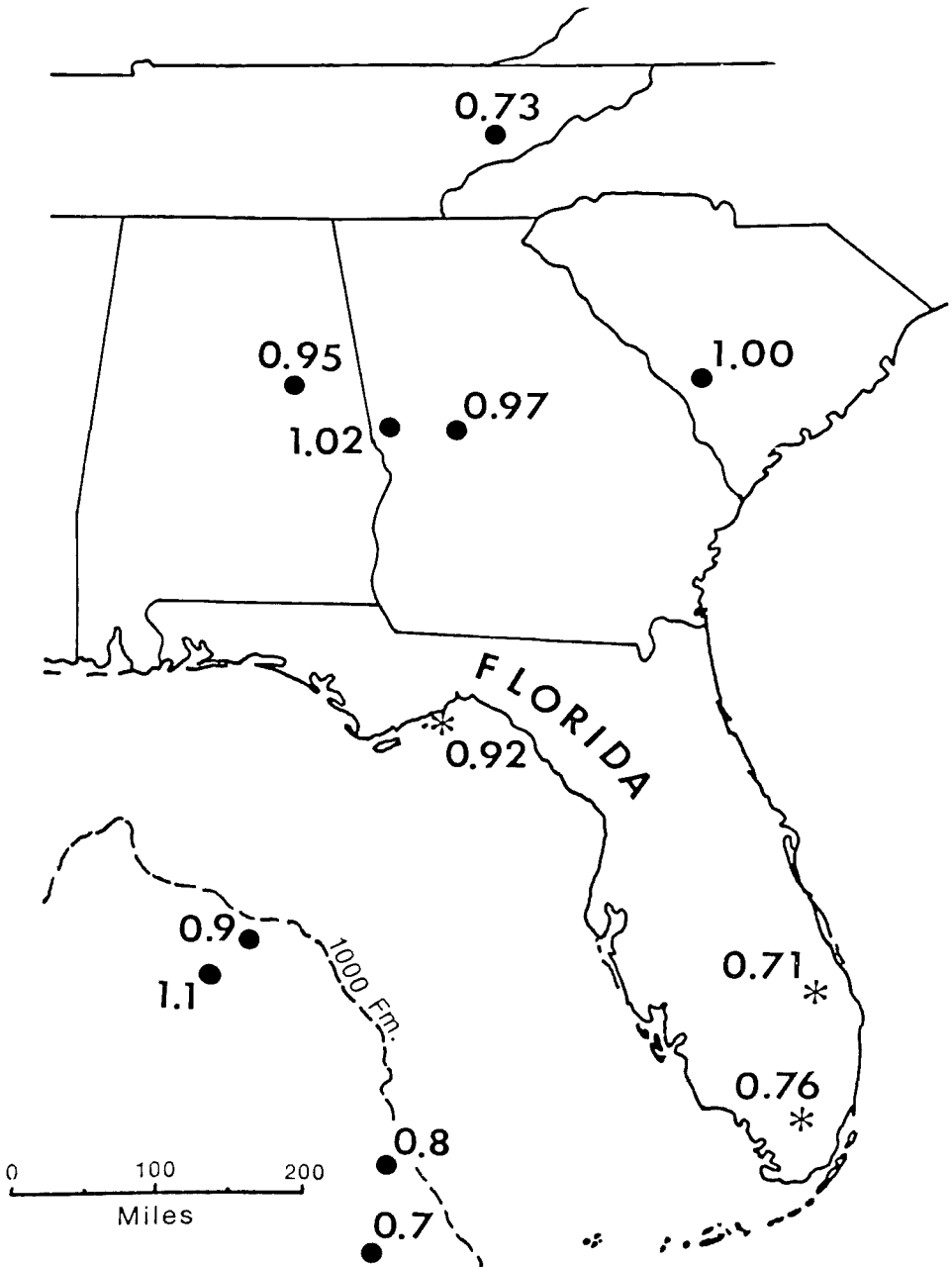


Figure 1. Heat Flow Values extant completion of this project. (Asterisks indicate new values; black dots are measurements prior to 1971 as reported by Lee and Uyeda, 1965; Roy et al, 1968; and Epp et al, 1970.)

Table 1 -- Heat Flow Measurements in Florida Oil Test Holes

Well Name and Location	Examined Depth Interval	Average Thermal Gradient	Thermal Conductivity** (Rock Type, Mean Con- ductivity, Thickness of this lithology)			Average Heat Flow (10 ⁻⁶ cal/cm ² sec)
			Rock Type	Weighted Mean	Thickness of Lithology	
California- Coastal Petrol- eum Co. -- No.2 State Lease 224 -A. (Franklin Co., Offshore, 27.7925°N, 84. 3619°W)	1,300 - 10,510 ft (397-3206m)	0.99°F/100ft (18.03°C/km)	Limestone	2.21	240 ft (73m)	0.92
			Dolomite	2.55	380 ft (116m)	
			Argillaceous	2.98	890 ft (271m)	
			Cherty Ls.	5.53	1230 ft (375m)	
			Sandstone	13.046	70 ft (21m)	
			Argill. Ss.	9.71	610 ft (186m)	
			Ss + Red SH	5.15	5320 ft(1595m)	
			Ss + Gray SH	4.62	650 ft (650m)	
			Weighted Mean	5.13	9300 ft(2837m)	
Humble Oil and Ref. Co. -- No.1 State Lease 1004 (Palm Beach Co, 2-485-35E)	4,650 - 12,800 ft (1418-3904m)	0.98°F/100ft (17.85°C/km)	Limestone	3.00	2790 ft (851m)	0.71
			Dolomite	3.69	710 ft (217m)	
			Anhydrite	7.40	270 ft (82m)	
			Ls. + Dol.	3.79	920 ft (281m)	
			Ls. + Anhyd.	4.84	670 ft (204m)	
			Dol. + "	4.52	2470 ft (735m)	
			Dol. + Ls.+ Anhyd.	4.06	810 ft (247m)	
			Weighted Mean			
			Average	3.95	8640 ft(2635m)	
Commonwealth Oil Co. -- No. 1 Wisehart- St. Board of Education (Dade Co., 16-54S-35E)	6,085 - 11,558 ft (1856-3525m)	*0.98°F/100ft (17.85°C/km)	Limestone	3.51	956 ft (292m)	0.76
			Argillaceous	3.26	150 ft (46m)	
			Dolomite	4.67	856 ft (261m)	
			Anhydrite	5.57	401 ft (122m)	
			Weighted Mean	4.26	2363 gy (729m)	

* Composite gradient for 3 wells in the same township as Commonwealth - No. 1 Wisehart, but not in this well.

** 10⁻³cal/cm sec°C

However, Sheridan (1971) has proposed a model based on crust of the Red Sea type, which includes 9.9 mi. of an intermediate layer (density 2.15), overlain by 2.1 mi. of oceanic crust (density 2.95), overlain by about 1.9 miles of sediment with a density of 2.35, and topped by about 3.1 mi. of limestone (density 2.50). The Sheridan model yields a mantle depth of 18 mi., which he believes is more in keeping with gravity data for the area. In neither the Dietz et al., Uchupi et al., or Sheridan models is the crust considered as continental, therefore the heat-flow data seem compatible with either of their proposals.

CONCLUSION

The data of this project support the general concept that oceanic crust, with very low heat-generating potential underlies the southern part of the Florida-Bahamas Platform. However, clear distinction between the models proposed by Dietz et al. (1970) and Sheridan (1971) is not possible from the heat-flow data; if Sheridan's intermediate layer (density 3.15) does in fact exist between the mantle and the oceanic crust, its heat generating potential must be very low.

APPENDIX

A. Generalities of Heat-Flow Measurements

The rate at which the earth's internal heat moves toward the surface is reported most commonly in terms of HFU (heat flow units), wherein $1 \times 10^{-6} \text{ cal/cm}^2 \text{ sec} = 1 \text{ HFU}$. The average heat flow from continental areas of all types centers at about 1.5 HFU.

Terrestrial heat flow measurements have generally been considered to require a borehole extending beneath the zone of climatic fluctuations and ground-water movement. If rigidly applied, this requirement restricts geothermal temperature measurements in Florida to depths approximately greater than 1000 ft. in north Florida and 5000 ft. in south Florida, that is, depths below the Floridan aquifer system. The three heat-flow measurements reported in this paper abide by this restriction, including only temperature and conductivity data collected below the Floridan Aquifer. However, as Smith and Fuller have shown in their work (1976, this volume), although the aquifer system affects subsurface temperatures markedly, it is possible to make high quality heat-flow measurements in shallow boreholes once the thermal effects of the aquifer are understood. Thus, the heat flow values reported herein for deep holes correlate very well with the values reported by Smith and Fuller except in areas of active ground-water recharge and similar disturbances of the thermal flow pattern.

B. Computation of Heat Flow and Measurement of the Thermal Parameters Used in this Study

Heat flow is defined by the relationship:

$$Q = K (\Delta T / \Delta Z), \quad (\text{eq. 2})$$

where, Q = heat flow in $10^{-6} \text{ cal/cm}^2 \text{ sec}$,

K = thermal conductivity of the rock between depths of temperature measurements in $10^{-3} \text{ cal/cm sec}^\circ\text{C}$, and

$(\Delta T / \Delta Z)$ = the rate of increase in temperature between measurement depths (i.e. the geothermal gradient), with T in $^\circ\text{C}$, and Z in cm.

Because it is never possible to measure both of the basic parameters in the heat flow equation under ideal, equilibrium, *in situ* conditions, various assumptions must always be made; those made in this study are explained below.

Geothermal gradients (Table 2) were calculated from the series of "bottom hole temperatures" or "maximum temperatures" recorded by oil well service companies during standard electric logging runs. These temperatures are assumed to represent near-equilibrium conditions at the bottom of the hole at the time of the probe in-

Table 2 -- Geothermal Gradients

Well Name	Depth Interval	Geothermal Gradient
California-Coastal Petrol, Co.-- No. 2 St. Lse, 224A (Franklin Co., FL.)	0-5000 ft (0-1525m)	1.14°F/100 ft (20.76°C/km)
	5000-10,560 ft (1525-3221m)	0.92°F/100 ft (16.75°C/km)
	Average*: 0-10,560 ft (0-3221m)	0.99°F/100 ft (18.03°C/km)
Humble -- No. 1 St. Lse. 1004 (Palm Beach Co., FL.)	4600-7800 ft (1403-2379m)	1.40°F/100 ft (25.49°C/km)
	7800-9000 ft (2379-2745m)	0.60°F/100 ft (10.93°C/km)
	9000-10,800 ft (2745-3294m)	1.08°F/100 ft (19.67°C/km)
	10,800-12,800 ft (3294-3904m)	0.60°F/100 ft (10.93°C/km)
	Average*: 0-12,800 ft (0-3904m)	0.98°F/100 ft (17.85°C/km)
Commonwealth -- No. 1 Wisehart- St. Bd. of Educ. (Dade Co., FL.)	Average**: 0-11,558 ft (0-3525m)	0.98°F/100 ft (17.85°C/km)

* Visual estimate from plotted T/Z data.

** Based on 6 subsurface temperature measurements in 3 other wells within the same township; data from Wisehart No. 1 appeared erroneous and were not used; see text.

sertion. Difficulties inherent in using temperatures of this type have been discussed previously (Griffin et al., 1969). The temperatures are "uncorrected" in the sense of the AAPG Geothermal Survey of North America. Temperatures at $Z = 0$ were taken from the average ambient surface temperature map of the U.S. Weather Bureau.

The geothermal gradient for the Commonwealth — No. 1 Wisheart was determined differently from the other two wells. The only temperature recorded for the well, 226°F at 11,558 ft., when plotted with the surface temperature of 75°F , yielded a gradient of $1.31^{\circ}\text{F}/100$ ft. Because this gradient is very much higher than gradients in the surrounding area, as shown on the geothermal gradient map of the state (Reel and Griffin, 1971; Reel, 1970), it was considered suspect and was not used. Instead, the composite average gradient for 6 subsurface measurements in 3 other wells in the same 54S-35E township was used in the heat-flow calculation; this composite gradient is $0.98^{\circ}\text{F}/100$ ft. (Reel, 1970). The composite 3 well, 6 measurement thermal gradient for an adjacent township (54S, 36E), in the same 40-Mile Bend Oil Field, was also calculated to be 0.98, lending additional credence to our assumption.

Thermal conductivity was determined by two different methods:

(1) In the California-Coastal — No. 2 State Lease 224A, and in the Humble — No. 1 State Lease 1004, conductivity was estimated from empirical relationships between lithology, porosity, and thermal conductivity. These relationships were examined by Bullard et al. (1956), Diment and Robertson (1963), Ratcliff (1960), Woodside and Messmer (1961), and Zierfuss (1969). Figure 2 is a composite plot of the published relationship, assuming that salt water saturates the pore network, which is true of our samples.

Entry into the working curves (Fig. 2) requires prior determination of lithology and porosity. For this purpose, regularly spaced core samples from these two wells were categorized into lithologies, and the porosity of each sample was measured by the "Varsol absorption method," described in detail in Table 3. The depth, lithology, porosity, bulk density, and derived thermal conductivity for each sample are listed in Tables 4 and 5. Weighted mean-conductivities were calculated for each lithology using the relationship:

(eq. 3)

where, K_{1x} = the mean thermal conductivity for this lithology, weighted in proportion to the thickness and conductivity of each segment of this lithology,
 k_{1x} = the arithmetic mean thermal conductivity of a particular segment, based on equally spaced measurements of porosity within this segment, and

$\frac{l_i}{\sum l_i}$ = the thickness of a particular segment divided by the total thickness of all segments of this lithology.

Similarly, the weighted mean thermal conductivity for each well was calculated from the relationship:

(eq. 4)

where, K_x = the mean thermal conductivity for the well, weighted in proportion to the thickness and mean conductivity of each Lithology,

K_{lx} = the mean thermal conductivity of a particular lithology, and

$\frac{L_i}{\sum L_i}$ = the thickness of a particular lithology divided by the total thickness of the stratigraphic section examined in the well.

(2) In the Commonwealth — No. 1 Wischart, the thermal conductivity of 33 core samples was measured directly with a divided-bar device similar to that described by Beck (1957). The apparatus was built so as to duplicate the Beck device as closely as possible, and the only deviations were: (a) instead of a single thermocouple at each level, three were used; these were arranged radially at 120° intervals; readings from the three thermocouples were averaged, thus improving the precision; (b) the size of the required sample was scaled down to 0.875 in. so that the only available well samples could be used; and (c) a Lexan plastic disc (General Electric Co.) was used for calibration because a quartz standard was not available.

Samples were cut with a 0.875 in. diamond corer, with the long axis of the disc parallel to the bedding. The discs were lapped with extreme care to produce smooth, parallel surfaces and a thickness of approximately 5mm. Each finished disc was soaked in saturated NaCl brine for several days immediately prior to measurement of thermal conductivity. The device was calibrated with the Lexan standard before and after each run. Resulting thermal conductivities are listed in Table 6. The mean thermal conductivity for the well, weighted in proportion to the approximate thickness of each major lithology (using equation 3) was 4.26×10^{-3} cal/cm sec°c.

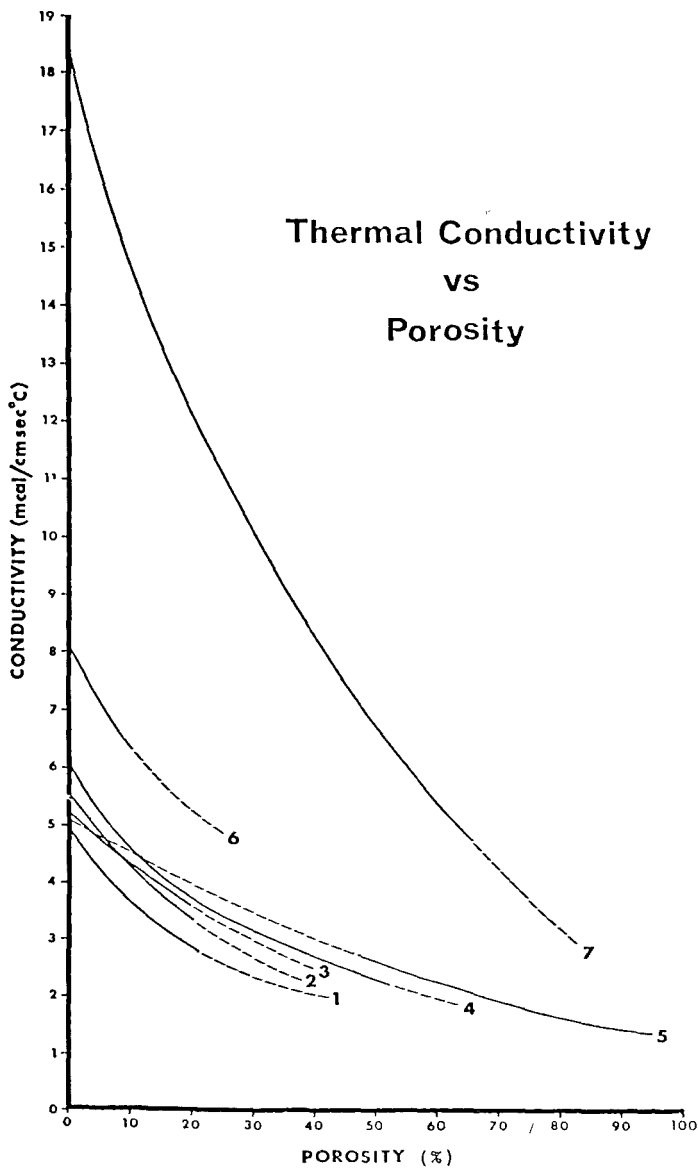


Figure 2. Empirical working Curves of Thermal Conductivity vs Porosity for Various Lithologies, based on Published Data. Extrapolations indicated by dashed lines. 1: Limestone, Archie Class II, Zierfuss (1969). 2: Limestone, Archie Class III, Zierfuss (1969). 3: Limestone, Archie Class I, Zierfuss (1969). 4: Dolomite, Zierfuss (1969). 5: Calcareous Shale, Bullard, Maxwell, and Revelle (1956) and Diment and Robertson (1963). 6: Anhydrite, Zierfuss (1969). 7: Sandstone, Woodside and Messmer (1961).

Table 3. Procedure for Measuring Porosity of Cutting Samples by the Varsol Absorption Method.

- (1) Select a representative 10 g sample and break into fragments one to four mm in diameter.
- (2) Saturate with Varsol.¹
- (3) Dry at 100°C for fifteen hours.
- (4) Cool in a dessicator and weigh ("dry weight").
- (5) Re-immerses in Varsol and saturate for two hours in a dessicator.
- (6) Roll quickly and briefly onto a paper towel to remove excess Varsol from the exterior.
- (7) Weigh quickly ("wet weight").
- (8) After weighing place immediately in a burette containing a known volume of Varsol, and determine the "bulk volume" of the sample by displacement of the Varsol.
- (9) Subtract the "dry weight" from the "wet weight" to determine the "weight of Varsol" in the pores.
- (10) Divide the "weight of Varsol" by 0.772 (its density) to yield the "volume of Varsol" in the pores.
- (11) Divide the "volume of Varsol" in the pores by the "bulk volume" to yield the ratio of the pore volume to total volume; multiply this ratio by 100 to yield percent porosity.
- (12) Divide the "dry weight" by the "bulk volume" to yield the "bulk density" of the rock.

¹Varsol is a cleaning naptha manufactured by Humble Oil Company. It has a density of 0.772 g/cm³ and is able to displace water from pores because of its greater attraction to pore walls.

Table 4. Depth, lithology, bulk density, porosity, and thermal conductivity of rock samples from California-Coastal Petroleum Company - No. 2 State Lease 224-A, offshore Franklin County, Florida.

DEPTH (ft.)	LITHOLOGY	DENSITY (g/cc)	POROSITY (%)	CONDUCTIVITY (10^{-3} cal/cm sec $^{\circ}$ C)
1300-10	Limestone	1.65	43.9	2.06
1400-10	Dolomite	1.76	38.6	2.76
1500-10	Dolomite	1.70	50.3	2.39
1600-10	Dolomite	1.64	45.9	2.50
1710-20	Dolomite	1.74	42.1	2.62
1800-10	Limestone	1.91	33.6	2.26
1900-10	Limestone, Chert	2.11	23.5	3.48
2000-10	Limestone, Chert	2.13	21.9	2.90
2100-10	Limestone, Chert	2.13	21.2	4.12
2200-10	Limestone, Chert	2.14	20.0	6.56
2300-10	Limestone, Chert	1.94	28.2	4.76
2400-10	Limestone, Chert	2.15	21.2	3.86
2500-10	Limestone, Chert	2.14	17.8	9.94
2600-10	Limestone, Chert	2.12	20.6	6.82
2700-10	Limestone, Chert	2.10	21.7	7.95
2800-10	Limestone, Chert	2.12	20.5	6.29
2900-10	Limestone, Chert	2.02	24.0	6.39
3000-10	Limestone, Chert	2.10	21.6	5.57
3100-10	Limestone, Chert	2.06	24.1	3.43
3200-10	Limestone, Shale	2.03	24.9	2.74
3300-10	Limestone, Shale	1.99	26.7	2.87
3400-10	Limestone, Shale	2.03	25.7	2.97
3500-10	Limestone, Shale	2.06	24.5	3.01
3600-10	Limestone, Shale	2.11	22.5	3.16
3700-10	Limestone, Shale	2.00	26.4	3.26
3800-10	Limestone, Shale	1.97	28.3	2.93
3900-10	Limestone, Shale	2.06	24.1	2.79
4000-10	Sandstone	2.23	16.6	12.82
4100-10	Gray Shale, Sandstone	2.08	23.5	3.83
4200-10	Gray Shale, Sandstone	2.10	22.3	4.11
4300-10	Gray Shale, Sandstone	2.05	25.2	4.03
4400-10	Gray Shale, Sandstone	2.13	22.5	5.03
4500-10	Gray Shale, Sandstone	2.08	23.3	4.43
4600-10	Gray Shale, Sandstone	2.16	21.9	5.22
4700-10	Gray Shale, Sandstone	2.18	21.7	5.79
4800-10	Red Shale, Sandstone	2.17	20.9	6.91
4900-10	Red Shale, Sandstone	2.16	22.4	5.36

Table 4 (con'd.)

DEPTH (ft.)	LITHOLOGY	DENSITY (g/cc)	POROSITY (%)	CONDUCTIVITY (mcal/cm sec°C)
5000-10	Red Shale, Sandstone	2.16	22.9	6.36
5100-10	Red Shale, Sandstone	2.27	18.4	5.18
5200-10	Red Shale, Sandstone	2.18	22.6	4.87
5300-10	Red Shale, Sandstone	2.20	20.7	7.32
5400-10	Red Shale, Sandstone	2.20	23.5	5.90
5500-10	Red Shale, Sandstone	2.27	17.7	5.76
5600-10	Red Shale, Sandstone	2.24	19.9	5.89
5700-10	Red Shale, Sandstone	2.37	16.8	6.91
5800-10	Red Shale, Sandstone	2.24	19.9	4.98
5900-10	Red Shale, Sandstone	2.22	20.2	6.80
6000-10	Red Shale, Sandstone	2.37	15.4	6.31
6100-10	Red Shale, Sandstone	2.30	16.1	6.08
6200-10	Red Shale, Sandstone	2.34	15.9	7.68
6300-10	Red Shale, Sandstone	2.33	14.9	7.45
6400-10	Red Shale, Sandstone	2.31	17.1	5.12
6500-10	Red Shale, Sandstone	2.83	25.8	4.57
6600-10	Red Shale, Sandstone	2.18	20.3	5.02
6700-10	Red Shale, Sandstone	2.24	17.7	5.56
6800-10	Red Shale, Sandstone	2.24	19.5	5.33
6900-10	Red Shale, Sandstone	2.25	18.2	5.70
7000-10	Red Shale, Sandstone	2.26	17.8	4.71
7100-10	Red Shale, Sandstone	2.23	19.1	4.38
7200-10	Red Shale, Sandstone	2.42	12.9	7.53
7300-10	Red Shale, Sandstone	2.17	21.7	4.14
7400-10	Red Shale, Sandstone	2.20	20.6	5.34
7500-10	Red Shale, Sandstone	2.39	13.7	7.25
7600-10	Red Shale, Sandstone	2.39	14.6	6.39
7700-10	Red Shale, Sandstone	2.31	17.8	4.79
7800-10	Red Shale, Sandstone	2.27	18.2	4.42
7900-10	Red Shale, Sandstone	2.35	15.4	5.88
8000-10	Red Shale, Sandstone	2.35	15.6	6.59
8100-10	Red Shale, Sandstone	2.35	15.3	7.42
8200-10	Red Shale, Sandstone	2.34	16.4	4.90
8300-10	Red Shale, Sandstone	2.40	14.6	6.50
8400-10	Red Shale, Sandstone	2.31	16.4	5.52
8500-10	Red Shale, Sandstone	2.42	15.5	4.96
8600-10	Red Shale, Sandstone	2.41	13.5	6.25
8700-10	Red Shale, Sandstone	2.34	16.0	5.02
8800-10	Red Shale, Sandstone	2.36	15.4	4.71
8900-10	Red Shale, Sandstone	3.21	14.4	5.04
9000-10	Red Shale, Sandstone	2.45	13.4	4.65
9100-10	Red Shale, Sandstone	2.46	12.4	4.62
9200-10	Red Shale, Sandstone	2.45	12.5	4.89
9300-10	Red Shale, Sandstone	2.44	12.2	4.64
9400-10	Red Shale, Sandstone	2.37	16.1	4.65
9500-10	Red Shale, Sandstone	2.44	13.1	4.78
9600-10	Red Shale, Sandstone	2.45	11.8	6.19

Table 4 (con'd.)

DEPTH (ft.)	LITHOLOGY	DENSITY (g/cc)	POROSITY (%)	CONDUCTIVITY (mcal/cm sec°C)
9700-10	Red Shale, Sandstone	2.40	9.7	13.07
9800-10	Red Shale, Sandstone	2.37	12.6	9.34
9900-10	Red Shale, Sandstone	2.37	12.2	8.97
10000-10	Red Shale, Sandstone	2.43	10.1	8.63
10100-10	Red Shale, Sandstone	2.37	13.0	9.49
10200-10	Red Shale, Sandstone	2.39	9.5	8.89
10319.5	Sandstone	2.40	10.7	14.4
10400-10	Red Shale, Sandstone	2.40	12.5	9.43
10500-10	Red Shale, Sandstone	2.41	12.8	9.04
Weighted mean conductivity				= 4.62

Table 5. Depth, lithology, bulk density, porosity, and thermal conductivity of rock samples from Humble Oil Company - No. 1 State Lease 1004, Palm Beach County, Florida.

DEPTH (ft.)	LITHOLOGY	DENSITY (g/cc)	POROSITY (%)	CONDUCTIVITY (mcal/cm sec°C)
4650-80	Dolomite, Anhydrite	2.59	12.1	5.48
4740-70	Dolomite, Anhydrite	2.31	20.2	4.03
4830-60	Dolomite, Anhydrite	2.41	13.9	4.69
4920-50	Dolomite, Anhydrite	1.98	10.3	5.33
5000-30	Dolomite, Anhydrite	2.94	8.2	6.28
5090-20	Dolomite, Anhydrite	2.07	40.8	2.95
5180-10	Dolomite, Anhydrite	2.50	15.1	4.60
5240-50	Dolomite	1.97	28.1	3.25
5300-01	Dolomite	2.15	25.2	3.38
5350-51	Dolomite	2.38	14.9	4.09
5400-01	Dolomite	2.16	23.8	3.47
5450-51	Dolomite	2.10	27.6	3.27
5510-40	Dolomite, Anhydrite	2.32	22.4	3.71
5600-30	Dolomite, Anhydrite	2.28	21.0	3.73
5690-20	Dolomite, Anhydrite	2.26	5.5	5.20
5780-10	Limestone	2.31	18.1	3.02
5870-00	Limestone	2.26	21.0	2.81
5960-20	Limestone	1.80	49.9	2.00
6050-80	Limestone	2.14	30.5	2.37
6140-70	Limestone	2.12	35.0	2.22
6230-60	Limestone, Dolomite	2.37	15.4	3.62
6320-50	Limestone, Dolomite	2.24	19.0	3.36
6410-40	Limestone, Dolomite	2.20	17.3	3.29
6500-30	Limestone	2.04	21.2	2.80
6590-20	Limestone, Dolomite	2.11	21.3	3.07
6680-10	Limestone, Dolomite	2.21	20.7	3.05
6770-00	Limestone	2.26	17.3	3.07
6860-90	Limestone	2.00	26.2	2.53
6950-80	Limestone	2.02	25.5	2.55
7040-70	Limestone	1.97	28.8	2.42

Table 5 (con'd.)

DEPTH (ft.)	LITHOLOGY	DENSITY (g/cc)	POROSITY (%)	CONDUCTIVITY (mc/cm sec°C)
7130-60	Limestone, Dolomite	2.05	25.9	2.95
7220-50	Limestone	2.22	19.9	2.88
7310-40	Limestone	2.18	21.8	2.88
7400-30	Limestone	2.08	23.4	2.67
7490-20	Limestone	2.25	20.8	2.83
7580-10	Limestone	2.16	21.4	2.78
7670-00	Limestone	2.13	20.1	2.87
7760-90	Limestone	2.10	22.4	2.55
7850-80	Limestone	2.25	17.6	3.05
7940-70	Limestone	2.16	19.4	2.92
8030-60	Limestone	2.00	25.2	2.57
8120-50	Limestone	2.21	18.4	3.00
8210-40	Limestone, Dolomite	2.33	17.4	3.37
8300-30	Limestone, Dolomite	2.39	16.0	3.58
	Anhydrite			
8390-20	Dolomite, Anhydrite	2.30	43.8	2.93
8480-10	Limestone, Dolomite	2.33	15.0	3.48
8570-00	Dolomite, Limestone	2.26	21.4	3.36
8660-90	Dolomite, Anhydrite	2.28	20.1	4.12
8750-80	Dolomite, Anhydrite,	2.62	10.7	5.72
8840-70	Dolomite	2.18	18.3	3.84
8930-60	Dolomite, Anhydrite	2.64	9.6	5.94
9020-50	Dolomite, Anhydrite	2.42	19.3	4.85
9110-40	Anhydrite	2.68	12.8	6.00
9200-30	Dolomite, Anhydrite	2.50	14.2	4.39
9300-01	Dolomite	2.05	28.6	3.22
9350-51	Dolomite	2.41	13.9	4.16
9400-01	Dolomite	2.17	31.4	3.08
9450-54	Anhydrite	2.92	1.1	7.83
9500-01	Dolomite	2.40	12.4	4.31
9550-51	Dolomite	2.30	20.1	3.70
9600-01	Limestone	2.06	26.6	2.97
9668-69	Dolomite	2.36	16.2	4.00
9700-01	Dolomite	2.14	20.8	3.67
9750-51	Dolomite	2.01	28.9	3.19
9800-01	Limestone	2.22	19.0	3.72
9850-51	Limestone	2.50	7.8	4.60
9900-30	Limestone	2.45	9.6	4.42
9990-20	Dolomite, Anhydrite	2.69	8.1	6.01
10080-10	Dolomite, Limestone	1.91	11.2	4.39
10170-00	Dolomite, Anhydrite	2.45	11.7	4.63
10260-90	Dolomite, Anhydrite	2.34	18.0	3.99
10350-80	Dolomite, Limestone	2.41	16.5	3.85
10440-70	Dolomite, Anhydrite	1.80	18.1	3.97
10530-60	Dolomite, Limestone	2.24	20.4	3.32
10620-50	Dolomite, Limestone	2.12	21.2	3.61
10710-40	Dolomite, Limestone,	2.50	11.8	4.47
	Anhydrite			
10800-30	Dolomite, Limestone,	2.41	15.6	4.02
	Anhydrite			

Table 5 (con'd.)

DEPTH (ft.)	LITHOLOGY	DENSITY (g/cc)	POROSITY (%)	CONDUCTIVITY (mc/cm sec°C)
10890-20	Dolomite, Limestone, Anhydrite	2.42	15.4	4.35
10980-10	Dolomite, Limestone	2.33	18.1	3.81
11070-00	Dolomite, Limestone, Anhydrite	2.39	15.4	4.19
11160-90	Dolomite, Limestone, Anhydrite	2.60	8.4	4.96
11250-80	Limestone, Anhydrite	2.50	9.3	5.38
11340-70	Limestone, Anhydrite	2.35	14.9	4.10
11450-51	Limestone	2.63	4.1	4.89
11500-01	Limestone	2.15	20.6	3.36
11551-52	Limestone	2.21	19.0	3.50
11600-01	Limestone	2.65	3.3	4.98
11655-80	Limestone, Anhydrite	2.52	10.8	5.42
11740-70	Limestone, Anhydrite	2.38	10.1	4.56
11830-60	Limestone, Anhydrite	2.40	15.1	4.39
11920-40	Limestone, Anhydrite	2.46	13.7	5.31
12000-01	Dolomite, Anhydrite	2.68	7.7	4.99
12030-93	Dolomite, Anhydrite	2.83	2.2	6.92
12149-60	Anhydrite	2.97	0.00	8.15
12200-01	Limestone	2.48	12.2	3.49
12244-58	Limestone	2.40	15.1	3.25
12300-12	Anhydrite	2.88	3.2	0.81
12350-51	Anhydrite	2.72	4.0	7.19
12400-01	Dolomite	2.62	20.6	3.68
12450-51	Dolomite	2.27	14.9	4.09
12500-01	Limestone	2.44	10.1	3.68
12550-51	Limestone	2.62	2.6	5.62
12590-20	Limestone	2.30	14.4	4.03
12680-10	Limestone	2.29	14.9	4.01
12770-00	Limestone	2.31	15.8	3.97

Weighted mean conductivity = 3.95

Table 6 -- Depth, lithology, and thermal conductivity of samples from Commonwealth
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Depth (ft)	Gross Lithology	Conductivity (10^{-3} cal/cm sec°C)
6085	Limestone and dolomite	(3.12)
6112	Limestone	3.00
6148	Limestone	2.90
6151	Dolomite	5.10
6156	Dolomite and anhydrite	(3.50)
6166	Limestone	3.00
9195	Anhydrite	5.20
9204	Dolomite	3.91
9208	Dolomite	4.21
9212	Anhydrite	5.28
9260	Dolomite	4.23
9288	Anhydrite	6.20
9290	Dolomite	6.10
9309	Limestone	4.53
9321	Dolomite	4.38
9329	Limestone	4.17
9820	Limestone	(4.90)
9854	Anhydrite and dolomite	(4.85)
9872	Limestone	3.50
9886	Limestone	3.56
10,798	Limestone	3.96
10,808	Limestone	3.60
11,315	Anhydrite and dolomite	(4.87)
11,327	Limestone	3.23
11,369	Limestone	3.38
11,378	Limestone	3.17
11,380	Argillaceous limestone	(3.15)
11,382	Limestone	3.35
11,432	Argillaceous limestone	3.26
11,447	Argillaceous limestone	(2.74)
11,496	Argillaceous limestone	(2.8)
11,527	Anhydrite	(4.5)
11,536	Anhydrite	5.6
Weighted mean conductivity		4.26

Note: Values in parentheses were based on inferior samples or mixed lithologies and were not included in averages or heat flow calculations.

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**SPATIAL DISTRIBUTION
OF
GROUND WATER TEMPERATURE
IN
SOUTH FLORIDA**

BY

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ABSTRACT

The Florida Aquifer in southern Florida is comprised of a thick section of generally southward-dipping Tertiary (pre-Miocene) carbonates. The aquifer is layered, having in most places several distinct water-producing zones. The producing zones are separated by less permeable limestone and dolostone. Water in the aquifer is confined under artesian pressure by younger Tertiary clastics.

Ground-water temperatures measured at the well frequently show poor correlation with well depth, usually because of local variations in the relative contribution of each producing zone penetrated. However, review of existing literature, and examination of a large amount of ground-water temperature data, show some distinctly anomalous distributions in ground-water temperature. Some of these anomalies appear to be related to upwelling of warmer, highly mineralized water along fracture systems.

A cooling anomaly along the east coast has been attributed to the cooling effect of the deep bottom water offshore in the Atlantic Ocean. Cooling by conduction and by cyclic inland flow of the cold sea water have been suggested as mechanisms for the cooling effect.

INTRODUCTION

At depths of 100 feet or so below the earth's surface, the temperature is not affected by seasonal variations of insolation. Below this depth, the temperature of the rocks and contained water remains nearly constant. The temperature is controlled by the relatively constant flow of geothermal heat from the earth's interior, modified by circulation of ground water, thermal properties of the rocks and contained water, and volcanic and tectonic activity.

The temperature of ground water normally increases at a rate of 1°F per 50 to 150 feet of depth. The actual rate of increase is controlled by the rate of geothermal heat flow and other factors, listed above. In an artesian system in which the water is moving down-gradient, at progressively greater depth, the temperature would be expected to increase at a regular and constant rate. Any perturbations in the rate of temperature increase or distribution of ground-water temperature in this situation should be useful in interpreting some of the flow characteristics of the aquifer.

This paper presents a synopsis of ground-water temperature data and known temperature anomalies in the principal artesian aquifer in south Florida.

HYDROLOGIC SETTING

The area of study, shown in Figure 1, is approximately the southern one-third of peninsular Florida. The dominant aquifer system in this area is the Floridan Aquifer, a regional artesian system which underlies all of Florida and adjacent parts of neighboring states.

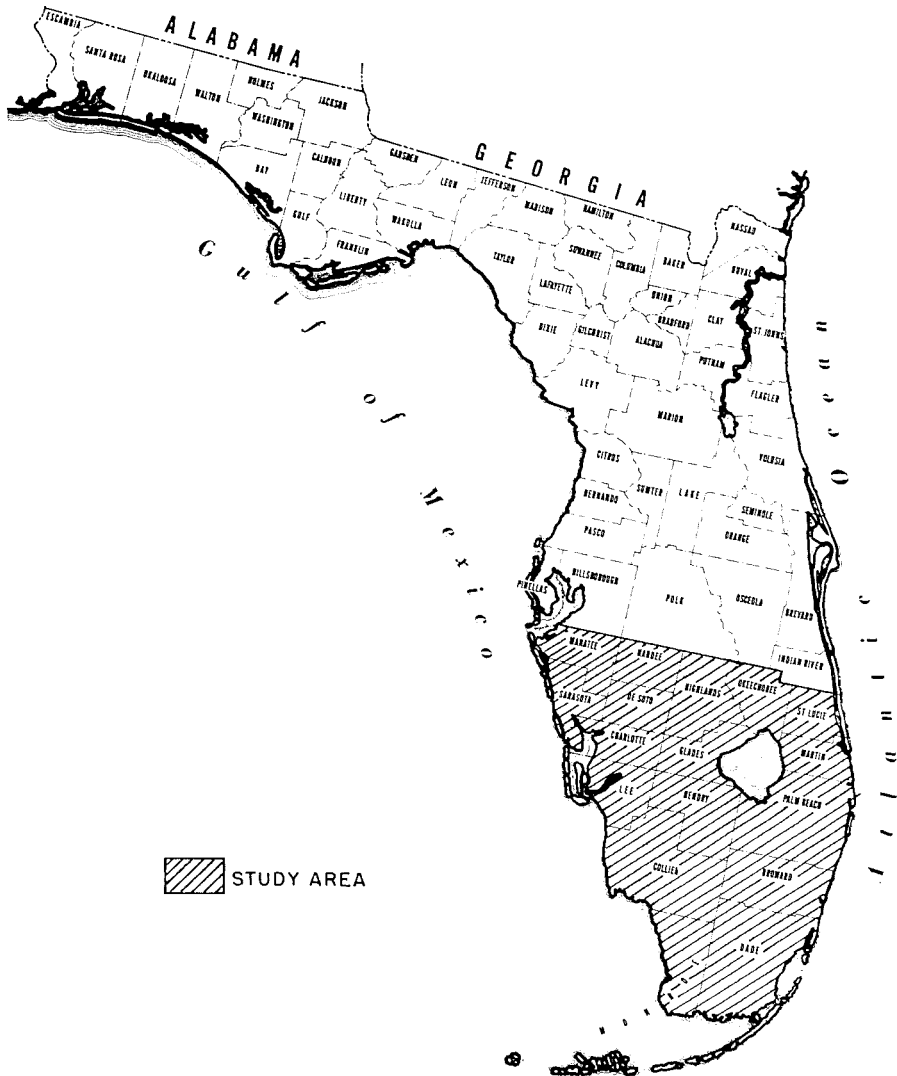


Figure 1. Area of Study

The Floridan Aquifer in this area is comprised of 1,000 to 3,000 feet of southeast to southwest dipping Tertiary limestone and dolostone. The elevation of the top of the Floridan Aquifer is shown on Figure 2. The aquifer is layered, having in most places three or more distinct zones of relatively high transmissivity, separated from one another by relatively impermeable limestone or dolostone. It is overlain by several hundred feet of relatively impermeable clastics, also mostly of Tertiary age, which confine the water under artesian pressure.

Younger Tertiary and Neogene limestones and sands overlie the confining beds of the Floridan Aquifer. These shallow strata produce a second aquifer system that furnishes the potable fresh ground water for much of south Florida.

Some recharge of the Floridan Aquifer occurs in the north central part of the study area; however, the principal recharge area lies further to the north, in the ridge area of central Florida. The ground-water flow regime in the aquifer is dominated by a large potentiometric high situated in central Florida, as shown on Figure 3. Ground-water flow is generally southward and toward both coasts. Discharge from the aquifer is through springs, both onshore and offshore at the submarine outcrop of the Tertiary limestones, and through a large number of wells.

Over most of the study area, the artesian water is too highly mineralized for direct use as a potable water source. Present use is primarily for irrigation. Potential future uses of the aquifer, in which interest is rapidly increasing, are: cooling, production of potable fresh water by desalination, as a reservoir for the storage and recovery of fresh water, and as a receptacle for liquid wastes.

In order to properly manage the resource and to accommodate these sometimes conflicting uses, ground-water flow patterns within the aquifer must be defined and understood. It seems clear that a study of the geothermal regime in the aquifer will contribute significantly to our understanding of these flow patterns.

Some of the regional geothermal features and local temperature anomalies described herein have been studied in some detail, and well-founded hypotheses can be proposed to account for them. In other cases there is little factual data available, and the hypotheses offered are quite tentative.

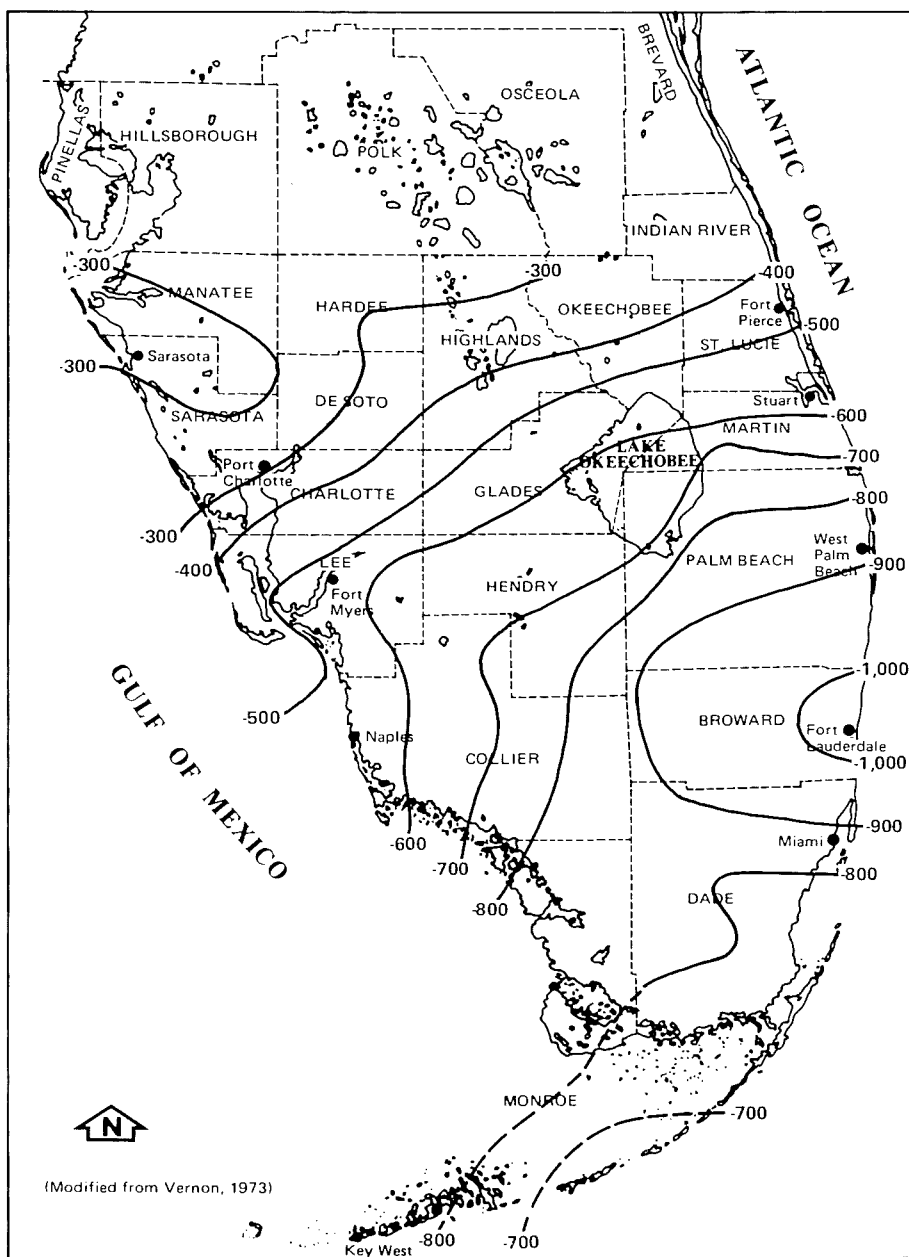


Figure 2. Elevation (in feet) of top of Floridan Aquifer

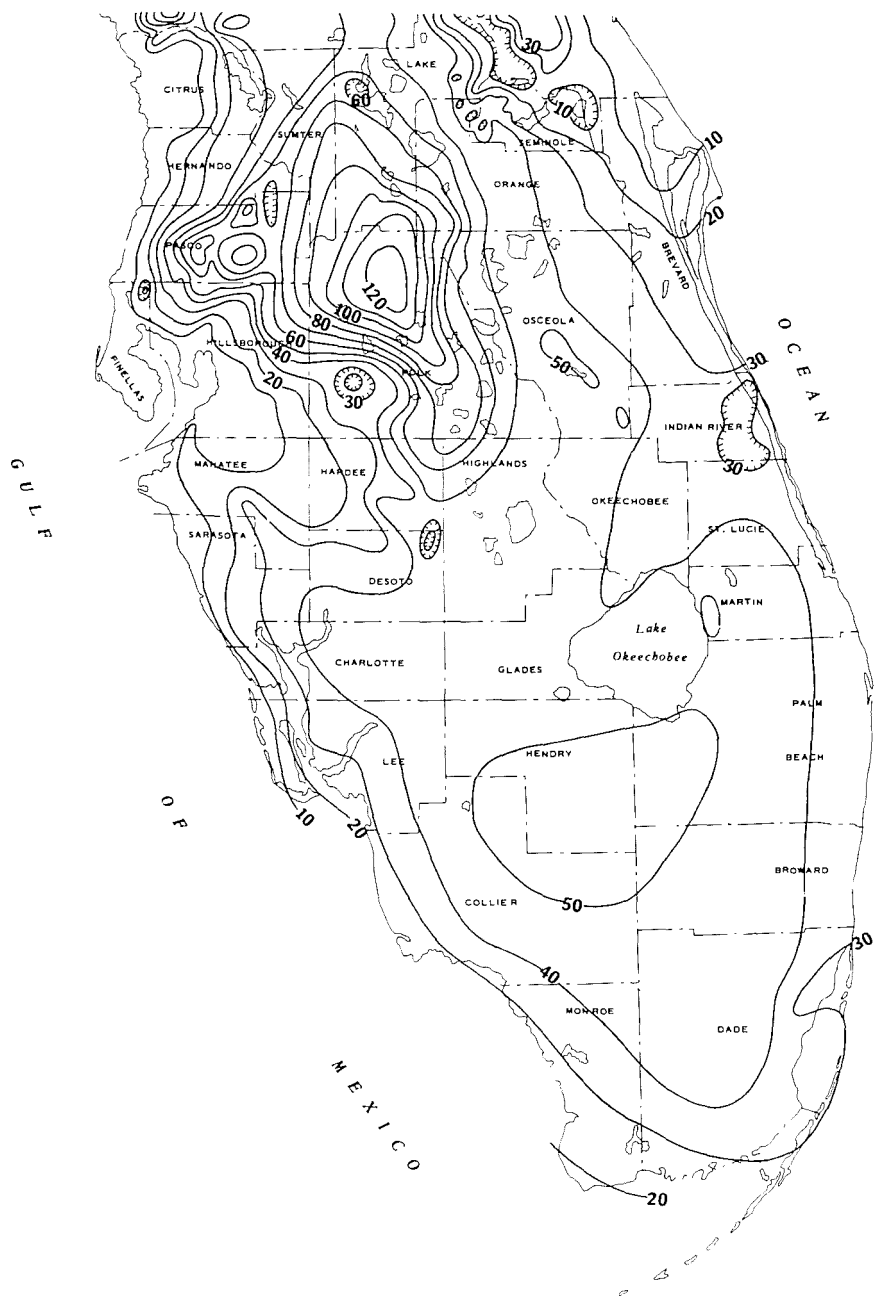


Figure 3. Potentiometric Surface

PREVIOUS STUDIES

Over the past 30 years or so, geologists and hydrologists noted the occurrence of seemingly anomalous ground-water temperatures in the Floridan Aquifer in south Florida. Because the temperature extremes reported (approximately 68° F to 91° F) had little bearing on potential uses of the water, little attention was given to the explanation of these anomalies. Many of the temperature data exist only in unpublished form, as field notes and well inventory records.

Among the writers who have commented on the anomalies: Lichtler (1960, p. 61-63) noted both hot and cool anomalies in Martin County. He postulated that the cool temperatures in the eastern (coastal) part of the area might be due to a cooling effect of the nearby Atlantic Ocean, and that higher temperatures inland might be due to radioactivity of the water.

Stringfield (1966, p. 152-153) noted temperature anomalies in several areas of south Florida. Stringfield attributed most of them to differences in the depth at which water entered the wells. He also mentioned the possible cooling effect of sea bottom temperature at the submarine outcrop of the aquifer as an explanation for low artesian water temperatures along the coast in Dade County.

Kohout (1965, p. 249-271) described a regional cool temperature anomaly in south Florida and presented a hypothesis as to its origin. In Kohout's paper, it was first suggested that ground-water temperatures might have significant implications with regard to ground-water circulation patterns in the Floridan Aquifer. In his initial work, and in a subsequent paper on the same subject (Kohout, 1967, p. 339-354), he hypothesized a cyclic flow of water in the aquifer produced by convection. According to this hypothesis, salt water moving inland from the submarine outcrop of the aquifer becomes less dense due to geothermal heating, rises, mixes with fresher water at a shallower depth, and flows down-gradient to discharge.

Kaufman and Dion (1967) described a linear ground-water temperature anomaly generally paralleling the Peace River in Hardee and DeSoto counties. They suggest that this anomaly may be due to the upconing of deep artesian water along a fracture.

Sproul et al. (1972) described a high temperature anomaly in Lee County which is associated with a fracture of fault system. Upward migration of warmer and more mineralized water along an open fracture is suggested.

SOURCES OF DATA

The majority of the ground-water temperature data used in this paper was obtained during an inventory of artesian wells in south Florida conducted by the Florida Bureau of Geology between 1956 and 1971. Records of approximately 5,000 Floridan aquifer wells were obtained during that period. The principle objective of the inventory was to obtain data on the numbers and locations of uncontrolled flowing artesian wells. In the course of the inventory a substantial body of hydrologic data, including ground-water temperature, was accumulated.

Data collected during the inventory included, whenever possible: location, depth, and sizes of wells; depth of casings; and use, yield, artesian pressure, temperature, and chloride content of the water. Inventory records were subsequently computerized to facilitate retrieval of the data.

Other sources of temperature data cited in this paper are published reports of the U.S. Geological Survey and the Florida Department of Natural Resources, Bureau of Geology, unpublished reports and materials from the files of various state agencies, and data collected by the writer in the course of hydrological investigations.

REGIONAL TEMPERATURE DISTRIBUTION

Ground-water temperature in the upper few hundred feet of the Floridan Aquifer is shown on Figure 4. This regional temperature map was constructed by plotting available ground-water temperature data on a map at a scale of 1 inch = 10 miles and drawing isothermal contours at a 5° F contour interval.

The density of temperature data points ranges from an average of about 3 per township (36 square miles) in the northwestern two-thirds of the area to only 3 or 4 per county in the southeastern one-third (Palm Beach, Broward, Dade, Monroe, and Collier counties).

Only data whose reliability could be reasonably established was used in the construction of Figure 4. For the present purpose, a data point was considered reliable if the well depth was known to within about 100 feet, and if the well had been flowing or pumped long enough for the water temperature to stabilize. Practically all of the wells used were drilled for water supply, predominantly for irrigation water. The usual well construction practice in the area is to set steel casing into the first competent rock and then continue drilling open hole, penetrating a succession of permeable zones, until the desired well yield is reached. In south Florida, at least one very prolific water producing zone is usually penetrated between 200 and 500 feet below the top of the aquifer, and this frequently determined the final depth

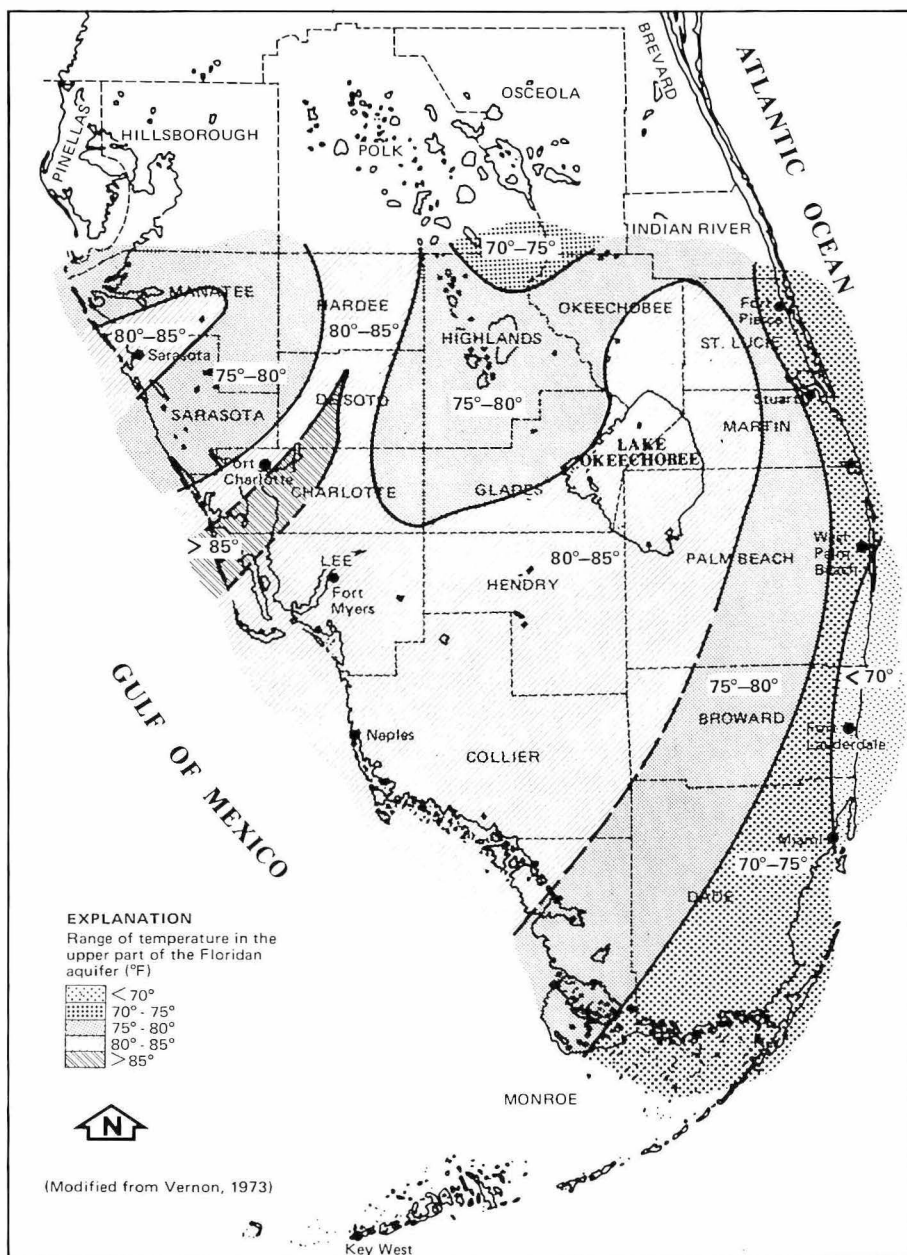


Figure 4. Regional groundwater temperature

of the well. Therefore, the temperatures shown on the regional ground-water temperature map are representative of a range of depths and of several different producing zones in the aquifer.

Ground-water temperature data in the area shows a fairly large amount of scatter, for reasons described above. Consequently, the contours on Figure 4 are highly generalized.

Ground-water temperatures are relatively low (70° to 75° F) in the north-central part of the study area, corresponding to the southern edge of the recharge area of the aquifer. Temperatures increase downdip, and in the direction of ground-water flow toward the west, southwest, and southeast. The expected gradual, regular, downgradient temperature increase is interrupted on the west by a band of above-normal ground-water temperatures generally paralleling the Peace River in Hardee and DeSoto counties. To the southeast, the normally expected downgradient temperature increase is interrupted by a reversal in gradient with temperatures decreasing downgradient.

The lowest ground-water temperatures in the area occur along the southeast coast, where a temperature of 69° F was recorded in a 980-foot well at Miami Beach. In this same area, a bottom temperature of 59° F was recorded in a 3,100-foot well at Margate in Broward County.

The highest ground-water temperatures mapped on Figure 4 are in the mid-80's and occur along the west coast from Fort Myers to Punta Gorda, and up the Peace River Valley nearly into Hardee County. Higher ground-water temperatures occur in several areas which are too small to be shown on the regional map. Some of the highest recorded ground-water temperatures, excluding those recorded in oil wells, are: 96° F in a 1,640-foot well near Punta Gorda, 93° F in a 710-foot well near Fort Myers, and 91° F in an 843-foot well about 15 miles west of Stuart in Martin County.

TEMPERATURE ANOMALIES

It is apparent from Figure 4 that there are substantial deviations from the expected distribution of ground-water temperatures in the Floridan Aquifer. Examination of the well inventory data referenced earlier reveals other cases of anomalous temperatures in certain areas too small to be depicted on the regional map. Other references to apparently anomalous ground-water temperatures are contained in various published reports.

Ground-water temperature anomalies in south Florida may be grouped into three major categories, as follows:

1. Definite local temperature anomalies, or "hot spots," ranging in size from a single well or small group of wells up to areas of a few square miles, occur where ground-water temperatures are about 5 to 10 degrees F higher than adjacent areas.
2. A region of above-normal temperatures occurs in a narrow band paralleling the Peace River in DeSoto and Hardee counties. Temperatures in this region are generally 3 to 5 degrees F higher than in adjacent areas.
3. A low temperature anomaly is present along the east coast in which ground-water temperature decreases downgradient and with increasing depth in the aquifer.

The latter described cooling anomaly along the east coast, in which both lateral and vertical temperature distribution is the reverse of the normal distribution, is the most striking feature of the ground-water temperature regime in peninsular Florida. This cooling anomaly, along with the "hot spots," is probably also the most significant of the above features with respect to implications regarding ground-water circulation patterns.

LOCAL ANOMALIES

As used in this report, the term "hot well" or "hot spot" refers to an individual well or a small area wherein the ground-water temperature is abnormally high for that area. This definition excludes cases in which the high temperature can be attributed to well depth alone or to local permeability changes within the aquifer.

Most of the data on ground-water temperature in south Florida are measurements taken at the well mouth of either flowing or pumped wells. As such, the temperatures measured represent a composite of the temperature in all producing zones penetrated by a well. Since ground-water temperature generally increases with well depth, a reasonable correlation would be expected between well depth and temperature, at least for small areas. However, in most of the area of this report, this correlation is very poor, making the delineation of actual anomalies difficult.

Most wells penetrate several producing zones in the artesian aquifer. Since permeability in limestone aquifers is typically somewhat randomly distributed within each producing zone, wells in the same area and of the same depth may derive the majority of their flows from different depths. Thus, temperatures measured at the well mouths would be different but would not be reflecting a geothermal anomaly. Apparent "hot spots" may also occur where permeability in the upper part of the aquifer is locally poorly developed. Wells in such areas will, as a group, produce water having

a higher temperature than identically-constructed wells in surrounding areas.

High-temperature anomalies which are "real," as opposed to those produced by local permeability changes, have been identified in several areas of south Florida. Almost all are thought to be due to upwelling of artesian water from deep sources feeding a shallower aquifer zone. Most, but not all, high-temperature anomalies are associated with high chlorides in the ground water, another indication of the deep source of the warmer water.

So far as is known, none of the ground-water temperature anomalies reflect a geothermal heat flow anomaly.

A discussion of specific "hot wells" and "hot spots" which have been investigated by the writer and others follows.

LEE COUNTY

Table 1 is a tabulation of well data for one township (36 square miles) in western Lee County. This tabulation demonstrates at once the mass of data available and the difficulties involved in identifying real versus apparent anomalies.

Well 5 in the table, 1,045 feet deep, temperature 80° F, is less than 1,000 feet from well 6 of almost the same depth (919 feet) producing water at 86° F. Well 6 appears anomalous on the basis of its temperature alone, when compared with temperature in other wells in the area. Its chloride content, however, is not unusual for wells of this depth in the area. The geothermal gradient in the area is about 1° F per 70 feet of depth (Sproul et al., 1972, p. 16). Thus, if well 5 produces most of its water from near the top of the aquifer (400 to 500 feet) and well 6 produces mostly from the bottom (800 to 900 feet) both wells could reflect normal ground-water temperatures for the area.

Well 19 also has a higher temperature than most wells in the area, though not as high as in well 6. However, the chloride content in well 19 is clearly higher than normal. Since this well is not unusually deep, it is highly likely that a communication is present between the upper part of the Floridan aquifer and a deeper saline aquifer in the vicinity of well 19.

Further investigations to confirm this hypothesis cannot be undertaken, since the wells involved are reported to be plugged with cement.

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TABLE 1

WELL INVENTORY DATA
Township 44 South, Range 23 East, Lee County, Florida

Well No.	Location					Depth of Well, ft	Depth of Casing, ft	Chloride mg/l	Temp. °F
	¼	¼	Sec.	Twp.	Rge.				
1	SE	SE	1	44S	23E	619	133	1,000	83
2	NE	SE	1	44S	23E	1,001	157	--	--
3	SE	SE	2	44S	23E	706	143	655	83
4	SE	SE	3	44S	23E	511	155	--	--
5	NE	NE	3	44S	23E	1,045	159	880	80
6	SW	NE	3	44S	23E	919	137	980	86
7	SE	NE	3	44S	23E	642	157	640	84
8	SE	NE	3	44S	23E	510	155	900	83
9	NE	NW	6	44S	23E	--	--	900	82
10	SW	NE	6	44S	23E	--	--	900	80
11	NE	SE	6	44S	23E	--	--	840	82
12	NW	NE	6	44S	23E	832	122	--	--
13	SE	NE	7	44S	23E	468	128	960	78
14	SW	SE	8	44S	23E	601	156	940	--
15	NE	SE	9	44S	23E	--	--	--	83
16	NE	SE	10	44S	23E	800	--	--	77
17	NW	NE	11	44S	23E	--	--	820	82
18	NW	NE	11	44S	23E	515	164	670	82
19	SE	NE	11	44S	23E	835	162	2,380	85
20	NE	NE	11	44S	23E	857	170	--	--
21	NE	SW	12	44S	23E	--	--	670	82
22	NE	SW	12	44S	23E	512	117	740	80
23	NE	NW	13	44S	23E	585	151	--	--
24	NE	NW	13	44S	23E	--	--	720	80
25	NW	SE	13	44S	23E	300	--	240	78
26	NW	NE	13	44S	23E	700	156	--	--
27	SE	NE	13	44S	23E	815	132	--	--
28	SW	SW	14	44S	23E	--	--	--	82
29	NW	NW	15	44S	23E	--	--	540	81
30	SE	NW	15	44S	23E	225	--	84	80
31	SW	NE	15	44S	23E	--	--	660	82
32	SE	SW	15	44S	23E	--	--	--	82
33	SW	SE	15	44S	23E	683	159	--	--
34	SW	SE	15	44S	23E	800	--	600	84
35	SE	SE	15	44S	23E	790	--	640	83
36	NE	SE	15	44S	23E	796	163	--	--
37	SW	NW	17	44S	23E	468	126	1,200	81
38	SW	NW	17	44S	23E	--	--	620	76
39	SW	SW	17	44S	23E	390	117	--	--
40	SW	SE	17	44S	23E	978	--	--	--
41	NW	SE	18	44S	23E	--	--	--	83
42	NW	NW	19	44S	23E	--	--	780	77
43	SE	NE	19	44S	23E	1,000	--	640	82
44	NE	SW	19	44S	23E	--	--	640	84
45	NE	SE	20	44S	23E	--	--	360	79
46	NE	NE	21	44S	23E	700	--	480	79
47	NE	SW	21	44S	23E	700	--	600	81
48	SE	SW	21	44S	23E	--	--	220	74
49	NE	NW	22	44S	23E	660	70	800	83
50	SE	NE	22	44S	23E	--	--	520	82
51	NW	NE	23	44S	23E	808	133	--	--
52	NW	SE	24	44S	23E	590	177	--	--
53	NW	NE	25	44S	23E	1,000	--	880	85
54	SW	SW	25	44S	23E	1,000	--	560	84
55	NE	NW	27	44S	23E	157	42	--	--
56	NW	NW	27	44S	23E	444	112	--	--
57	SW	NW	27	44S	23E	630	--	560	81
58	NE	NW	28	44S	23E	--	--	240	74
59	SE	NW	28	44S	23E	--	--	620	78
60	SW	SE	32	44S	23E	--	--	600	79
61	SE	SE	32	44S	23E	--	--	600	79
62	NE	SW	33	44S	23E	--	--	560	78
63	SW	SW	33	44S	23E	--	--	600	78
64	SE	SE	36	44S	23E	1,000	--	1,000	--

McGREGOR ISLES (LEE COUNTY)

An investigation by Sproul et al. (1972) of a group of high-salinity wells south of Fort Myers led to the delineation of a "hot spot" in this area. The location of the area is shown on Figure 5. Normal ground-water temperature in the surrounding area ranges from 81° F to 83° F in wells 500 to 700 feet deep. The highest temperature measured in the anomalous area was 93° F in a 710-foot well.

The "hot spot" encompasses about two square miles. Within this area, 25 wells exhibiting abnormal temperature and water quality characteristics were found. Data from an intensive geophysical logging program suggests that the anomaly is associated with a series of faults, as shown on Figures 6 and 7. Other later data (Boggess, personal commun., 1975) suggests that the structurally high area is an anticline rather than a faulted structure.

Whether or not faulting is involved, it appears certain that this thermal anomaly is produced by warm, salty water from a deep artesian aquifer invading a shallower brackish aquifer. The hypothesis best fitting the observed data is that a conduit is present near the center of Section 16, Township 45 South, Range 24 East, connecting the deep aquifer with shallower aquifers. The shape of the body of intruding warm water (Figure 6) suggests that the conduit may be developed along complementary components of a fracture system. The pattern exhibited by the spread of high-chloride water (Figure 7) is even more suggestive of fault or fracture acting as a line source of intruding saline water.

The conduit most probably is a zone of increased permeability produced by solution along a fault or fracture plane at a time when the base level of solution was much lower than at present. The depth to which the conduit extends is estimated to be 1,600 to 1,700 feet, on the basis of ground-water temperatures. The intrusion of warmer water was probably initiated by heavy withdrawals of irrigation water from the Floridan Aquifer in the area.

CHARLOTTE COUNTY "HOT SPRINGS"

A deep well in Charlotte County has been flowing salt water at a temperature of 96° F for many years. The location of this well, which was once the subject of a commercial development as a spa, "Hot Springs of Florida," is shown on Figure 5.

Since this well is at least 9° F warmer than any other well in the vicinity, it might be considered a likely candidate as an anomalous "hot well." However, geophysical logging of this well shows it to be 1,640 feet deep. The well terminated in a large solution cavity from

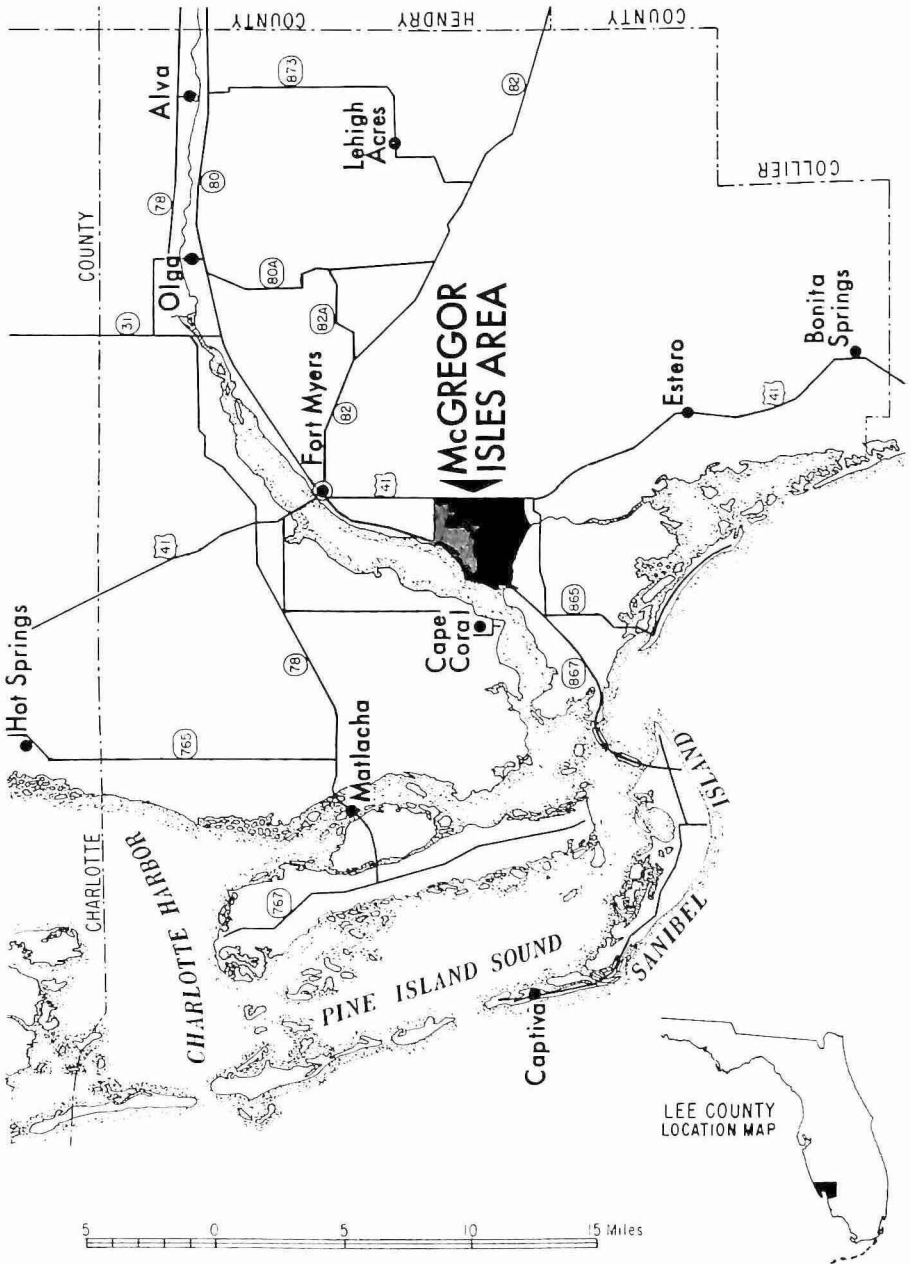


Figure 5. Map of Lee County showing the location of the McGregor Isles area (from Sproul et al., 1972)

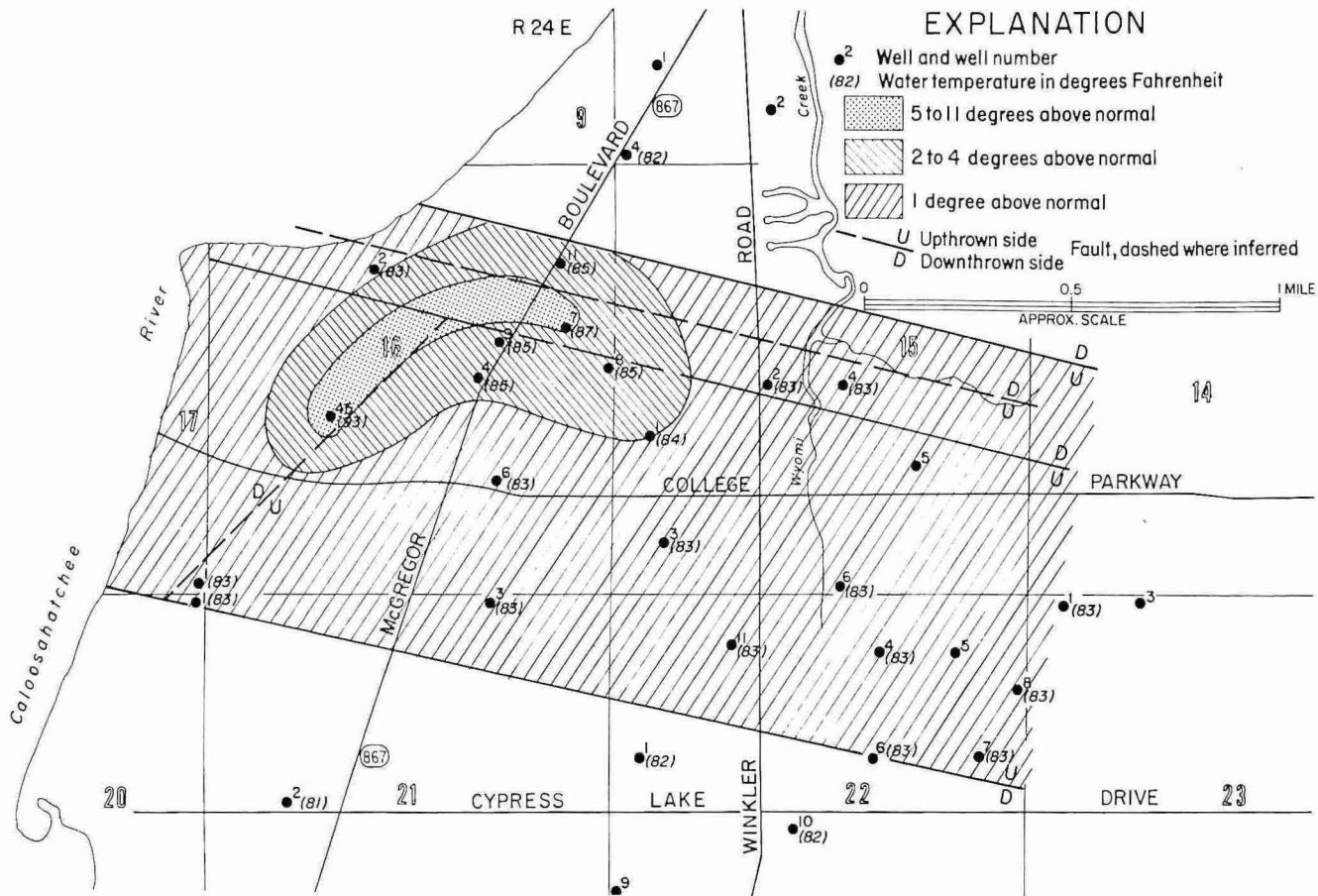


Figure 6. Map showing the effects of intrusion on water temperatures in the lower Hawthorn aquifer (from Sproul et al., 1972)

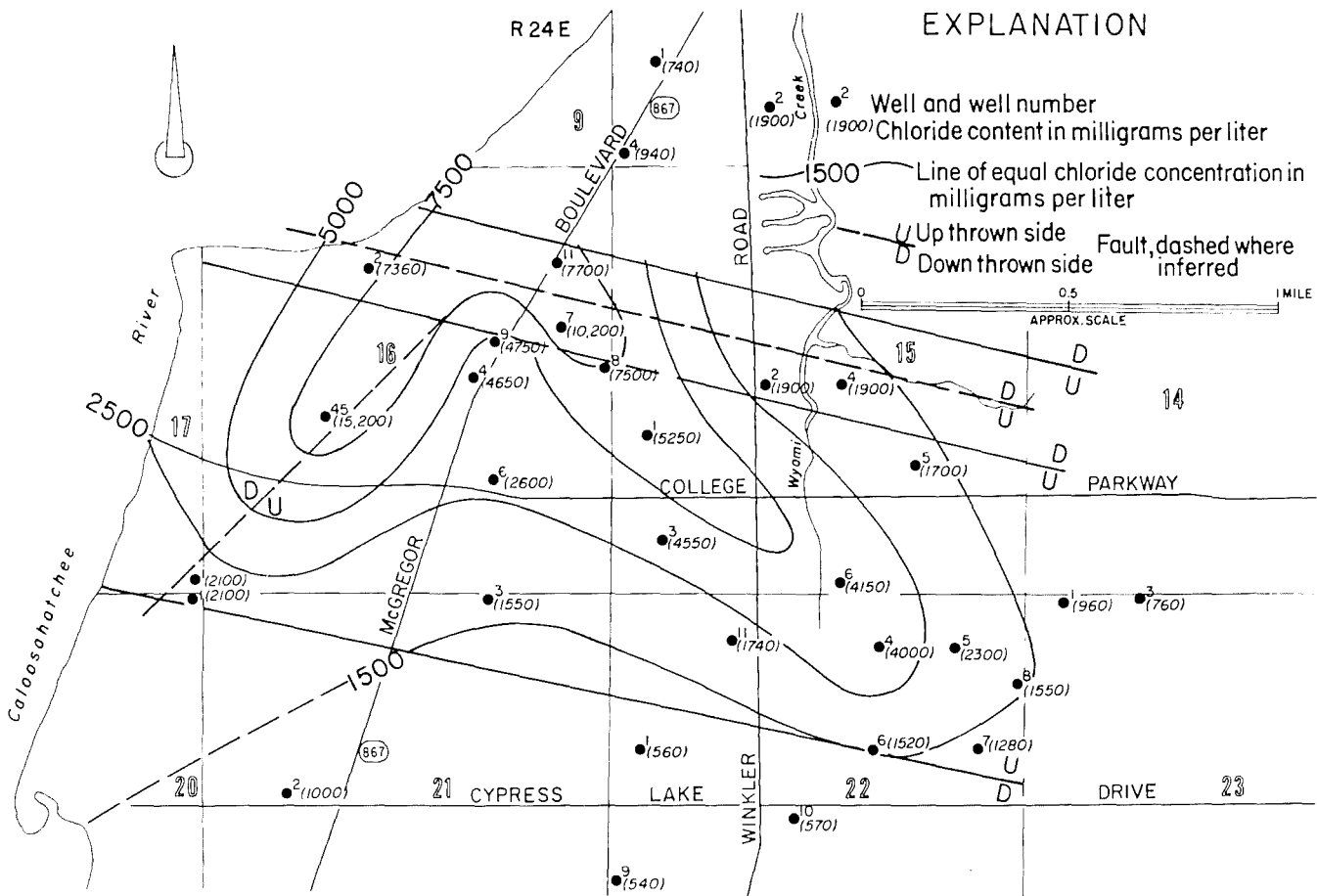


Figure 7. Map of McGregor Isles showing the extent of the saline-water intrusion into the lower Hawthorn aquifer (from Sprout et al., 1972)

which most of the well flow emanates. Records of this well in the files of the Florida Bureau of Geology indicate that it was abandoned by the driller due to a large flow of salt water that prevented further progress.

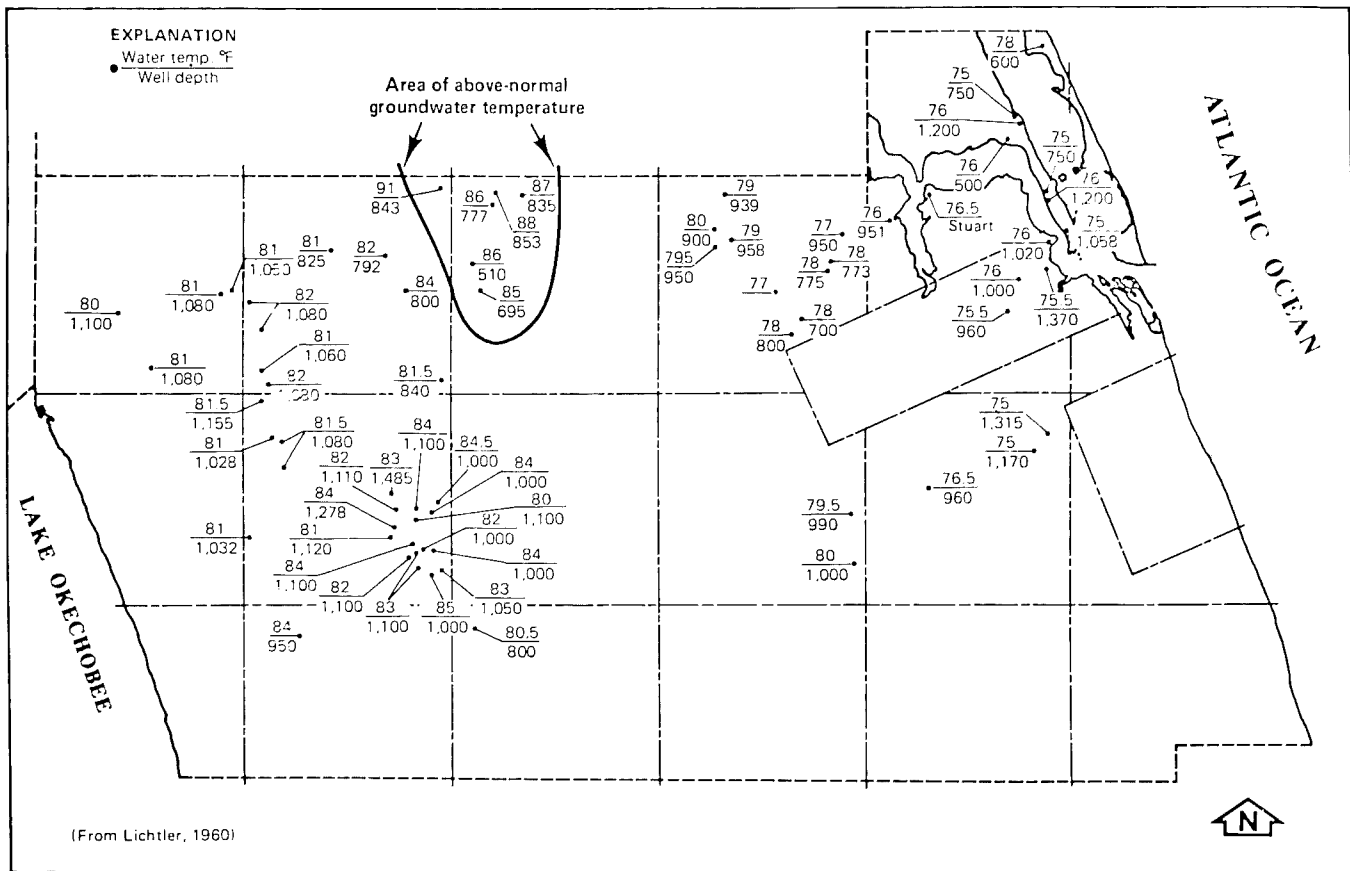
Most of the other wells in this area are 500 to 600 feet deep and have a temperature of about 82° F. If a geothermal gradient of 1° F per 70 feet, as determined for the aquifer in Lee County, prevails here, a 1,640-foot well would be expected to have bottom hole temperature of about 97° F. The "hot springs well" represents an unusually deep well for the area, but not an anomalous "hot well."

MARTIN COUNTY "HOT WELL"

An apparently anomalous "hot well" in the northern part of Martin County is described by Lichtler (1960, p. 62). The location of this well is shown on Figure 8. The reason for the high temperature (91° F) in this well has not been established. Lichtler (p. 63) speculates that radioactivity may be responsible. However, Stringfield (1966, p. 152) feels that this is unlikely. An analysis of radioactive elements in the water from this well, presented in Lichtler's report (p. 52), does not indicate the presence of any unusual concentration of these elements.

Water from the well does not have, for this area, any apparent unusual chemical properties such as high chlorides that would indicate a deep source. Nevertheless, its temperature is clearly anomalous. Normal ground-water temperatures in the area are about 82° F at 500 feet and 85° F at 700 feet, a gradient of 1° F per 67 feet. Even if all of the well flow came from the bottom of the well (843 feet) the temperature would be only 87° F.

No investigations have been undertaken to explain the anomalous temperature in this well. A working hypothesis is suggested as follows: The well is in close proximity to a vertical conduit connecting with a deeper artesian aquifer. If this is the case, the deeper aquifer contains brackish water similar in quality to the aquifer zones between 500 and 900 feet. An aquifer zone at a depth of approximately 1,100 feet would satisfy both temperature and salinity requirements to fit the criteria of this hypothesis. The "hot well" may only be the warmest of a group of wells affected by such a connection with a deeper zone. The latter is suggested by temperatures in surrounding wells, as shown on Figure 8.



PEACE RIVER VALLEY

A generally north-south trending area of high ground-water temperatures was mapped by Kaufman (Kaufman and Dion, 1967) in DeSoto and Hardee counties. This apparent anomaly follows generally the valley of the Peace River. Coincident with the thermal anomaly are trends in several water quality parameters, including concentrations of total dissolved solids, sulfate, and hardness.

The occurrence of a thermal anomaly in conjunction with highly mineralized water is consistent with an upwelling of deep artesian water in this area. Kaufman postulates that the deeper water is ascending along a linear fracture zone or fault paralleling the Peace River. A more intensive study of ground-water conditions in the area (Wilson, 1975) shows the anomalous conditions less sharply defined than mapped by Kaufman. In his study, Wilson found no evidence of faulting in the area; likewise, test drilling data across the area obtained by an electric utility company did not show any evidence of faulting.

It is suggested here that the thermal anomaly along the Peace River is due to a combination of the following factors:

1. The area of the apparent anomaly coincides generally with the area of artesian flow. Thus, the river valley is a ground-water discharge area with recharge to the aquifer occurring on the adjacent uplands. This situation results in a temperature and water quality contrast between the valley and uplands.
2. The upper producing zones of the Floridan Aquifer are less productive along the Peace River Valley than elsewhere in these counties. Thus, the average depth to the first major water-producing zone penetrated by wells in the area is greater and the temperature of the water higher.

Downhole temperature measurements made by the author in northeast DeSoto County indicate a vertical temperature gradient of 1° F per 107 feet. If this gradient is applicable to the river valley area, a temperature between 84° and 85°F would be predicted for a depth of 800 to 900 feet. These values are consistent with actual temperatures and well depths in the area.

EAST COAST COOLING ANOMALY

Due to the kinetics of ground-water flow, ground-water temperature in a confined aquifer normally increases with distance downgradient and depth in the aquifer. However, as Figure 4 shows, ground-water temperatures decrease downgradient along the east and southeast coast. The downgradient decrease in temperature is accompanied by a reversed vertical gradient with temperature de-

creasing with depth.

The cooling anomaly is evident at least as far north as St. Lucie County and extends down the coast to the upper Keys. The lowest temperature measured to date has been 59° F in a 3,100-foot deep well at Margate, near Fort Lauderdale. The lowest temperature measured in a well in the upper part of the aquifer is 69° F in a 980-foot well at Miami Beach.

At least two hypotheses have been proposed to account for this cooling anomaly. Early investigators, cited by Stringfield (1966, p. 153), suggested that low temperatures observed in Dade County were due to cooling of the aquifer water by the cold ocean water present at the submarine outcrop of the aquifer. Lichtler suggested the same mechanism to account for a seaward cooling anomaly in Martin County (see Figure 8). Vernon (1970, p. 13) also cited heat loss to the cold ocean water as a likely cause of the generally lower temperatures of ground water along the southeast coast.

A hypothesis involving cyclic convective flow of cold ocean water has been proposed by Kohout to account for the cooling anomaly. According to this hypothesis, geothermal heating causes cold ocean water (43° to 40° F) to move inland along the base of the aquifer, where it would become warmer and less dense, rise, mix with less saline water, and flow back toward the ocean.

At present, there is insufficient data to fully support either hypothesis. The cyclic flow mechanism suffers from three principle difficulties:

1. In order for the cyclic flow proposed by Kohout to occur, there must be at some depth in the aquifer system a landward gradient. No such gradient has been measured to date. It should be noted, however, that most determinations to date of the potentiometric gradient are rather imprecise.
2. The cyclic flow proposed by Kohout should be accompanied by an increase in salinity with depth. This seems to be true in extreme south Florida, but not in Martin and St. Lucie counties. Figure 9 shows the temperature and chloride content at different depths in a deep well at Stuart in Martin County. These data show a reversed temperature gradient accompanied by less saline water in the lower part of the Floridan Aquifer. Obviously, mixing of Floridan Aquifer water with cold salt water cannot be responsible for both. Freshening of water with depth in the aquifer has also been observed by the author and confirmed by drill-stem testing and geophysical logging in St. Lucie County.

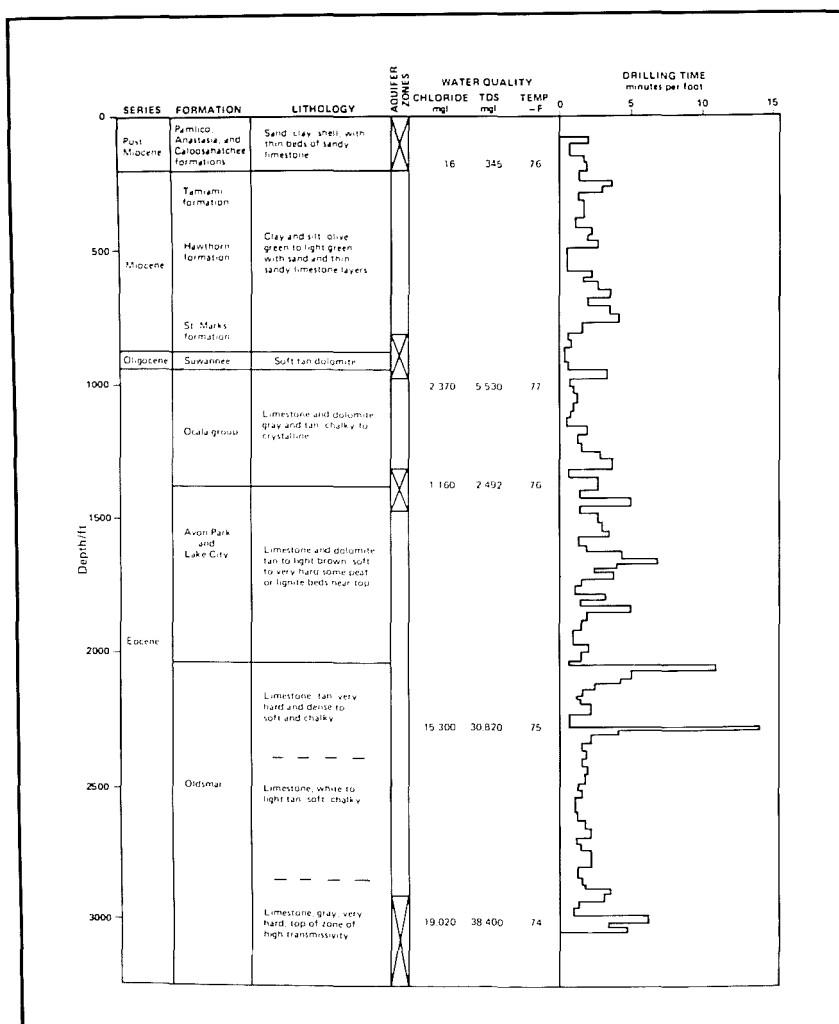


Figure 9. Drilling and water quality data from a deep well at Stuart, Martin County

3. Within the aquifer system there are extensive beds having low permeability which would seem to prevent the development of a convective cell, as proposed by Kohout.

A quantitative analysis of the conductive cooling hypothesis will require data on the thermal properties of the aquifer system which are not now available, along with rates of ground-water movement in various components of the system.

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**TERRESTRIAL HEAT FLOW VALUES IN FLORIDA
AND THE THERMAL EFFECTS OF
THE AQUIFIER SYSTEM**

by

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ABSTRACT

Geothermal gradients measured in nonflowing boreholes with a thermistor probe assembly and a limited number of conductivity measurements on borehole rock have yielded seven new terrestrial heat-flow values for Florida ranging from 1.3 heat-flow units (Mcal/sec cm²) in Santa Rosa County to 0.1 HFU in Gilchrist County. Based on results of this study and existing data, the average heat flow for Florida is $0.71 \pm .35$ (s.d.) HFU. General deviations from this value occur in the western panhandle, and in and adjacent to the interior region of central highlands. Higher than average heat flux in the extreme western panhandle exists despite the presence of a thick clay unit (the Pensacola clay) acting as a "geothermal insulator" above the Floridan Aquifer, and lower than average heat flux in the central region may be related to the general hydrogeologic recharge nature of the area.

Interpretation of the values is complicated by uncertainties in the nature of heat transport within the extensive Floridan aquifer system. Although large scale comprehensive hydrologic effects are difficult to assess, major variations of geothermal gradients and conductive heat-flow values within individual boreholes are attributed to local convective and circulatory properties of the aquifer. Measurements in Nassau County suggest a convective heat transfer equivalent to 0.7 HFU and an upward flow velocity in convection cells of 0.3 m/yr. A maximum heat flow loss of 1.0 HFU from lateral flow of recharge water is estimated from measurements made in Sarasota County.

The relatively low heat-flow values in Florida apparently represent an extension and perhaps more pronounced expression of the marginally low heat-flow values (~ 1.0 HFU) of the southern Appalachians. This trend of decreasing heat-flow values toward the southeast is evident in the Florida peninsula, implying a possible modification of the continental crust underlying the peninsula.

INTRODUCTION

Of the several thousand measurements of geothermal heat flow from the earth's crust, perhaps only one-third have been made on the continents. A preponderance of these measurements has been made in areas characterized by crystalline rocks, and only a few reliable heat-flow values are known for areas with thick sedimentary terrains. This is due, in part, to the variability of thermal conductivity among various sedimentary units and the difficulty in obtaining high quality conductivity and temperature gradient values in poorly consolidated sedimentary rocks.

Geothermal knowledge of the Florida Plateau is limited by a marked paucity of heat-flow measurements in the state. Thermal investigations in Florida are complicated not only by the thick sequences of clastic and carbonate sedimentary rocks comprising the plateau, but more importantly, by the pervasive and enigmatic Floridan aquifer system. Nevertheless, a few theoretical geothermal models for the Florida subsurface have been proposed; these range in purpose from an assessment of potential thermal energy (Johns, 1975) to an association with tectonic models of continental blocks (Long and Lowell, 1973).

This paper utilizes previously existing data in combination with seven new, directly-measured values of terrestrial heat flow in order to better define the thermal nature of the Florida peninsula. Geothermal gradients and heat-flow values have been analyzed for thermal distortions related to the Floridan aquifer system, and possible effects of lateral flow and convection are estimated. Because the near surface vertical heat flux may be related to the thermal nature of basement rocks and crustal composition, the Florida heat-flow values are useful in evaluating the uncertainty (Bass, 1969) concerning the presence of continental crust in the southern peninsula.

PREVIOUS WORK

Using bottom hole temperatures from approximately 300 electric log surveys, Griffin et al. (1969) and Reel and Griffin (1971) developed a geothermal gradient map of Florida. The data pool was later expanded and published as a segment of the Geothermal Survey of North America (American Association of Petroleum Geologists, 1974). The primary purpose of these maps was to define areas with subsurface temperatures potentially favorable for oil and gas production. Gradients ranged from approximately $1.6^{\circ}\text{F}/100\text{ ft.}$ ($27^{\circ}\text{C}/\text{km}$) in the western panhandle to $0.8^{\circ}\text{F}/100\text{ ft.}$ ($13.5^{\circ}\text{C}/\text{km}$) in the southern part of the peninsula. Even lower gradients were reported from the extreme southern Keys. Two potentially favorable trends for hydrocarbon production were identified: (1) extreme northwest Florida in the Jurassic trend of the Jay Field, and (2) the southwest peninsula in the lower Cretaceous Sunniland Field.

Kohout (1967) and Henry and Kohout (1972) employed temperature surveys from selected Florida oil test holes to demonstrate a negative thermal gradient in the lower portions of the Floridan aquifer system in southern peninsular Florida. Apparent, a lateral influx of cold sea water into the aquifer system extracts the natural heat flowing into the Florida platform from below. Kohout (1967) concludes that the average gradient of $20^{\circ}\text{C}/\text{km}$ below the 1-4 km depth of the aquifer system is a "more normal" indication of thermal flux, but cautions that the effects of cold sea water may also exist at depths greater than the 4 km base of the aquifer system.

Much of the work published previously was based on uncorrected bottom hole temperatures recorded for petroleum concerns. Those values were sought for specific purposes (i.e., for computing resistivity of drilling muds), and were determined immediately following drilling activity, while abnormal thermal effects were still present; consequently, the bottom hole temperatures did not reflect equilibrium steady-state geothermal conditions.

Previously published heat-flow measurements for Florida are limited to the work done by King and Simmons (1972) at a site near Orlando. The gradient at Orlando, measured over a 400 foot (125 m) interval at a depth exceeding 1.5 km, was approximately $22^{\circ}\text{C}/\text{km}$ ($1.3^{\circ}\text{F}/100\text{ ft.}$). Using conductivity values obtained from direct measurements with a divided-bar apparatus, King and Simmons calculated a heat-flow value of 0.92 ± 0.03 HFU (1 Heat Flow Unit = $1\text{ microcalorie}/\text{cm}^2\text{sec}$).

Reel (1970) used gradients obtained from uncorrected bottom hole temperatures in combination with estimates of thermal conduc-

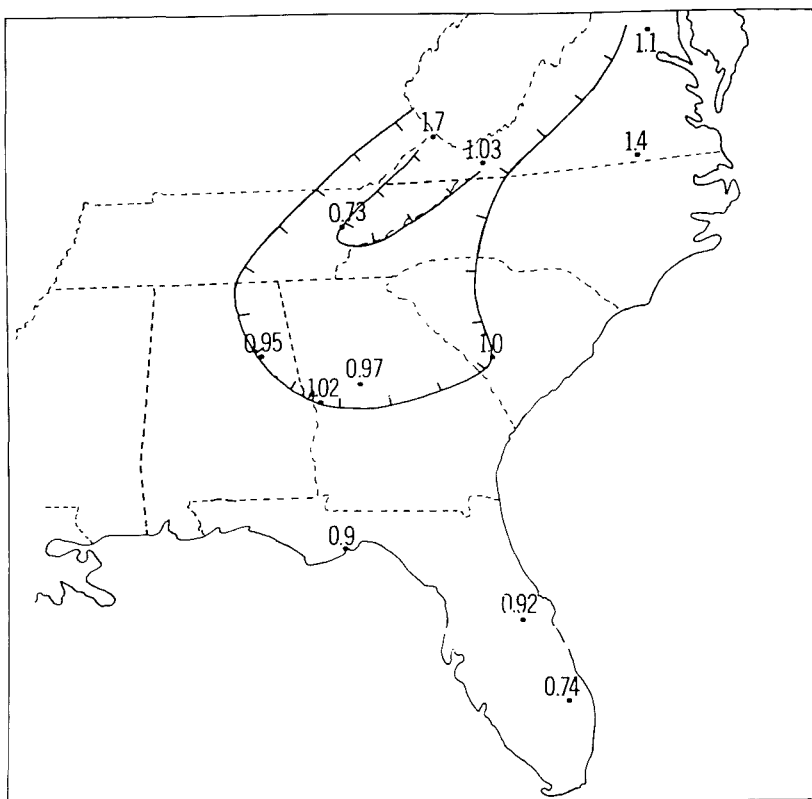


Figure 1. Previously determined heat flow values in southeastern United States. Values are in heat flow units and the hachured lines depict the 1.0 and 0.8 HFU contours as presented by Diment et al. (1972). After Diment et al. (1972), figure 3, with data additions from Reiter and Costain (1973), King and Simmons (1972), and Reel (1970).

tivity based on sample porosity to calculate heat flow at two locations in Florida. Reel's calculations of heat flow for Franklin County (0.9 HFU) and for Palm Beach County (0.7 HFU) are consistent with the values reported by King and Simmons and in this paper, thereby lending credibility to the validity of gradients from electrical logging records.

Diment et al. (1972) summarized published heat-flow values for the eastern United States and proposed a distribution of heat-flow contours (figure 1). Four existing heat-flow values and estimates in South Carolina, Georgia, and Alabama were used to delineate the southern terminus of an anomalously low thermal zone closed about the southern Appalachians. Subsequent measurements in Vir-

ginia (Reiter and Costain, 1973) and the data of King and Simmons (1972) and Reel (1970) suggest the necessity of a revised model embracing a possible southerly continuation into Florida of the zone of low heat-flow values. The only heat-flow value available for the area bounding the northern Gulf of Mexico basin is an estimate of 1.2 HFU presented by Jam L. et al. (1969) for southern Louisiana. Jones (1970) has described high temperature gradients in geopressured zones, zones of high interstitial fluid pressure, at several kilometers depth in southern Louisiana.

METHODS

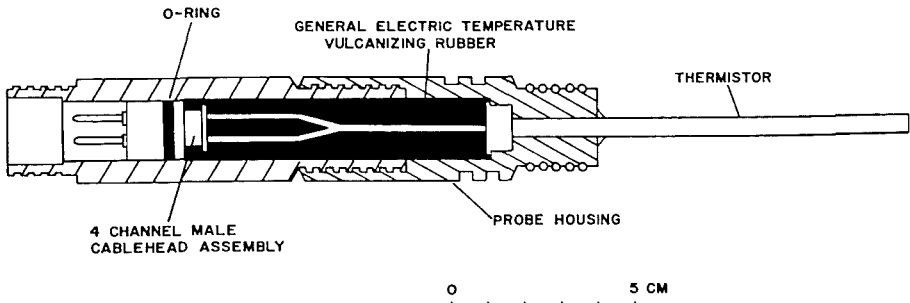


Figure 2. Probe assembly used for borehole temperature measurements.

Downhole temperatures were measured with a probe assembly (figure 2) consisting of a single 5-inch long Fenwal UUA 35J3 thermistor and a one-inch diameter Gearhart-Owen stainless steel housing. The probe assembly was coupled to a 1000 meter, four-conductor cable and lowered into boreholes using a reel mechanism adapted with an eight brush Fabricast 1401 slip ring. A Mueller-type Wheatstone bridge, similar to that described by Roy et al. (1968a), with an ESI six-decade variable resistor and a Leeds and Northrup 2437 null detector was used to match thermistor resistances.

The best-fit equation:

$$T = \left[B \ln \frac{R}{R_0} + \frac{1}{T_0} \right]^{-1} \quad (1)$$

relating temperatures and resistance was developed with the parameter $B = f(R)$ based on calibrated readings of R_0 (base resistance) at 5°C intervals of T_0 (base temperature) from 10°C to 40°C . Borehole temperatures were usually measured at 10 or 20 meter intervals and least square gradients were derived by computer from the relationships:

$$T_o = \frac{\sum z \cdot \sum z T - \sum z^2 \cdot \sum T}{(\sum z)^2 - N \cdot \sum z^2} \quad (2)$$

and,

$$\text{GRAD} = \frac{\sum z T - T_o \sum z}{\sum z^2}$$

where $\sum = \sum_{i=1}^N$ (3)

and N is the number of temperature (T) and depth (Z) values.

We estimate an accuracy of $\pm 0.1^\circ\text{C}$ for our temperature measurements, but the accuracy of temperature differentials used for gradient values is considered to be much better, perhaps $\pm 0.01^\circ\text{C}/\text{km}$. The cable used was marked at 20 meter and some 10 meter intervals, and depth values are presumed accurate to ± 0.1 meter.

Thermal conductivities of representative core samples were determined with a divided-bar apparatus similar to that described by Beck (1957). Cylindrical samples were ground to 0.5 cm thickness, stored in fresh water, and placed in series with two 10 cm brass cylinders. Circulating baths maintained the upper bar at 32°C and the lower bar at 10°C , which kept the sample at approximately 21°C in order to approximate (within $\pm 10^\circ\text{C}$) the *in situ* earth temperature for the core samples. Temperature ratios were measured with six copper-constantan thermocouples, three in each bar, connected to a digital voltmeter; General Electric Lexan was used for calibration. Mean harmonic values for conductivity (K) were calculated from N samples of individual conductivity K_i using the relationship:

$$K = \left[\frac{1}{N} \sum_{i=1}^N \frac{1}{K_i} \right]^{-1} \quad (4)$$

Each cylindrical sample was measured several times. In general, precision was within 10% of an average value, but an absolute accuracy of 10-20% may be more likely. Repeated calibration with Lexan (table 1) provided the only basis for determining accuracy.

Values for vertical heat flow were calculated from

$$Q = -K \frac{dT}{dz} \quad (5)$$

where K is the mean harmonic conductivity and dT/dZ is the least squares vertical temperature gradient. The uncertainties presented later reflect variances in counting statistics, whereas the absolute deviations from actual values may be on the order of $\pm 20\%$ (see DISCUSSION). Topographic corrections of calculated gradients were not deemed necessary because of the low topographic relief in Florida.

OBSERVATIONS

Equilibrium temperature gradients were determined from direct measurements in nine boreholes in Florida (figure 3). Figure 4 shows the temperature-depth profiles for each of the holes measured plus an additional profile from Palatka supplied by D. G. Jopling (Personal commun., 1975). Table 2 summarizes the thermal conductivity data, and table 3 lists the geothermal gradients and calculated terrestrial heat-flow values for each well. A complete listing of individual temperature and conductivity values is given by Fuller (1976). The various sites are discussed below:

MILTON

The highest thermal gradient determined in this survey was recorded in an American Cyanamid monitor well approximately five miles southwest of Milton in Santa Rosa County. The hole penetrated sand and gravel in the upper 100 meters, Pensacola Clay from approximately 100-250 meters, and limestone below 250 meters. The overall least squares gradient was computed to be $34.29^{\circ}\text{C}/\text{km}$. However, the gradient profile was highly segmented, yielding values obviously related to the lithology:

Gradient ($^{\circ}\text{C}/\text{km}$)	Depth Interval (m)	Lithology
14.95	60-140	sand and gravel; clay
40.28	160-240	clay
30.24	260-320	limestone

Measurements of thermal conductivity on three separate samples of Pensacola clay prepared from a single core specimen (198-201 m) average $2.99 \text{ mcal/sec cm}^{\circ}\text{C}$ (units omitted hereafter for convenience), whereas two core specimens of limestone (445 m and 460 m) yielded an average value of 4.84.

Using the mean harmonic conductivity values for both the clay and limestone layers, and the separate gradient values for each zone, heat-flow (Q) values of 1.2 HFU above approximately 260 meters and 1.5 HFU below that depth were calculated. The overall heat flux, based on the mean harmonic conductivity and the overall least squared gradient, was 1.3 HFU.

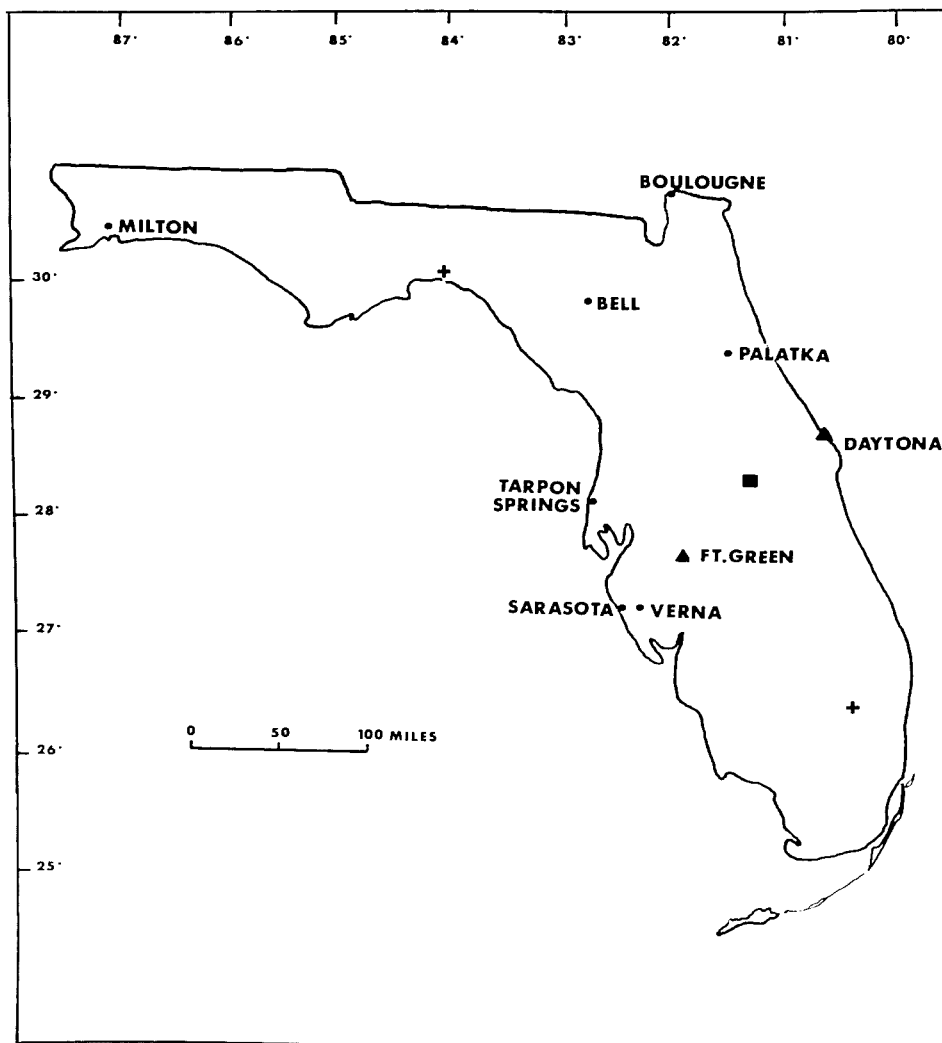


Figure 3. Distribution of heat flow measurement sites in Florida. Circles and triangles represent new values and estimates, respectively, presented in this study. Previous measurement sites are located by crosses (Reel, 1970) and square (King and Simmons, 1972).

BOULOUGNE

An inactive water well drilled for the Humphreys Mining Company in extreme northwestern Nassau County near Boulougne penetrated interbedded clay and sand near the surface and limestone at 160 meters depth. The temperature log of this borehole (figure 4) shows a striking difference in gradient between the shallow clastic layers ($16.38^{\circ}\text{C}/\text{km}$ between 20 and 140 meters depth) and the

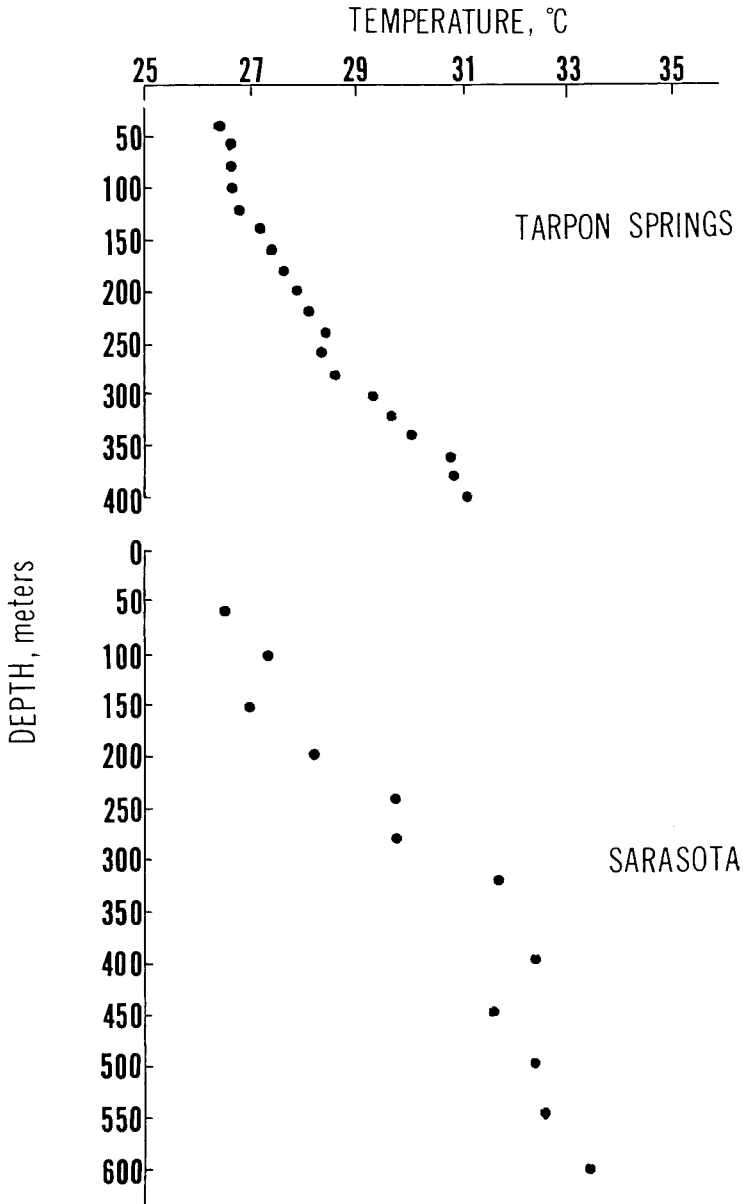
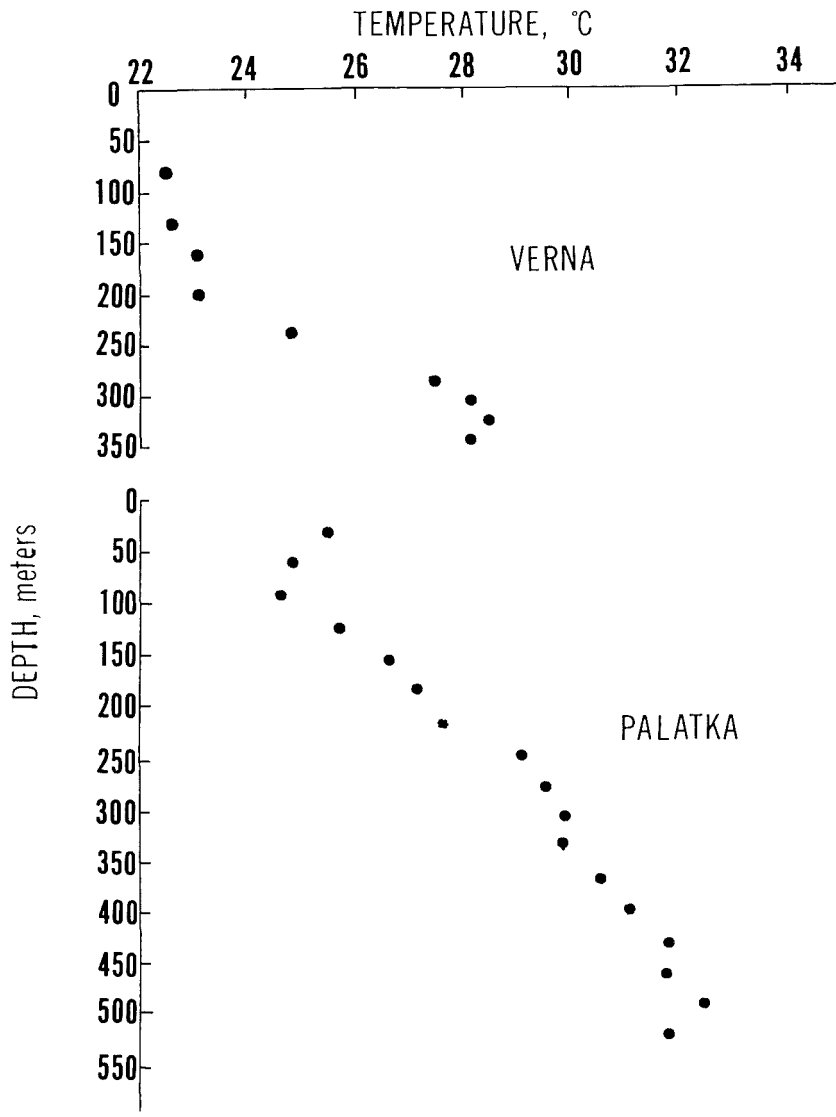
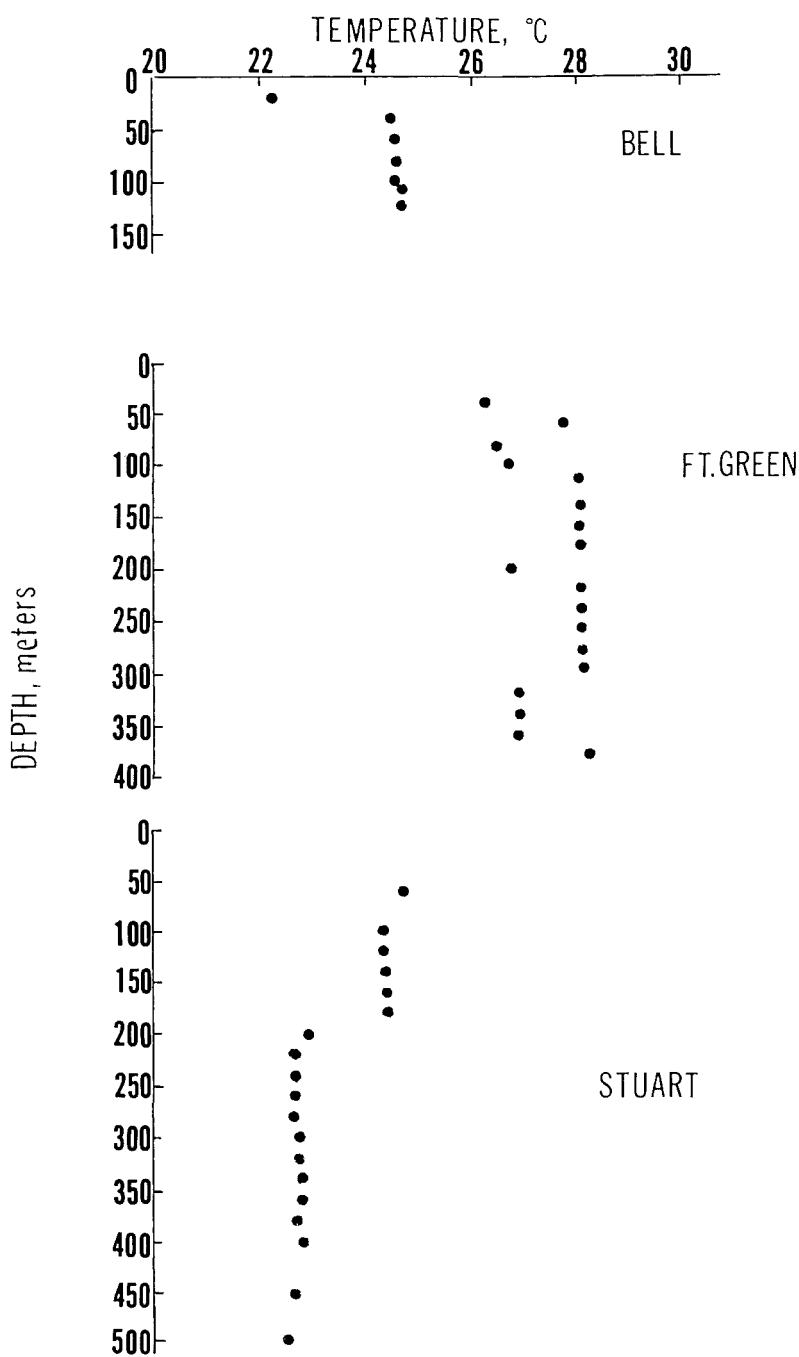


Figure 4. Temperature-depth profiles in Florida boreholes. Values for Palatka are from data supplied by Florida Power and Light Corporation.

BUREAU OF GEOLOGY





BUREAU OF GEOLOGY

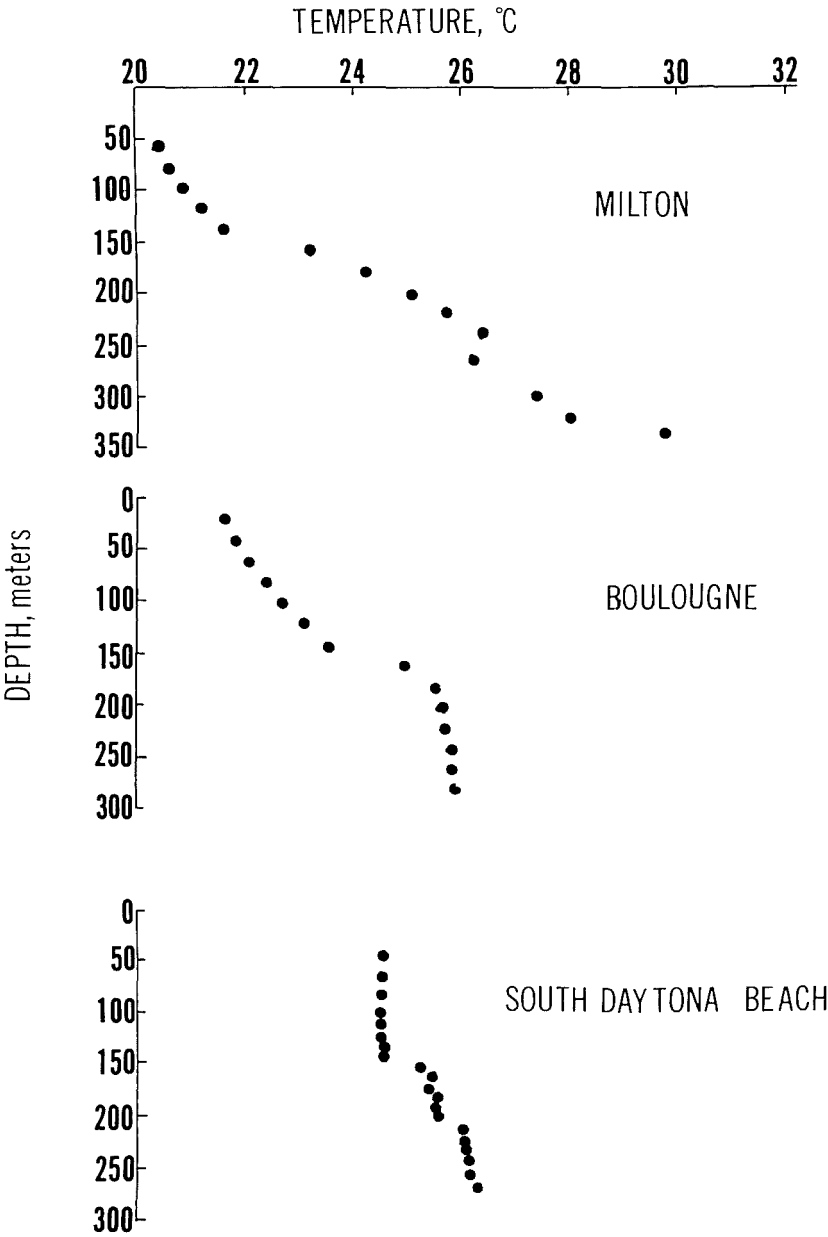


Table 1. Measured Thermal Conductivity for Lexan.

<u>Date</u>	<u>Value (10⁻³cal/sec cm °C)</u>
13 Aug 75 ¹	1.95
1 Oct 75	2.26
4 Oct 75	2.13
12 Oct 75	2.08
16 Oct 75	2.06
26 Oct 75	2.27
6 Nov 75	2.20
10 Nov 75	2.05
Standard ²	2.103

¹Values selected randomly

²Provided by representatives of General Electric Co. (personal communication)

limestone (3.61° C/km between 180 and 280 m). Between these two zones lies a thin transition zone with a calculated gradient of 50.57° C/km (140 to 180 m).

Conductivity values were determined for three clastic specimens and two limestones (22 m to 268 m depth) from two nearby holes. The mean harmonic conductivity for the clastic samples is 3.16, whereas the conductivity of the limestone is 3.84. These data yield a heat flow of 0.5 HFU for the clastic segment (20-140 m), and a heat flow of 0.1 HFU for the deeper, limestone portion of the hole.

Table 2.

<u>Location</u>	<u>Depth (m)</u>	<u>Average Conductivity (10⁻³ cal/cm sec°C)</u>	<u>Standard Deviation</u>	<u>Mean Harmonic Conductivity</u>
Palatka	64	3.35	0.21	
(cores from other	73	2.54	0.19	5.21
holes in Putnam	896	5.21	0.16	
County)	326	5.20	0.34	
Daytona Beach	566	5.42	0.15	
(cores from other	756	4.14	0.29	
holes in Volusia	806	4.73	0.48	
County)	819	5.51	0.56	
	841	4.10	0.40	4.88
	871	5.56	0.11	
	1425	4.70	0.50	
	1510	4.33	0.27	
	1698	5.69	0.31	
Tarpon Springs	88	4.04	0.19	
	152	3.53	0.16	
	183	4.80	0.31	
	244	5.30	0.39	4.41
	281	6.00	0.28	
	335	3.82	0.15	
Milton	198-201 ¹		0.33	3.67
	198-201 ¹		0.19	2.61
	198-201 ¹	3.42	0.17	2.71
	442-447		0.19	4.95
	457-465		0.27	4.73
Boulougne	22 ²		0.54	3.77
(cores from	46-53		0.17	2.14
other holes in	157	3.16	0.27	3.64
Nassau County)	195		0.24	3.52
	268		0.13	4.16
Bell	62		0.22	3.34
	69		0.10	3.32
	76		0.22	3.57
	91	3.55	0.20	3.61
	99		0.11	3.67
	107		0.21	3.86
	114		0.12	3.57
Sarasota-Verna	133		0.51	5.56
(cores from	140		0.38	5.10
other holes in	143	4.50	0.87	4.88
Sarasota County)	154		0.28	3.42

¹not saturated in water²damaged sample

Table 3.

Location	Depth(m)	N. Lat., W. Long.	N	Conductivity (mcal/sec cm °C)	Gradient (°C/km) (°F/100 ft)		Elev. (m)	Uncorrected Heat Flow (HFU)
Milton	60-140	30°35' 87°07'	3	2.99	14.95	0.9	30	1.2
	160-240				40.28	2.4		
	260-320				30.24	1.8		
Boulougne	20-140	30°47' 82°01'	3	3.16	16.38	1.0	27	0.5
	140-180				50.57	3.0		
	180-280				3.61	0.2		
Bell	20-120	29°42' 82°53'	7	3.55	2.10-2.75	0.1	18	0.1
Tarpon Springs	40-240	28°04' 82°47'	6	4.41	10.09	0.6	6	0.4
	260-400				20.83	1.2		
	100-400				15.04	0.9		
Sarasota	0-260	27°21' 82°33'	4	4.58	16.11	1.0	6	0.7
	260-600				10.44	0.6		
	100-400				17.98	1.1		
Verna	80-200	27°22' 82°16'	4	4.58	5.43	0.3	24	0.2
	200-340				40.65	2.4		
	80-340				26.46	1.6		
Palatka	91-274	29°38' 81°38'	2	5.21	26.66	1.6	23	1.4
	243-487				13.82	0.8		
	426-518				1.87	0.1		
	100-518				16.27	1.0		

Table 3. Thermal conductivity geothermal gradients, and heat flow values

BELL

Temperatures measured in a relatively shallow drill hole near Bell in Gilchrist County represent the only values determined from a hole drilled expressly for scientific purposes. Two series of temperatures were measured: the first series was made one day after cessation of drilling, and the second series was recorded three days later. The temperatures for the two series varied less than 0.05°C at any depth, and the gradient calculated, 2.10 versus $2.75^{\circ}\text{C}/\text{km}$, were not greatly different. The similarities suggest little or no thermal disturbance from drilling.

The significantly low gradient measured here was determined entirely within limestone strata. It is similar to the $3.61^{\circ}\text{C}/\text{km}$ mentioned above in the lower, or limestone, portion of the Boulougne drill hole.

Seven core samples were analyzed for thermal conductivity yielding a mean harmonic value of 3.55. Based on the measured gradient and conductivity of the limestone, a heat-flow value of 0.1 HFU was calculated.

TARPON SPRINGS

Measurements in Pinellas County were accomplished in a relatively deep well drilled for the Pinellas County Pollution Control Department near Tarpon Springs. The hole passed primarily through carbonate rocks with occasional lenses of sand or clay. In general, dolomite predominated from 180 to 260 meters, whereas limestone and dolomitic limestone, each associated with gypsum, were the typical rocks below 260 meters depth.

The temperature gradient for this hole is not characterized by visually apparent major discontinuities, and a least squares gradient of $15.04^{\circ}\text{C}/\text{km}$ was calculated for the range 100-400 meters. Closer inspection, however, revealed a subtle gradient change at approximately 260 meters, and computer derived gradient values above ($10.09^{\circ}\text{C}/\text{km}$ from 40-240 m) and below ($20.83^{\circ}\text{C}/\text{km}$ for 260-400 m) this depth demonstrates a discernible contrast.

Six core samples were analyzed for thermal conductivity, and the mean harmonic conductivity representative of the entire hole is 4.41. Using this conductivity value and the least squares gradient of $15.04^{\circ}\text{C}/\text{km}$, a heat flow of 0.7 HFU was computed. However, based on individual conductivity values for the two gradient zones, a flux of 0.4 HFU was calculated for the zone above 260 m and 1.0 HFU for the depth range of 260-400 m.

SARASOTA AND VERNA

Temperature values were measured in two drill holes, about 28 km apart, in Sarasota County. Measurements to a depth of 600 m in a City of Sarasota Water Department monitor well revealed an overall least squares gradient of $13.59^{\circ}\text{C}/\text{km}$. A considerably higher gradient, $26.46^{\circ}\text{C}/\text{km}$, was calculated from measurements made near Verna, to the east, in a 340 meter deep county recharge test well. A further disparity between the thermal conditions in the two wells is evident from figure 4. The nature of the thermal gradient in the Sarasota hole changes at approximately 260 m depth from a higher value of $16.11^{\circ}\text{C}/\text{km}$ above that depth to $10.44^{\circ}\text{C}/\text{km}$ between 260 and 600 m. On the other hand, the Verna borehole had a remarkably low gradient, $5.43^{\circ}\text{C}/\text{km}$, from 80 to 200 m, and then a contrasting value of $40.65^{\circ}\text{C}/\text{km}$ below 200 m. This sense of temperature progression with depth is consistent with that observed in the Tarpon Springs well.

No core or cutting samples were available from the Sarasota or Verna boreholes for study, but four core samples from a nearby (40 km south of Verna) hole were analyzed for thermal conductivity values. An incomplete driller's log of the Sarasota hole and descriptions of general stratigraphy for west-central Florida (Puri and Vernon, 1964) suggest that the carbonate samples analyzed are representative of the relatively uniform limestone rock sequences present in that area.

The mean harmonic conductivity value for the four samples analyzed is 4.50 which leads to an overall heat-flow value (conductivity x complete gradient) of 0.6 HFU for Sarasota and 1.2 HFU for Verna. Since the core samples available for analyses were from a depth range of 134-154 m in a nearby borehole, the calculated conductivity value may be applied to the top portions of the two borehole gradients and heat-flow values of 0.7 HFU and 0.2 HFU for Sarasota and Verna, respectively, are calculated. If, as we postulate, the physical properties of the rocks are relatively uniform with depth and the cores are also representative of the deeper portions of the boreholes then heat-flow values for the lower portions of the drill holes are 0.5 HFU for Sarasota and 1.9 HFU for Verna. Finally, a gradient of $17.98^{\circ}\text{C}/\text{km}$ can be computed for the 100-400 m range in the Sarasota hole, leading to a heat-flow computation of 0.8 HFU for that zone.

PALATKA

A water supply well near East Palatka in Putnam County was drilled for the Florida Power and Light Company and logged by a

commercial agency before it was placed in service. Figure 4 shows the temperature profile in that borehole. Least squares gradients of $26.66^{\circ}\text{C}/\text{km}$ (91-274 m), $13.82^{\circ}\text{C}/\text{km}$ (243-487 m), $1.87^{\circ}\text{C}/\text{km}$ (426-487 m), and $16.27^{\circ}\text{C}/\text{km}$ (100-487 m) are calculated for various depth ranges in the hole. The depths of gradient discontinuities may be correlated to formational changes. Extrapolations of formational depths given by Puri and Vernon (1964) for this area suggest that the Hawthorn Formation overlies the Ocala limestone at about 100 m depth, and the tops of the Avon Park limestone and the Oldsmar limestone are at about 270 m and 410 m respectively.

(Four core samples from a nearby hole 30 km west of Palatka) in Putnam County were available for thermal conductivity measurements, but two of the samples were from shallow depths and were representative of only the Hawthorn Formation. The remaining two samples, each with a value of 5.21, were of carbonate rocks from a greater depth than that penetrated by the measured hole. An application, therefore, of a thermal conductivity value based on only two samples of underlying carbonate rocks can only be made with some reluctance. Nevertheless, computations of heat flow for various zones of the Palatka drill hole yield 1.4 HFU for the range 91-274 m, 0.7 HFU for the range 243-487 m, 0.1 HFU from 426 to 518 m, and 0.8 HFU for the portion of the hole in carbonate rock (below 100 m).

OTHER ESTIMATES

Thermal investigations at three additional sites have resulted in two calculations of heat flow that can only be presented as estimates. Figure 4 shows the temperature profile determined in an old, but recently located, drill hole near the Daytona water tower in South Daytona Beach, Volusia County. The well is apparently 30 or more years old and is situated near the eastern edge of the barrier island. The temperature gradient is sharply divided into three segments: $0.29^{\circ}\text{C}/\text{km}$ from 40 to 140 m, $6.14^{\circ}\text{C}/\text{km}$ from 150 to 200 m, and $2.58^{\circ}\text{C}/\text{km}$ from 210 to 268 m. Each segment is offset, however, and an overall gradient of $9.85^{\circ}\text{C}/\text{km}$ can be computed.

No core samples of representative rock from the depth range 40-270 meters near Daytona were available for thermal conductivity measurements. As an alternative, a suite of nine core samples from depths of 550 m to 1,700 m in western Volusia County were measured. The mean harmonic conductivity value for these deeper samples is 4.83, yielding an estimated heat flow of 0.5 HFU for the South Daytona Beach site.

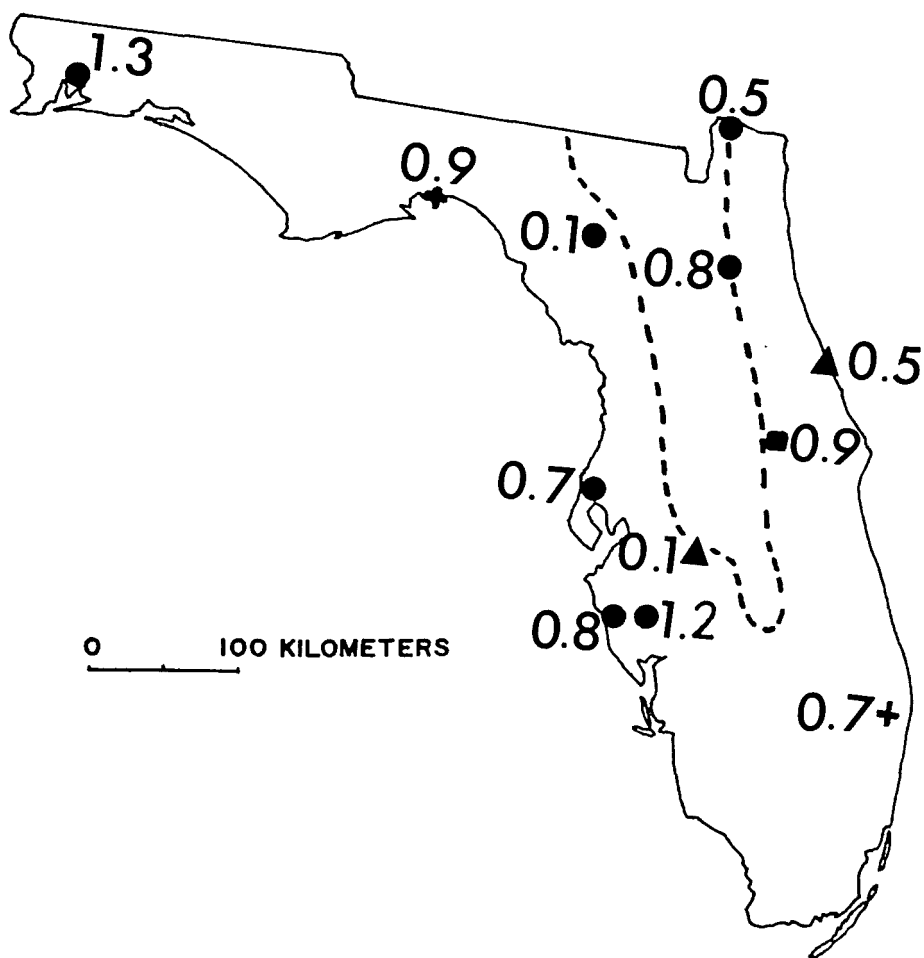


Figure 5. Calculated (circles) and estimated (triangles) uncorrected heat flow values for Florida. Values from Reel (1970) (crosses) and King and Simmons (1972) (square) are also included. All values in heat flow units.

A borehole near Fort Green in Polk County was drilled for the Agrico Chemical Company as a water well and was logged prior to installation of a pump. According to the driller's log, the hole passes through alternating limestone and clays to about 100 meters and is then entirely in limestone. A uniform gradient (fig. 4) is not evident above 100 m depth, but below that depth an unusually linear temperature profile with a gradient of $0.67^{\circ}\text{C}/\text{km}$ extends to 380 meters except for two offsets. A single measurement at 200 m and three measurements over the range 320-360 m were more than 1°C colder

but, when considered separately, approximately the same gradient as the remainder of the hole. Measurements of the hole one month later showed a similarly low gradient ($1.74^{\circ}\text{C}/\text{km}$ from 60-230 m), but did not detect an offset at 200 m depth. No core samples or cuttings were available for conductivity analyses for this site. Consequently, any determination of heat flowing to the surface must be based on estimates of thermal conductivity. The low thermal gradient of this hole combined with any typical estimate of limestone conductivity (4.0 to 5.0) will result in an anomalously low conductive heat flow estimate of approximately 0.1 HFU.

A single attempt to determine a temperature profile in southern Florida was made in a monitor well at the Stuart water treatment plant in Martin County. This well was the only nonflowing well in south Florida that we were able to locate. The gradient (figure 4) displays one discontinuity at about 200 m depth and is consistently negative ($-4.13^{\circ}\text{C}/\text{km}$) throughout. Measurements of thermal conductivity on four samples representative of the rock penetrated by the Stuart drill hole were completed, but calculation of a positive (upward) conductive heat flow is not possible, and no estimate can be presented.

DISCUSSION

The variability of geothermal gradients within many drill holes and the resulting diversity of calculated heat-flow values dictate that some explanation of the values be offered. Figure 5 summarizes the computed, uncorrected heat-flow values and estimates resulting from this investigation as well as previous values from other workers. The values range from 0.1 to over 1.0 HFU with no regular discernible pattern and with abrupt transitions between extreme values. The nature of variations among the heat-flow values suggests an influence on the upward migration of heat at a shallow rather than great depth. Anomalies at depth tend to be diffuse and appear as regional variations. Congruent with this hypothesis is the observation that the relative uniformity of heat-flow calculations from Franklin, Palm Beach, and Orange counties (Reel, 1970; King and Simmons, 1972) resulted from studies of temperature gradients at depths in excess of 1 km.

As a further test of this hypothesis, we sought to correlate the distribution of extreme or anomalous heat-flow values with suspected patterns of basement structure or basement rock type. Several models and discussions of the Florida basement are present in the literature (i.e. Puri and Vernon, 1964; Milton and Grasty, 1969; Bass, 1969; and Krivoy and Pyle, 1972). In general, these postulate a sub-

horizontal basement of uncertain rock type that ranges in age from Precambrian to middle Paleozoic and in depth from about 1 km in the northern peninsula to over 6 km in the southern portion of the peninsula. In no case, however, is there a readily identifiable relationship between the disordered pattern of apparent uncorrected heat flow and sediment thickness, basement structure, or basement rock type.

GROUND WATER EFFECT

The presence of the extensive series of aquifers and other water-saturated permeable rock layers collectively referred to as the Floridan Aquifer strongly suggests the possibility of a disruption of conducted heat by convective overturn or lateral migration of ground water. Cartwright (1971), Domenico and Palciauskas (1973), Cheng and Lau (1974), and Gringarten and Sauty (1975) have presented models of the interrelationship between ground-water flow and heat transport, and Henry and Kohout (1972) addressed the problem of a simplified mathematical model for a portion of the Floridan Aquifer. Each of the models presented in the available literature deals essentially with rigid and uniform systems possessing well-defined boundary conditions. No single approach seems appropriate to reflect the Floridan Aquifer with its composition of separate aquifer systems and aquicludes, irregular distribution of discharge and recharge areas, and highly variable parameters of depth, flow velocity, permeability, and artesian pressure. It is perhaps more constructive to recognize that the aquifer system, which is penetrated by each of the holes studied in this investigation, probably has an effect and attempt to roughly determine the extent of disruption by estimating the degree of percentage of vertical change seen in the gradients or conductive heat flow.

A generalized pattern of vertical heat transport across a convecting aquifer is summarized in figure 6 after White (1973). Line A in figure 6 represents the temperature profile in a medium of uniform conductivity and normal heat flow. Line B shows the expected mutation of the gradient if a convecting aquifer is inserted in the medium. Within the aquifer, conduction will be insignificant in comparison to convective heat transport and the aquifer will essentially behave as a heat sink at its base and a heat source at its top as temperature equilibration is reached throughout. A very low gradient (ideally zero) may be present within the aquifer while anomalously high gradients will extend immediately above and below the convecting layer.

Correlation of actual temperature profiles with the model in

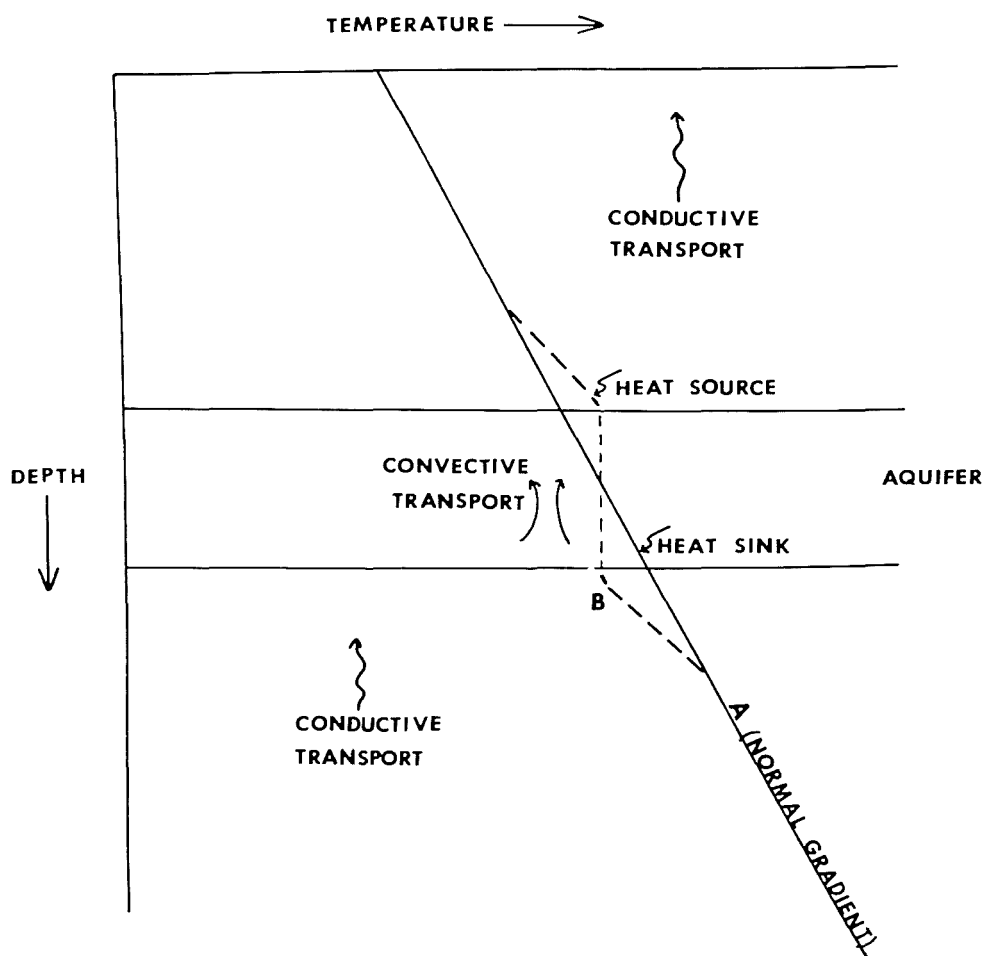


Figure 6. Theoretical response of a geothermal gradient to an aquifer with convective flow (after White, 1973). Line A represents a normal temperature gradient produced by conductive heat flow. Line B shows the temperature profile to be expected if a convecting aquifer is inserted in the medium producing line A.

figure 6 could lead to credible estimates of the thermal effect of the aquifer if the model provided a realistic portrayal of the system. However, if one constructs an inconsistent medium for heat transfer containing an aquifer composed of several layers with individual lateral and vertical flow properties and superimposes uncertain conditions of recharge/discharge and possible ocean water contamination, then the complexity of affecting factors becomes overwhelming. Nevertheless, the approach to first-order estimates of heat transfer across the aquifer must adhere to this simplified model.

Although the thickness of the Floridan Aquifer may be the subject of some contention, its top has been mapped by Vernon (1973)

and usually conforms to the top of the major carbonate rock layer. The temperature profile for the drill hole at Boulougne (figure 4) displays a marked correlation to the aquifer and is similar to the model shown in figure 6. The profile shows a very low gradient after entering the aquifer at 180 m depth, but above the aquifer a characteristic "normal" gradient is present. An anomalously high gradient segment immediately above the aquifer results from the convective heat sources at the top of the aquifer. If the thermal environment is in a steady state, it may be concluded that only 0.1 of the 0.5 HFU in the upper layer is transported by conduction through the aquifer. The remaining 0.4 HFU must be a result of the vertical component of convective overturn. Any lateral loss of heat within the aquifer may not be demonstrated by thermal gradients in the upper layers.

Profiles of temperature (figure 4) within the aquifer in holes at Bell (below 7 m) and Fort Green (below 100 m) also demonstrate a very low gradient and an anomalously low conductive heat flow. This suggests either a lateral transfer away of natural heat and/or an unmeasurable convective component of heat flow. Both the Bell and Fort Green sites, as well as the Boulougne drill hole, are situated on or immediately adjacent to the topographically higher inner peninsula area referred to as the Central Highlands by Puri and Vernon (1964). The generally higher piezometric surfaces in this area and the exposure of the aquifer formations, either directly or through permeable layers, to surface waters create a basic recharge function for the Central Highlands (Stringfield, 1966). The recharge conditions are particularly pronounced in areas of Polk and Gilchrist counties (Parker, 1975), suggesting a contribution to the low thermal gradients identified in those areas. If the simplest thermal concept of a recharge area is graphed (figure 7), it becomes apparent that heat transfer in such an area is analogous to the downward limb of a convection cycle, negating the image of a large component of positive convective heat flow.

As ground water flows down into and away from a recharge area, an outward flushing of heat can occur at the base of the zone of principal flow (figure 7). This process would tend to stabilize temperatures within the zone of principal flow to a value representative of its top, i.e., the zone would appear only as a variable heat sink with its maximum absorption near the base. That the resultant temperature gradient in the underlying layer could experience an increase as it supplied the heat for lateral flushing is supported by the temperature profile for the borehole at Verna, an area of local recharge.

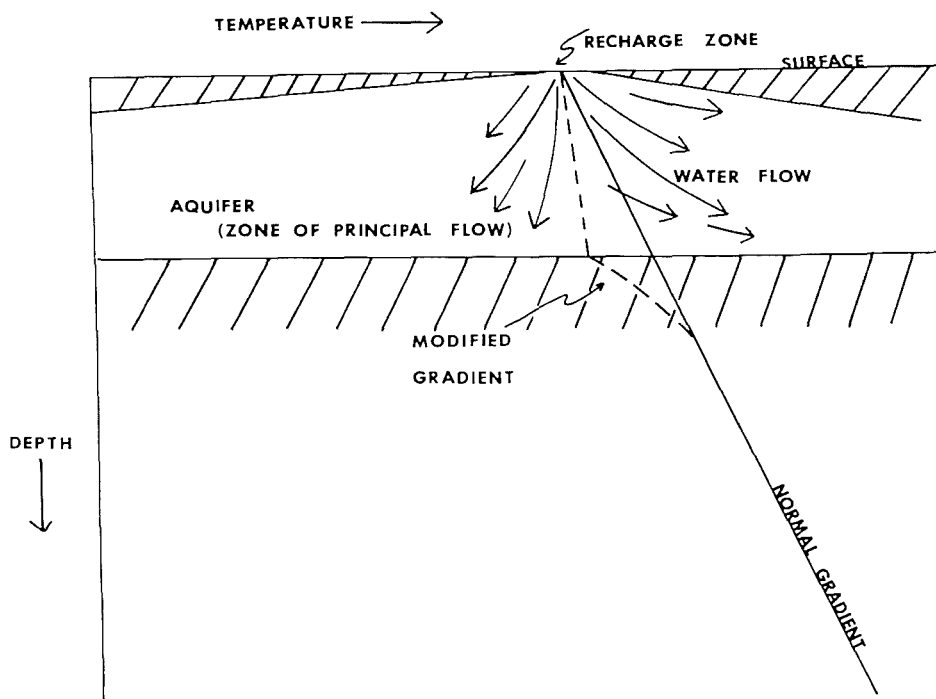


Figure 7. General thermal disturbance caused by aquifer recharge. Surface waters entering an aquifer absorb heat and depress the temperature at the base of the zone of principal flow.

The Verna profile (figure 4) exhibits a low temperature gradient characteristic of recharge in the upper zone and a relatively high gradient below. The inference here is that the lower layer conductive heat flux of 1.9 HFU is reduced to 0.2 HFU by divergent water flow, but that the heat sink properties of the flowing zone have contributed to the higher heat flow in the underlying layer. If the system is considered to be in a quasi-steady state and the gradient disturbance extends no deeper than our measurements at 340 m (an unlikely assumption), then an overall gradient may be reconstructed and a maximum possible heat flow of 1.2 HFU is calculated. By considering the observable surface heat flow (0.2 HFU) at Verna, it can be argued that surface heat flow at recharge areas can be reduced by as much as 1.0 HFU by ground-water flow. This does not imply that a similar, but opposite, flux change is expected in areas of discharge.

The proximity of the Verna drill hole to the hole measured in Sarasota suggests that the mechanism of water flow influencing thermal conditions at Verna also governs those at Sarasota. Recharge conditions are not prevalent at Sarasota; indeed, most drill holes in the area are flowing. Accordingly, a situation may be postulated whereby aquifer water, transporting heat from recharge areas, flows laterally westward and uniformly warms the zone of principal flow but does not necessarily disrupt the existing gradient (figure 8). A uniform warming of the flowing zone would effectively restrict the free flow of heat into the base of the zone from below as shown in figure 8 and as demonstrated by the decreasing gradient in the lower portion of the Sarasota profile (figure 4).

The temperature change at the top of the laterally flowing zone from Verna to Sarasota is approximately 3.5°C . Ideally, uniform heating of this zone by a lateral flow would not create additional vertical heat flow within the zone (as opposed to an absence of the aquifer) but would preclude a valid flux measurement below the flowing zone. Thus the 0.7 HFU determined in the upper, or flowing zone, at Sarasota is a representative conductive flux value, and the laterally flowing warm water has reduced the heat flow up into the aquifer by at least 0.1 HFU. This approach, however, does not incorporate a component of convective heat transfer which, although not predominate, is probably significant. We prefer the 0.8 HFU value calculated for the composite 100-400 m gradient at Sarasota, thereby bringing the heat flow at Sarasota into contiguity with the maximum value of 1.2 HFU determined for Verna.

The temperature profile from the Palatka hole (figure 4) appears to be in response to hydrologic conditions similar to those at Sarasota. Stringfield (1966) has noted chief ground water yield in Putnam County in both the Ocala limestone and the Avon Park limestone. A lateral, but uniform, eastward transfer of heat within the Avon Park — Lake City limestone zone ($\sim 270\text{-}430\text{ m}$) would justify the near-zero temperature gradient in the underlying and possibly less permeable Oldsmar limestone as well as the higher gradient in the overlying Ocala limestone. This simplistic reasoning favors the 0.7 HFU heat flow value, exclusive of convective flow, but a more realistic appraisal allows differential horizontal flow in the entire section between the Hawthorn and the Oldsmar (100-430 m). In this case, a maximum heat-flow value of 1.4 HFU may be assigned to the Palatka area, but a compounded average value of 0.8 HFU is more acceptable.

Three other borehole profiles, all along the coastline, indicate dominant influence by convective heat transfer in accordance with

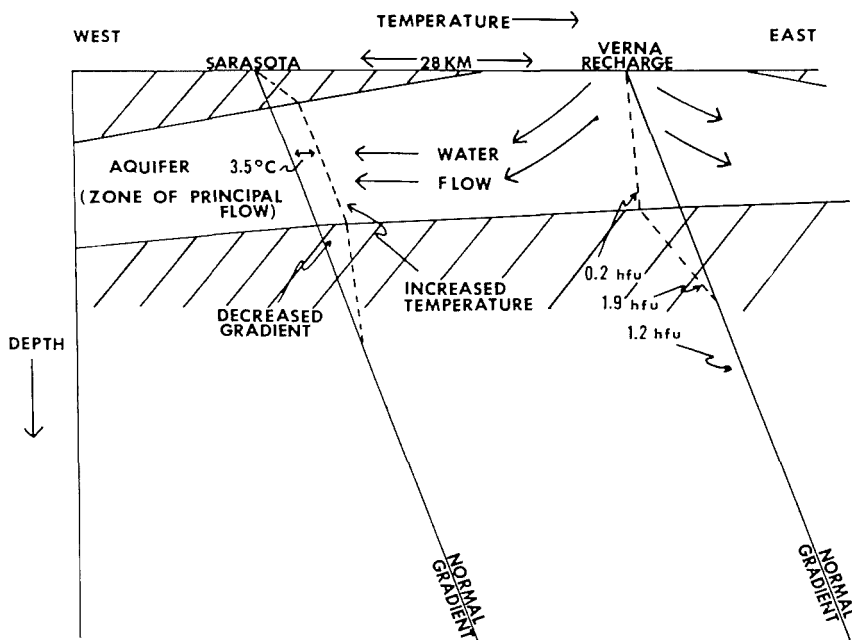


Figure 8. Proposed hydrologic effect on geothermal conditions in the Sarasota-Verna area. Recharge water entering the zone of principal flow at Verna modifies the normal temperature gradient by absorbing heat and flowing laterally away. An anomalously low gradient results in the zone of flow at Verna, but a relatively high gradient is necessary below the zone as the temperature profile approaches a normal pattern with depth. Aquifer water at Sarasota, having absorbed heat, is sufficiently warmed to uniformly elevate aquifer temperatures by 3.5°C and thus cause a slightly lower geothermal gradient below the zone of principal flow.

the process depicted in figure 6. The Tarpon Springs temperature distribution (figure 4) is interpreted to reflect thermal conditions in an aquifer (40-240 m) underlain by a relatively impermeable gypsum bearing limestone that may be equated to the Oldsmar limestone. The segmented conductive heat-flow calculations disclose a convective heat transfer of 0.6 HFU through the aquifer and, if the system has reached a steady-state equilibrium, a maximum heat flow of 1.0 HFU can be associated with the Tarpon Springs area. The temperature profiles (figure 4) from the Daytona Beach and Stuart sites show obvious disruptions which are attributed to convective overturn in the aquifer near the coastline. The conductive heat-flow estimate (0.5 HFU) calculated for Daytona Beach probably represents a minimum value. A preponderance of flowing wells and a negative gradient observed at Stuart are indicators of uninhibited vertical hydrologic flow and heat transfer that is completely controlled by thermal convection.

GEOPRESSURED ZONES AND THERMAL BLANKETS

It is tempting to seek an association of the high gradients and heat flow observed at Milton to the existence of a geopressured zone in the extreme western panhandle. Basically, a geopressured zone is best described as a clastic lens in which trapped and immobile interstitial water prevents continued compaction by surrounding clay layers. Dehydration of certain clays produces additional fresh water which, without convection, facilitates a zone of abnormally high thermal gradients since the thermal conductivity of water is only a fraction of that for rocks. The presence of a potentially economic geopressured zone along the boundary of the northern Gulf of Mexico basin is well known (Jones, 1970; Dorfman and Kehle, 1974; Papadopoulos et al., 1975), but its extension into the Florida panhandle is not substantiated. Moreover, Jones (1970) has shown that the top of the geopressured zone along the northern Gulf of Mexico basin generally conforms to the 120°C isotherm which is at least 2.5 km deep. Although thick shales are known to underlie the limestone sequences in the panhandle and north Florida (Puri and Vernon, 1964), the relatively shallow depth of the Milton drill hole (or any drill hole in this reconnaissance) obviates a direct thermal influence by possible geopressured zones.

It is more likely, we believe, that the high gradients and unique decrease of heat flow from 1.5 HFU in the aquifer to 1.2 HFU in the overlying caprock at Milton can be related to the effects of a "thermal blanket." Birch et al. (1968) have discussed the refraction of heat flux resulting from rapid sedimentation and Diment et al. (1975) have outlined the temperature, and therefore gradient, differences which arise within layers of low-conductivity sediments. The blanketing effect of a low conductivity layer is simply an accumulation of poorly-transported heat and thus higher temperatures at the base of the layer.

The 100-meter-thick Pensacola clay layer apparently has a sufficiently low (~ 3.0) thermal conductivity to force a temperature excess at its base, but we also consider the limestone zone (240-320 m) penetrated by the Milton borehole as a zone of low-conductivity and low heat transfer with respect to an underlying limestone zone. Other drill holes in the immediate vicinity of the one logged at Milton were slightly deeper but were all flowing. This is interpreted as indicative of a free-flowing aquifer zone, possibly with a higher permeability, just below (<100 m) the 320 m depth penetrated. Presumably, convective heat conveyance is dominant in the limestone zone of maximum flow and delivers heat to the nonconvective, relatively low-conductivity (water-saturated) upper layer which, in turn, develops a basal temperature build-up and high gradient. Thus, con-

vective overturn in the deeper aquifer of the western panhandle is pictured as delivering heat to a system of thermal buffers with compensating high gradients and heat fluxes that are a function of their relative thermal conductivities.

CONDUCTIVITY MEASUREMENTS

The determination of thermal conductivity values was described in METHODS above, but a complete discussion of some factors possibly undermining full confidence in the measured values is appropriate at this point. The greatest cause for concern, and reason for numerous frustrating measurement repetitions, was the difficulty associated with grinding the faces of the cylindrical sample disks flat. This work was done manually due to the friability of many core samples, but inevitable imperfections in the surfaces undoubtedly contributed to lower than actual values of measured conductivity. To combat this, in addition to fastidious caliper measurements, we sought to improve the surface thermal contact between the sample faces and the enclosing brass cylinders by coating the sample disks with a household liquid detergent.

Although the conductivity analyses were accomplished with the core samples approximately at their *in situ* temperatures, efforts to duplicate *in situ* conditions of fluid saturation and hydrostatic pressure were not precise. All but a very few seemingly soluble core samples were soaked for several days in water (no attempt was made to retain original salinity), but Walsh and Decker (1966) argue that thorough saturation can only be achieved through a vacuum process. They also emphasize the importance of measurements on crystalline rock samples under compressive stress to minimize thermal contact resistance and to reproduce *in situ* conditions of pore compaction. No vacuum saturation apparatus was available for this project and the divided-bar assembly could not accommodate axial stress other than a small weight to effect thermal contact. Nevertheless, we believe that the permeable nature of most of the samples considered in this study facilitates saturation by soaking. It may even be speculated that the effects of confining pressure on conductivity in a medium of flowing water are minimal.

Each of the factors discussed above, if valid, leads to erroneously low measured values of thermal conductivity. While regarding the factors above as genuine points of concern, we consider their net effects to be limited and appraise the measured values to be within the stated errors although the negative errors seem more probable. The general conductivity values reported herein compare favorably

with measurements on Florida rock reported by King and Simmons (1972).

ASSESSMENT OF HEAT-FLOW VALUES

Based on the above discussions concerning the possible effects of ground-water flow on the thermal regime of Florida, an analysis of the validity of the values displayed in figure 5 is essential. While some of the heat-flow values require an obvious correction as a result of hydrologic activity, a uniform correction factor or relationship is clearly not warranted. Instead, a more relevant correction estimate for each heat-flow value may be attempted by considering the geographic position of the drill holes measured and asking whether the measured gradients are indicative of a particular aquifer influence. Of course, some appreciation of the necessity for a correction can be acquired by judging a new value in light of the existing calculated and estimated values which, because of the depth of their measurements, are probably devoid of ground-water effects.

The terrestrial heat flow at Milton is considered to be 1.3 HFU despite the presence of an apparent heat flow of 1.5 HFU in the underlying limestone. The concept of an assumed steady state heat flow in an impermeable clay layer has more merit insofar as representative heat flow is concerned than an underlying water-saturated and porous limestone layer with an uncertain thermal equilibrium. We also believe the compound, or weighted average, heat-flow calculations of 0.7 HFU for the Tarpon Springs site and 0.8 HFU for the Palatka site can be regarded as indicative of the true flux at those localities.

Although it would appear that the upper layer heat flow of 0.5 HFU calculated for the Boulougne measurements should be representative, the effect of the 40 m thick zone of rapid temperature increase directly over the aquifer is difficult to ignore. The heat flow in this zone amounts to 1.6 HFU, and a weighted average flux from 180 m depth is 0.8 HFU. This value is more consistent with previous values (Reel, 1970; King and Simmons, 1972) for north Florida, but it implies a convective heat transfer in the aquifer amounting to at least 0.7 HFU.

The heat transfer h , per unit area, of a rising current in a convection cell may be described as (Garland, 1971, p. 356) where

$$n = pcv\Delta T \quad (6)$$

is heat capacity, v is the vertical velocity, and ΔT is the temperature difference over the convective aquifer. If we assume an aquifer thickness of 200 m at Boulougne and a gradient of $3.6^{\circ}\text{C}/\text{km}$ in the aquifer, then $\Delta T = 0.7^{\circ}\text{C}$. Using a heat capacity of $1 \text{ cal}/\text{cm}^3^{\circ}\text{C}$ and requiring a heat transfer per unit area of $0.7 \times$

10^{-6} cal/sec, we calculate an overturn velocity in the aquifer of
 $v = h/\rho c \Delta T = 1 \times 10^{-6}$ cm/sec or ~ 0.3 m/yr.

(7)

This rate does not appear excessive and we accept as credible a correction for potential convective heat transfer of up to 0.7 HFU.

It is important to emphasize that the corrective value for convection is an estimate and cannot be indiscriminately applied to any area of Florida in which convective overturn is suspected. The dimension and distribution of convection cells in the Floridan Aquifer are unknown and the vertical velocity given above may not be a maximum since it would be only coincidental that the rising current of a cell would be directly under the Boulougne measurement site. However, the Atlantic coastal measurements a near-zero gradient at Daytona and a negative gradient at Stuart are convincing evidence for a thermal system dominated by convective overturn. It is interesting that the three locations with striking evidence for aquifer convection are relatively near the Atlantic coast, corroborating an earlier idea (Kohout, 1967) that cold sea water enters the aquifer system at the Florida Plateau edge and is subjected to cyclic flow. Since the axis of the Florida Plateau nearly coincides with the Gulf coast of the peninsula, this process, or any mechanism of heat leakage into an adjacent colder medium (cf., Lachenbruch, 1969) is primarily restricted to the Atlantic coast or to the much thicker aquifer system in southernmost Florida.

The reasoning associated with the calculations of maximum heat flow at Sarasota (0.8 HFU) and nearby Verna (1.2 HFU) was outlined earlier, and a regional value of 1.0 HFU might be assigned to that area. This value is slightly higher than others measured or estimated for the Florida peninsula, but additional work may eventually reveal a mild thermal anomaly in the Sarasota-Charlotte county area of warm springs (Waring, 1965; Rosenau and Faulkner, 1974).

The idea of recharging ground water removing heat at a rate equivalent to 1.0 HFU from the Verna area and warming the top of the zone of principal flow at Sarasota by 3.5°C can be somewhat substantiated by computing the necessary lateral rate of water flow. If we assume a 200 meter thick zone of principal flow in the aquifer that may be internally warmed by approximately 1°C for each calorie of heat absorbed by a cubic centimeter of material, then, for a square centimeter column of thickness Δz warmed by 3.5°C , we need an amount of heat equivalent to

$$H = (1 \text{ calorie/cm}^3) \Delta z \text{ cm}^2 \Delta T = 7 \times 10^4 \text{ calories}$$

(8)

Since the system extracts heat at its base at the rate of 1×10^{-6}

calories/cm²sec, each 1 cm² column in the aquifer must be exposed to the base for a time t , where

$$t = H/Q = 7 \times 10^{10} \text{ sec.} \quad (9)$$

This merely warms a vertical column of the aquifer by about 3.5°C; it does nothing to restore a representative gradient to the zone as it approaches Sarasota. Restoration of the aquifer gradient at Sarasota from that at Verna requires each cm² column to receive enough heat to warm it by approximately $\frac{1}{2} \times 3.5^\circ\text{C}$ or 1.75°C. This value arises from the additional increase of temperature by 3.5°C of the base of the aquifer zone at Sarasota with respect to the top. Thus, the need is imposed for additional heat of 3.5×10^4 calories and additional time of 3.5×10^{10} seconds.

Therefore, each unit area column in the aquifer must be exposed to the basal input of heat for $\sim 10.5 \times 10^{10}$ seconds. Realizing a distance of ~ 28 km between Verna and Sarasota, a flow velocity of 8.5 m/yr is calculated. A very favorable comparison may be made to the 7 m/yr velocity calculated with radiocarbon data by Hanshaw et al. (1965) for the aquifer in central Florida, and to the velocity range 2.5-6.6 m/yr presented by Palciauskas and Domenico (1976).

If the dilution of vertical heat flow by aquifer recharge amounts to a maximum decrease of 1.0 HFU as theorized for the Verna site, then a first-order estimate of actual heat flow at both the Bell and Fort Green sites ensues. We can estimate a maximum limit of heat flux equal to 1.0 HFU at each of these sites. Figure 9 summarizes the values and revised estimates of heat flow in Florida as well as other values for the southeastern United States.

REGIONAL SIGNIFICANCE OF FLORIDA HEAT-FLOW VALUES

The distribution of heat-flow values and estimates shown in figure 9 amply demonstrates the need for a modification of the heat flow contours first proposed by Diment et al. (1972) (figure 1). The overall low heat-flow anomaly associated with the central Valley and Ridge province (Reiter and Costain, 1973) apparently extends into the southern Blue Ridge province, but more meaningful is the possible extension of that zone into the Florida peninsula. Indeed, if the preliminary estimates (Smith and Gregory, in prep.) given for Alabama prove valid and the Milton, Florida, value is not an isolated anomaly, a southern Appalachian thermal pattern may be envisioned with a southeastern trend into peninsular Florida.

Within Florida a somewhat recognizable trend can be identified from the values and estimates in figure 9, which includes an addi-

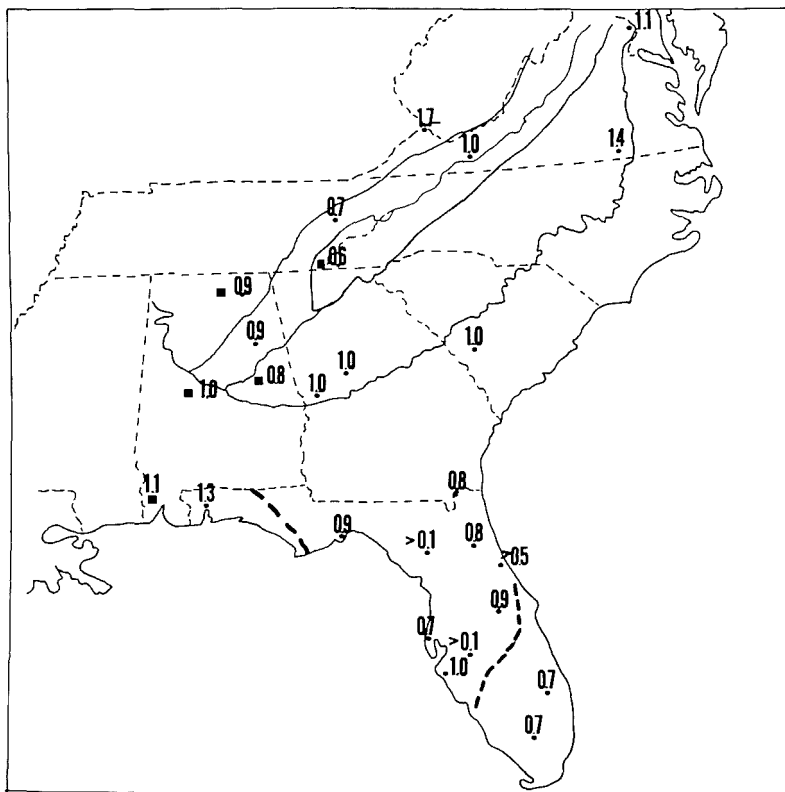


Figure 9. Distribution of heat flow values (in heat flow units) in the south-eastern United States. Margins for the Piedmont, Blue Ridge and Valley and Ridge provinces are included. Dashed lines in Florida depict proposed zones of corrected heat flow of > 1.0 HFU in the western panhandle, $0.9-0.8$ HFU in the north-central peninsula, and < 0.7 HFU in the southern peninsula. Additional values include data presented by Griffin et al. (this volume) for south Florida and tentative values (squares) for current work by Smith and Gregory in Alabama and Tennessee.

tional heat-flow estimate in Dade County by Griffin et al. (this volume). It would appear that the surface heat flow decreases from a high of approximately 1.3 HFU in the extreme western panhandle to a characteristic value of $0.8-0.9$ HFU in the northern peninsula, and then is gradational to a value of 0.7 HFU for much of the southern peninsula and perhaps the Atlantic coastal fringe. This trend, placed in juxtaposition with the belt of 1.0 HFU heat-flow values in the southern Piedmont (figure 9), suggests a progressive southeasterly decrease in heat flow from the southern Appalachians through Florida.

A linear relationship between surface heat flow Q and radioactive heat generation A of surficial plutonic rocks has been demonstrated (Birch et al., 1968; Roy et al., 1968b; Lachenbruch, 1968) to be

$$Q = q^* + bA \quad (10)$$

where q^* represents the reduced heat flow or that portion of the heat flow arising from beneath an upper crustal layer of thickness b and radiogenic heat production A . Roy et al. (1968b) described as heat-flow provinces those regions in the United States in which q^* and b were uniform and could be considered as defining parameters. Within a thermal province, such as the Basin and Range province, the reduced heat flow is largely constant and indicative of general tectonic conditions whereas small variations in the surface heat flow are attributed to variations in the radioactive heat production of surficial rocks.

Although largely based on measurements in New England, the definitive parameters for the Central Plains — Eastern United States thermal province are $q^* = 0.8$ HFU and $b = 7.5$ km (Roy et al., 1972). Combs and Simmons (1973) have shown that these constants are not consistent with measurements in the midwest, and suggest that subdivisions of the originally defined province are justified. Smith et al. (1975) and, more specifically, Garvey (1975) have reported results of analyses by gamma ray spectrometry to determine abundances of heat generating elements and, therefore, radioactive heat production in rocks of the Georgia Piedmont. Although heat generation A varied with rock type, an average value of 6.9×10^{-13} cal/cm³ sec, or 6.9 heat generation units (HGU), was calculated for the Georgia Piedmont.

If the calculated A value for northern Georgia is applicable to the southern Piedmont heat-flow values, then the q^* and b constants calculated from New England measurements become contradictory. An adherence to the 0.8 HFU value for reduced heat flow in the southern Piedmont requires (using equation 10) a b value of about 3 km. Assuming a more acceptable 7-10 km range for effective pluton thicknesses, or b , we calculate a reduced heat flow of 0.3-0.5 HFU. This value is more characteristic of the Sierra Nevada thermal province (Roy et al., 1972), but more importantly, it advocates a different thermal regime for the southern Appalachians than that in the New England area. Furthermore, a southeasterly gradation of decreasing heat-flow values into and through Florida may be construed as indicative of: 1) yet another area with unique q^* and b values, 2) a variable reduced heat flow throughout the southeast, or 3) a significant decrease in heat production A in the igneous basement of Florida as opposed to the exposed plutons of Georgia.

The latter option above amounts to a speculative interpretation of thermal data with important implications about the Florida crust. If even a mild contrast in heat flow between northern (0.9 HFU) and southern (0.7 HFU) Florida is attributed to underlying thermal conditions, and not hydrologic causes, a significant disparity must exist not only between the peninsular crust and that of north Georgia, but on a north-south basis within the peninsula itself. A hypothetical crust underlying the Florida peninsula with $b = 7\text{-}10$ km and $q^* = 0.4$ HFU (similar to northern Georgia) would require a radioactive heat generation of 5-7 HGU for northern Florida and 3-4 HGU for southern Florida. In the same sense, a Florida crust with radioactivity similar to that in the southern Piedmont would have effective thermal thicknesses of 7 km in northern Florida and 4 km in southern Florida.

Although an inference equating the thermal natures of the northern Florida and southern Piedmont crusts may be made, the potential similarities are lacking for southern Florida. These speculations do not justify identification of an oceanic crust underlying south Florida, but do suggest a crust that is either more basic with a corresponding paucity of heat generating elements or a crust somewhat thinner than that of northern Florida.

CONCLUSIONS

Thermal measurements in deep boreholes throughout Florida have yielded thirteen uncorrected heat-flow values and estimates, including four from other workers, that average 0.71 ± 0.35 (s.d.) HFU. Geothermal gradients measured with a thermistor probe for the ten sites investigated in this research were both discontinuous and variable, ranging from high values of 40.28, 50.57, and 40.65°C/km in certain depth zones in Santa Rosa, Nassau, and Sarasota counties respectively, to lows of 2.10, 0.67, and -4.13°C/km in Gilchrist, Polk, and Martin counties respectively. The average of mean harmonic conductivity values determined from 40 representative core samples from 7 drill holes is 4.16 mcal/cm sec°C.

The average uncorrected heat flow for Florida is relatively low in comparison to other continental heat-flow measurements, but a disrupting influence on the upward migration of heat is attributed to the extensive Floridan aquifer system. Although the determination of a single large-scale effect from the aquifer is elusive because of its localized variations and composite nature, local hydrologic characteristics of the aquifer may be inferred from the temperature profiles of penetrating boreholes and appropriate corrections may be estimated. We find no evidence for the marked local variations of heat flow being

related to existing descriptions of the Florida basement composition and structure, and accordingly ascribe those deviations to hydrologic effects of ground water.

To facilitate interpretation, we considered a basic model of temperature profiles through a convecting aquifer (figure 6) with low gradients throughout the fluid zone where convective heat transfer is predominate, but higher than average gradients immediately above and below the aquifer. Analyses of the measured gradients in boreholes entering the aquifer system allowed us to postulate two primary thermal effects of the aquifer and develop compensating correction estimates. Low thermal gradients in the aquifer, often with higher gradients in overlying non-porous material, are associated with convective heat transfer in rising currents of cyclic water flow. Based on measurements at Boulougne, we estimated a convective heat transfer equivalent to 0.7 HFU and an upward flow velocity in convection cells of 0.3 m/yr. The second major effect is assigned to the absorption and redistribution of heat by water entering the aquifer system in recharge areas. This effect is probably most prevalent in the Central Highlands region of the inner peninsula, but may be exemplified by measurements in the Verna recharge area of Sarasota County. We calculate a maximum heat flow loss of 1.0 HFU from lateral flow of recharge water in Sarasota County and estimate a horizontal flow velocity of 8.4 m/yr.

Based on estimated corrections arising from hydrologic conditions, a series of revised heat-flow values raises the Florida average to 0.8-0.9 HFU. In general, the Florida heat-flow values range from a high of 1.3 HFU in the western panhandle to values of 0.8-0.9 HFU in the northern peninsula and 0.7 HFU in the southern peninsula (figure 9). A mildly high geothermal anomaly may be associated with the relatively high heat flow and warm springs of the Sarasota-Charlotte county area. Kohout's (1967) theory of an influx and convective overturn of cold sea water along the Atlantic coast of the peninsula appears justified by the thermal evidence for aquifer convection at sites along the east coast. A thermal blanket effect of temperature and gradient increase related to a low porosity, low conductivity, sedimentary layer is identified at Milton in the western panhandle. This effect is probably pertinent only in the northernmost areas of the state where a thick clastic overburden covers the water-saturated limestone rocks.

Even with estimated aquifer corrections, the peninsular heat-flow values are relatively low. In fact, the heat-flow values of northern Florida appear to sustain an extension of southwestern thermal

trends associated with the southern Appalachians towards the southeast and Florida. However, the possibility of slightly lower values in the southern Florida peninsula implies inconsistent thermal conditions in the peninsula and suggests a thinner or less radioactive crust under the southern one-third of Florida.

In summary, heat flow in Florida is generally less than 1.0 HFU, but is strongly affected by ground-water motion. The regional distribution of values implies a north-south variation of crustal properties for the peninsula, and the northern peninsula heat-flow values are comparable to those in the southern Appalachians.

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**URANIUM SERIES ISOTOPIC ANOMALIES
IN
THERMAL GROUND WATERS
FROM
SOUTHWEST FLORIDA**

BY

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URANIUM SERIES

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ABSTRACT

Two deep ground-water samples from the Charlotte Harbor area of southwest Florida have unusually low $^{234}\text{U}/^{238}\text{U}$ alpha activity ratios. Three nearby well water samples have high $^{226}\text{Ra}/^{238}\text{U}$ activity ratios. Both of these ratio types are associated with high temperature geothermal systems in the western U. S. Although only moderate temperatures are measured in southwest Florida, the isotopic pattern is consistent with a local area of upwelling of water from deeper horizons. Elsewhere in the region, the isotopic pattern is indicative of normal lateral water circulation.

INTRODUCTION

An important aspect of geothermal resource evaluation is the ground-water circulation pattern. Higher subsurface temperatures can be projected if the heat transfer process is known to be primarily conductive rather than convective. Another important consideration is whether or not the high temperature waters have been mixed with low temperature surface waters.

The estimation of deep aquifer water temperatures has been made by means of the Na-K-Ca content (Fournier and Truesdell, 1973), dissolved silica content (Fournier and Truesdell, 1970) and oxygen isotope variations (Truesdell, 1974).

There are some indications that dissolved uranium isotopes may be a clue to high temperatures in deep aquifers (Cherdyntsev, 1970) (Osmond and Cowart, in press). Their use in deducing circulation pattern and mixing proportions in shallow aquifers has also been described (Osmond et al., 1974).

The abundance of radium, radon, and other short-lived daughter isotopes and the relative scarcity of the parent uranium in thermal waters is well known (Miholic, 1958; Wollenberg, 1975).

This report describes a study of dissolved uranium isotopes and radium in aquifer waters of southwest Florida, where a minor temperature anomaly has been reported (Kaufman and Dion, 1967).

THEORY

Wide variations in the proportions of ^{234}U to ^{238}U in dissolved uranium in aquifers have been observed, despite the fact that no significant mass-effect fractionation is possible. Inasmuch as ^{234}U is a daughter of ^{238}U (Figure 1), their alpha activity ratio (A.R.) should be 1.00. However, selective accumulation of the radiogenic daughter in the liquid phase is the rule, and preferential leaching of ^{234}U is the mechanism of fractionation appealed to by many investigators (eg. Cherdyntsev, 1971). In this view, the decay chain produces weakened chemical bonds and causes lattice destruction, thereby making the resultant daughter nuclide more susceptible to mobilization or leaching. Evidence is accumulating, however, which shows that alpha recoil of the intermediate daughter ^{234}Th across grain boundaries may be the most important process of fractionation (Kigoshi, 1971) (Osmond and Cowart, in press).

Oxidized ground waters leach uranium from the minerals of rocks and soil. The A. R. at the time of leaching is generally low (less than about 1.2). As the redox potential becomes more reducing the dissolved uranium is reduced in valence from +6 to +4, and is precipitated as oxide coatings on aquifer grain surfaces. As these low concentration waters circulate over long time periods, the A.R. tends to increase, due to the effect of recoiling daughter atoms from the previously precipitated ^{238}U .

Many aquifers show systematic variations in their dissolved uranium concentrations and associated $^{234}\text{U}/^{238}\text{U}$ activity ratios. In general, high uranium concentration is associated with A.R. values which approach, or are less than 1.00. Such trend lines are depicted in Figure 2. One interpretation of such a trend line is in terms of a "leaching" term, the slope of the line, and a "recoil" term, the intercept on the ordinate axis. Osmond and Cowart (in press) have classified aquifers on this basis, as shown in Figure 3. Of interest here is the difference between normal confined aquifer waters with reducing barriers and geothermal systems. The latter are characterized by a low value for both the leaching term and the recoil term. In other words, whereas most confined aquifer samples are high in either uranium concentration or A.R., geothermal samples are low in both. This is probably a function of the extreme reducing conditions and elevated temperatures at depth. Leaching or mobilization of uranium is inhibited and any tendency for ^{234}U to accumulate in the liquid phase is nullified by isotopic exchange (equilibration) with uranium in the solid phase (Syromyatnikov, 1960).

As an example of the differences between aquifer waters, we have plotted uranium isotope variations for three aquifers on a log ^{234}U

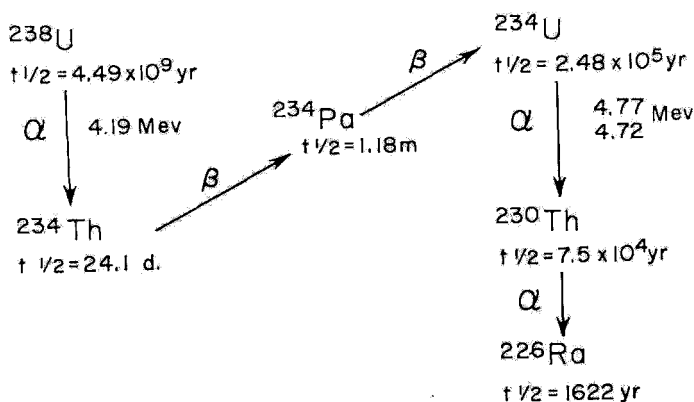


Figure 1. Uranium series decay scheme through the first five daughters. Both ^{238}U and ^{234}U are alpha emitters, and at secular equilibrium their alpha activity ratio (A.R.) is 1.00; however, the half-life of ^{234}U is much shorter so its contribution to uranium concentration by weight (e.g., ppb) is negligible. Dissolved uranium in aquifers is generally out of equilibrium because of factors related to decay processes: alpha recoil, lattice disruption, oxidation, and intermediate daughter chemistry.

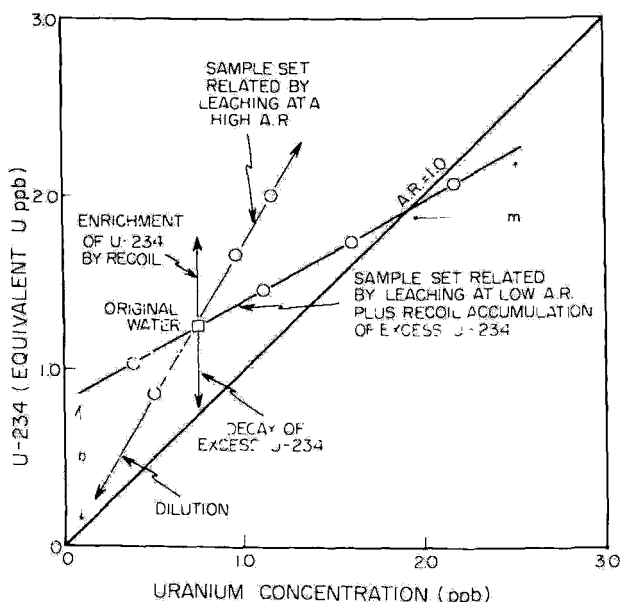


Figure 2. ^{234}U vs. ^{238}U variations in ground water (uranium concentration $\approx$ ^{238}U). Most natural waters have ^{234}U higher than the equilibrium amount (heavy line labeled A.R. = 1.0). A common distribution pattern for plotted samples from a given aquifer is a series of points from lower left to upper right on the diagram. Two such trend systems are shown (connected circles). One has a trend line characterized by a relatively low slope, 'm', indicative of leaching at a low A.R., and a relatively high ordinate intercept, 'b', indicative of appreciable accumulation of excess ^{234}U by recoil-related processes.

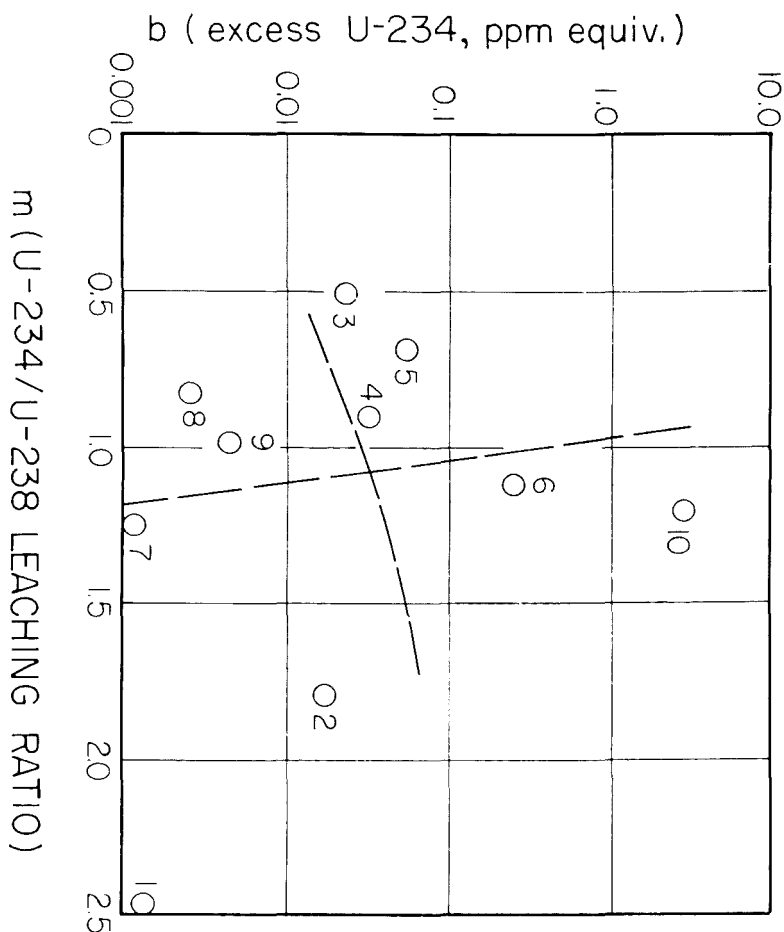


Figure 3. Plot of b vs. m for several aquifer systems, which exhibit trend line distributions of uranium isotopes, as shown on Figure 2 (From Osmond and Cowart, in press).

Key: Lower right; shallow aquifer and surface waters
 Upper left, closed system aquifers with reducing barriers
 Upper right, uranium bearing aquifer rocks
 Lower left, geothermal waters

vs. $\log^{238}\text{U}$ diagram. On such a diagram, the trend lines are curved, but the differences between the trend lines in terms of slope and intercept is apparent (Figure 4). The Yellowstone Park samples, a geothermal suite, display a much flatter curve than do the Texas and north Florida aquifer samples.

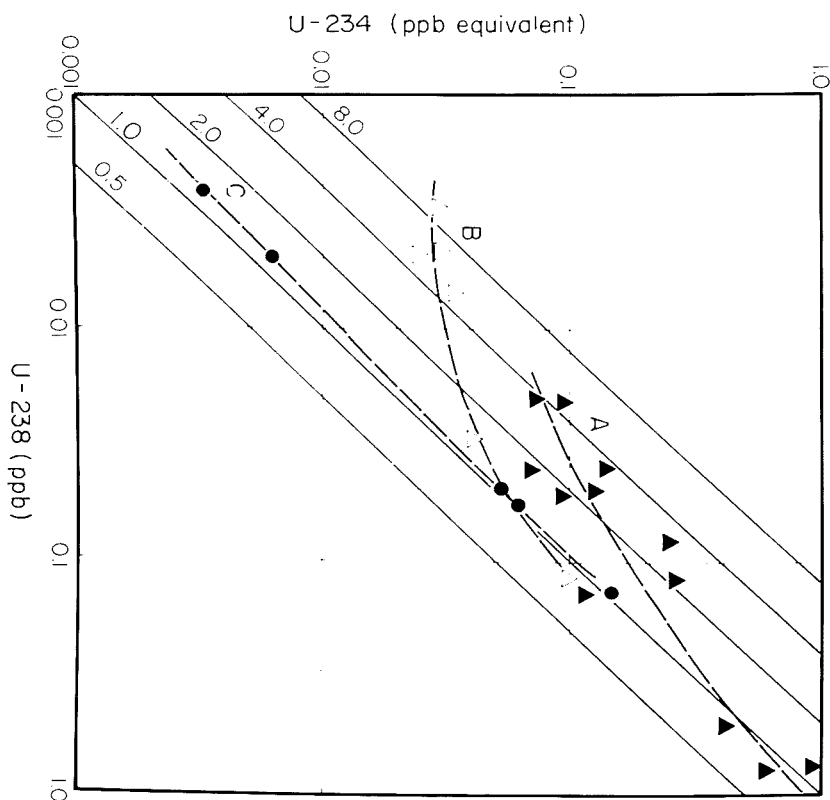


Figure 4. ^{234}U vs ^{238}U trend lines for three aquifers. Log-log scale is used because of extreme ranges of concentration values. Group A is Floridan aquifer waters from North Florida. Group B is Carrizo Sandstone aquifer samples from Texas. Group C is Yellowstone Park, Wyoming, array of samples which exhibits the 'geothermal' pattern. (Osmond and Cowart, in press).

METHODS

Uranium isotopic analyses in ground waters requires from 4 to 30 liters of water. Only suitably cased wells with known producing horizons have been sampled in this study, and most wells were free-flowing or pumped extensively before sampling. A known amount of ^{232}U was added to each sample for yield determination, along with iron carrier and sufficient acid to obtain a pH of about 1.0. After several days to allow tracer equilibration, the iron carrier was precipitated as $\text{Fe}(\text{OH})_3$ and separated by decantation and centrifugation. The uranium was isolated by solvent extraction and anion exchange procedures and then electroplated onto stainless steel planchets for alpha pulse height analysis (Figure 5). Yields of 30 to 70 per cent were obtained. Counting from 24 to 100 hours usually pro-

Table 1. Uranium isotope data from Floridan aquifer samples from southwest Florida

FSU #/County	Location	Depth (ft.)	U ppb	234 _U /238 _U Activity Ratio	
Deep Aquifer Samples					
441	Polk	Mulberry, Kaiser Plant	2775-2788	.033	1.96
492	Pinellas	McKay Creek Monitor #1	1250-1730	.041	1.99
510	Pinellas	S. Cross Bayou	1850-3260	.017	2.59
649	Sarasota	Sarasota	2008-3513	.065	2.39
677	Polk	Mulberry, Kaiser Plant	4037-5000	.596	1.72
481	Charlotte	"Hot Springs"	648-1900	.024	0.94
Main Aquifer Samples					
440	Polk	Lakeland, City #10	323-1216	.015	2.38
442	Polk	Mulberry, Kaiser Plant	1254-1264	.029	3.14
447	Sarasota	Verna #12	125-0525	.026	1.39
448	Lee	Big Pine Island	c.1000(?)	.004	2.98
490	Pinellas	McKay Creek Monitor #1	1100-1310	.020	4.72
491	Sarasota	Sarasota Disposal #1	1118-1232	.388	1.40
541	Pinellas	S. Cross Bayou	960-1080	.035	3.58
654	Pinellas	McKay Creek Monitor #1	820-0840	.043	2.06
655	Pinellas	McKay Creek Monitor #1	990-1010	.056	2.15
699	Hardee	Zolfo Springs City Well	350-1002	.022	2.92
701	DeSoto	Tropical River Groves(J-15)	164-1361	.031	2.14
703	DeSoto	NE of Arcadia	900-1410	.044	1.61
706	Charlotte	"Old Faithful"	124-1454	.010	3.68
708	DeSoto	Deep Creek	917	.040	0.94
719	DeSoto	General Dev. Corp.	1326-1411	.020	2.00
887	DeSoto	Anderson Groves	-1540	.033	3.15
889	DeSoto	Burlschor Ranch	100-1325 (?)	.077	2.73
890	DeSoto	L. H. Avant	1100-1447	.039	1.82
Shallow Aquifers Samples					
446	Sarasota	Sarasota, Alameda Way	300-0570	.117	1.77
447	Sarasota	Verna #12	125-0525	.026	1.39
449	Lee	Ft. Myers, Terry Park	132-0746	.021	1.29
450	Lee	Alva	340-0894	.016	1.41
482	Charlotte	Herren State,Nursery(H-2)	180-0220	.038	1.19
489	Sarasota	Warm Mineral Springs	-----	.104	1.53
501	Pinellas	County Well Field(PC-8)	-330	.046	1.11
515	Off Shore	Mud Hole Springs	-----	.71	1.38
702	DeSoto	Tropical River Groves(TB-2)	150-0300	.324	0.90
709	DeSoto	Deep Creek	575-	.263	1.12
711	Hillsborough	Riverview	210-0750	.009	3.03
712	Hillsborough	Sun City #5	240-0700	.011	1.57
715	Hillsborough	Tanner's Fishery,Gibson	ton32-0250	.688	0.88
717	Charlotte	San Casa	258-0298	.016	1.94
720	Sarasota	Oscar Scherer St.Park	51-0096	.125	1.54
043	Hillsborough	Lithia Springs	-----	.69	0.69
439	Hillsborough	Sulphur Springs Well	80-0318	.78	1.73

duced uncertainty limits of 5 to 20 per cent for uranium concentration and alpha activity ratios.

Radium was scavenged quantitatively from selected wells, or from bottled samples transported to the laboratory, by use of especially prepared filters of manganese impregnated acrylic fiber. The fibers were then analyzed by non-destructive gamma-ray spectrometry, in which the 1.76 Mev gamma ray of bismuth 214, daughter of radium-226, is measured. The fibers were sealed in plastic containers for about two weeks so that the intermediate daughter, radon-222 was present in equilibrium amounts. Counting efficiencies were estimated by comparison with standard sources.

RESULTS

Table 1 lists the samples analyzed for this study, along with their producing horizons, and uranium isotopic results; and Figure 6 shows the sample locations.

Wells which obtain water from depths of about 800 feet or less are considered by us to be shallow. Sample 439, a well at Sulphur Springs, Tampa, and sample 702, east of Arcadia, have relatively high concentrations and A.R.s less than 1.00. These values are similar to springs further north which are thought to result from water-rock interaction in the weathering environment.

Although many shallow wells do not conspicuously display the weathering environment characteristic, we have chosen to exclude shallow wells from geothermal consideration because of the possibility of local recharge or mixing with surface waters. A relatively small amount of high uranium concentration water could effectively mask the isotopic character of a low concentration water.

Wells which obtain water from depths of about 900 to 1200 feet are considered to be tapping main aquifer water. This horizon will be considered to be essentially isolated from the surface aquifer. The pattern of occurrence of carbon-14 at this level, and somewhat shallower, was used by Hanshaw et al. (1965) to infer the regional flow rates. The water temperatures of this horizon show a regional thermal anomaly roughly coincident with the Peace River valley, as shown in Figure 7, taken from Kaufman and Dion's report (1967).

Six wells sampled in this study obtain water from depths greater than 1500 feet in depth. The degree of isolation of this horizon from the main aquifer above is not known. Given a normal thermal gradient, temperatures in these waters are expected to be somewhat higher than in the upper parts of the aquifer.

The uranium isotope distribution in the medium and deep aquifer

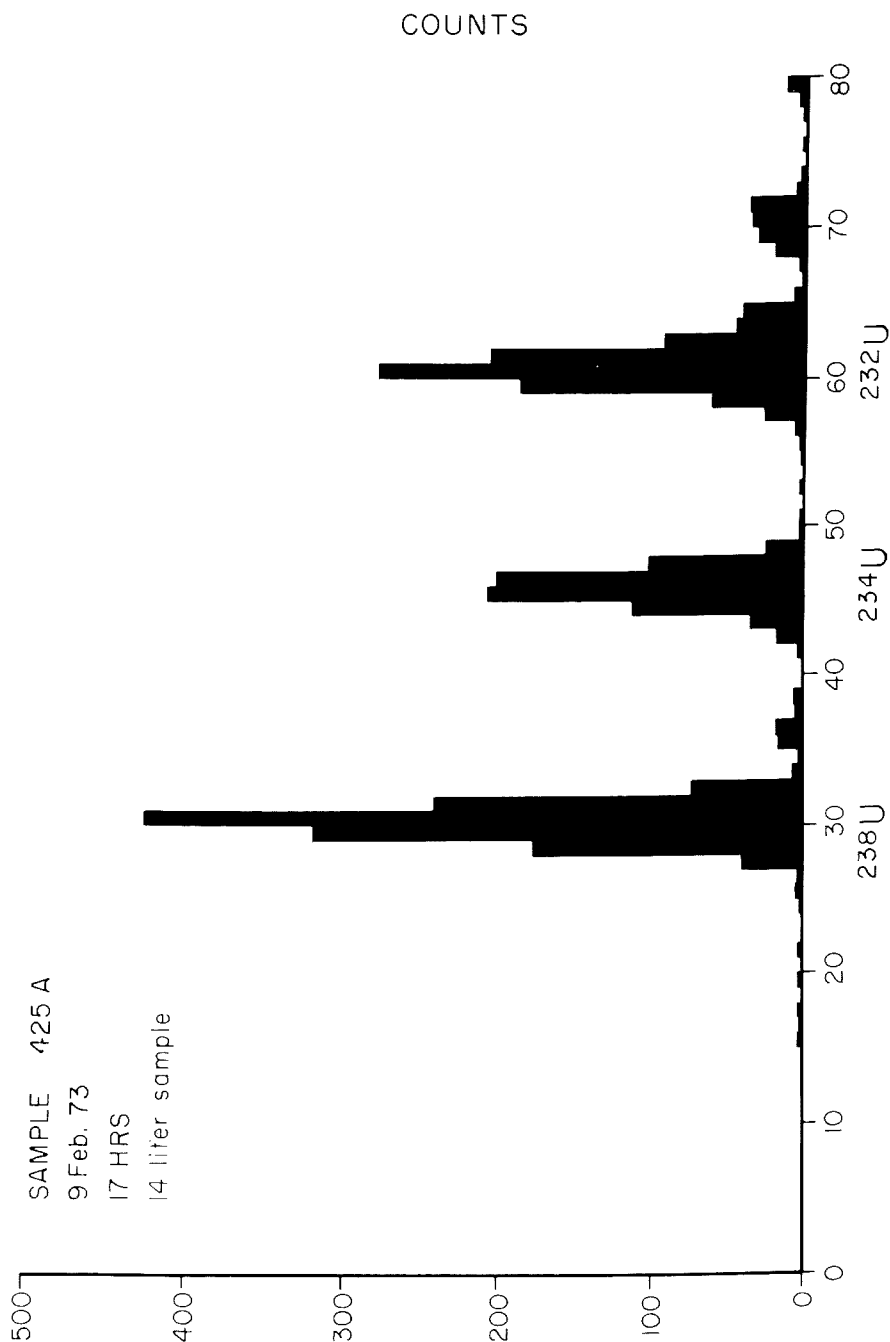


Figure 5. Alpha pulse height analysis spectrum of a ground water sample. ^{232}U is the analytical tracer isotope, added at the time of sample collection.

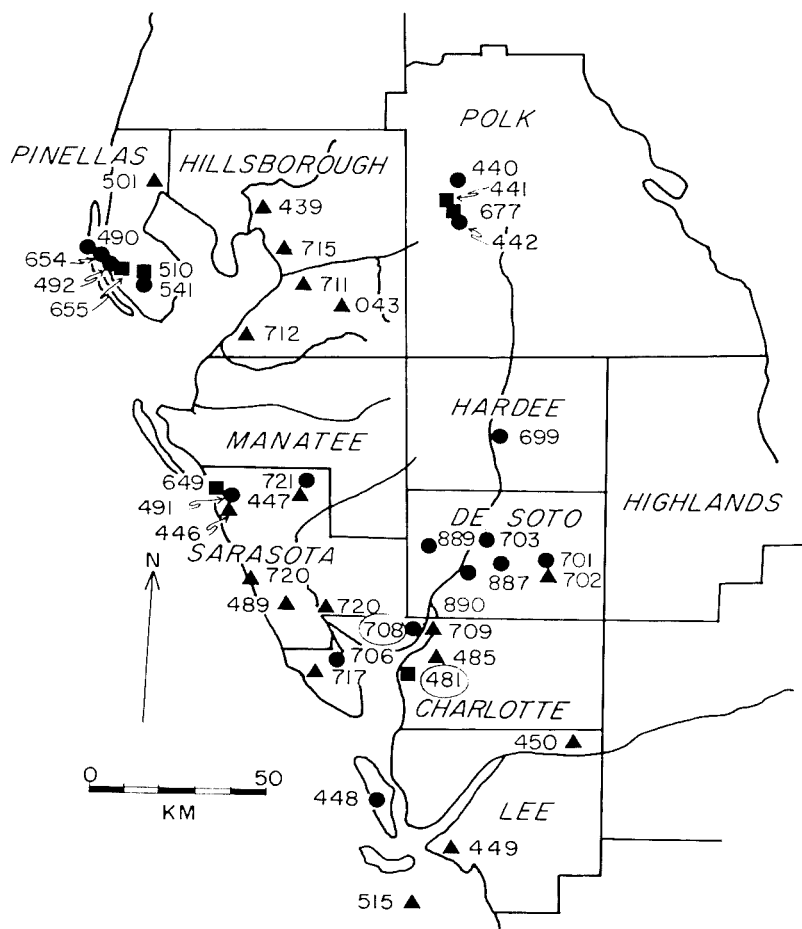


Figure 6. Geographic distribution of samples in the Tampa Bay and Charlotte Harbor areas. Sample numbers circled are anomalously low in $^{234}\text{U}/^{238}\text{U}$ activity ratio (Figure 8).

Key: Triangles, shallow aquifer or spring
 Circles, main aquifer
 Squares, deep aquifer

samples is shown in Figure 8 and is compared with the trend lines for other closed system aquifers (from Figure 4).

The deep aquifer samples from southwest Florida, with one exception, form a trend line in themselves, with a relatively high slope value of about 1.6. This may be indicative of uranium concentrations in the host rock which are higher than normal. (The slope value is strongly affected by the inclusion of sample 677, a hyper-saline sample which may come from a horizon which is isolated from the other deep samples.)

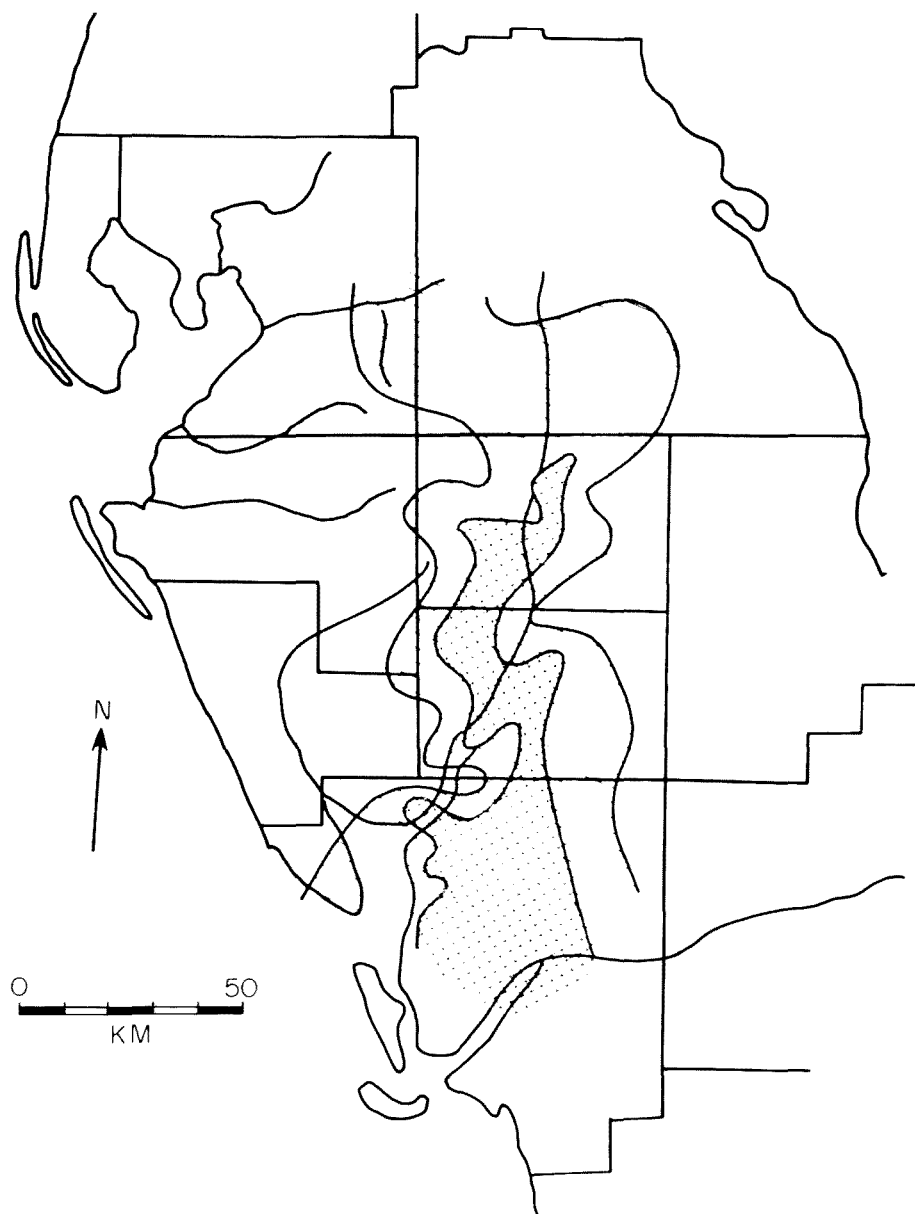


Figure 7. Temperature anomaly map of main aquifer water samples, as reported by Kaufman and Dion (1967).

Key: Cross-hatched, above 85° F
Shaded, 80°-85° F
Unshaded, below 80° F

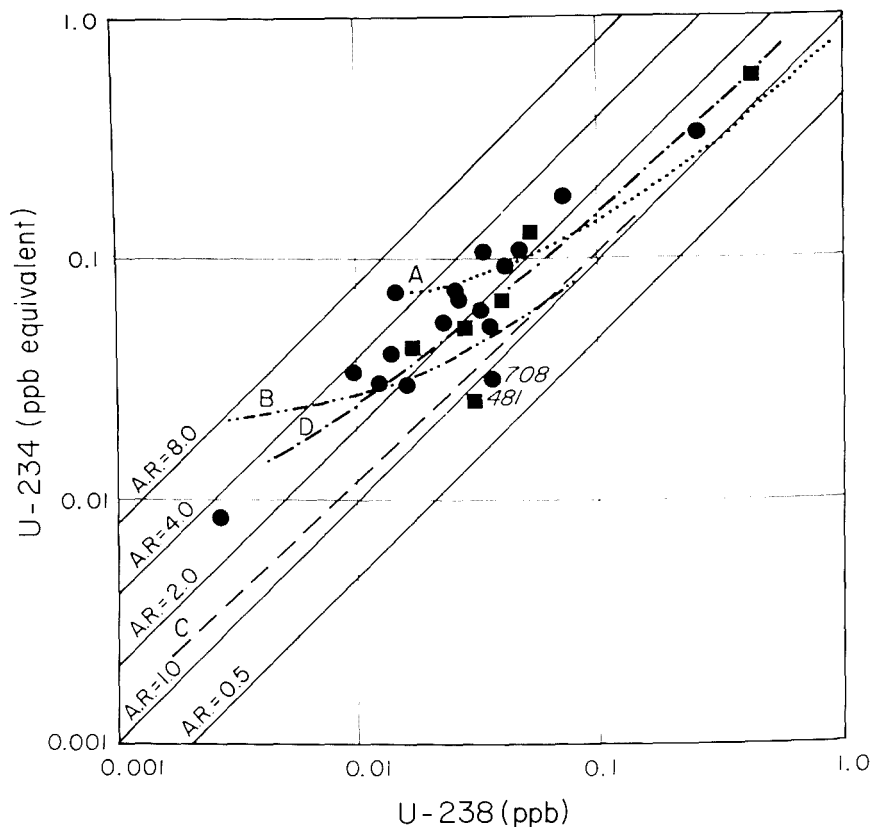


Figure 8. ^{234}U vs. ^{238}U plot of deep and main aquifer samples from southwest Florida. Samples 708 (main aquifer) and 481 (deep aquifer) fall near the Yellowstone geothermal trend line (C), and are considered, a priori, to be geothermally anomalous. Trend lines A, B, and C are the sample sets shown on Figure 4. Trend line D is drawn through the deep aquifer samples, shown by squares.

The one deep aquifer sample which plots below this trend line, and which might be interpreted as isotopically anomalous in the same sense as are geothermal samples, is number 481 from the Charlotte Harbor area.

Among the main aquifer samples, only a rough trend pattern can be constructed because of the scatter of points on Figure 8. This is primarily because of an unusually large variation of A.R. values for samples with about the same uranium concentration. However, a general distribution similar to that of the deeper aquifer waters is suggested. One of these samples also falls in the region of geothermal interest. This is sample 708 which comes from the lower Peace River valley region.

Table 2 shows the result of preliminary radium 226 analyses for

Table 2. Radium-226 concentrations

FSU No.	County	Location	Horizon	Ra-226 (A equiv.)	U-238 (ppb)	$\frac{A(Ra-226)}{A(U-238)}$
--	Leon	Tallahassee	Floridan	0.002	0.90	.002
766b	Imperial	Imperial Valley, Ca.	Geothermal	0.80		
706	Charlotte	"Old Faithful"	Floridan	0.20	0.01	20
708	DeSoto	Deep Creek	Floridan	0.04	0.04	1
717	Charlotte	San Casa	Shallow	0.40	0.02	20
721	Sarasota	Verna, #38	Floridan	0.20	0.023	9

four of the regional water samples compared with two other reference water samples. Three of these samples exhibit large excesses of Ra-226 over the amount which would be in equilibrium with the uranium present. This can be interpreted as an indication of uranium accumulation at depth, which implies conditions in which uranium is insoluble but radium is not (Wollenberg, 1975).

DISCUSSION

The simplest explanation for these data is that there exists a localized upwelling of warm water from depth in the Charlotte Harbor area.

The two anomalous samples, one each from the main and deep aquifers of this area, carry isotopic indications of reducing conditions and an isotope equilibration environment. Although these are probably the same conditions existing in geothermal systems, investigations are not yet sufficiently extensive to consider this isotope relationship as *prima-facie* evidence of high temperatures.

Three samples from the area are unusually high in dissolved solids. Sample 481, the warmest and deepest in the Charlotte Harbor area, has a major ion chemistry similar to sea water. Sample 515 is an offshore spring which also has a sea water chemistry and an elevated temperature, but lacks the geothermal character of its uranium isotopes. Warm Mineral Springs, sample 489, also lacks the isotopic evidence for elevated temperatures. (See Kohout et al., this volume, for more extensive description of these samples.)

All of these samples are located in the Charlotte Harbor area and together may reflect the effects of upwelling of thermal water. However, the lack of isotopic and saline anomalies elsewhere suggests that any such plume is localized, and that over most of the region, the circulation pattern of water is mainly horizontal.

The presence of excess radium 226 in 3 of the 4 samples analyzed may be an indication of reducing conditions and uranium accumulation within the aquifer. Such an accumulation must be within a few kilometers of the site of sample collection inasmuch as the short half-life of radium 226 (1700 years) does not allow extensive migration at the rate of water movement suggested by Hanshaw et al. (1965). Sample 708, for which a thermal component is possible, does not have an excess of Ra - 226, which means that any site of uranium accumulation at depth must be very deep or that the vertical flow rate is slow, or both.

In any case, it can be shown that such aquifer accumulations of uranium are not large enough to contribute significantly to the crustal heat generation and flux.

In summary, the over-all pattern of uranium and radium isotope occurrences is consistent with the hypothesis of a local upwelling component of flow in the region of Charlotte Harbor. Elsewhere in the region, the isotopic pattern suggests normal lateral water circulation of the type deduced from hydrologic and carbon isotope studies.

If so, over much of the area of the temperature anomaly of Kaufman and Dion (1967) the heating of main aquifer water must be by conduction from a heat source below. In this case, the geothermal gradient, corrected for lateral water movement, may be greater in the upper Peace valley than in the Charlotte Harbor area.

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THERMAL MODEL FOR THE FLORIDA CRUST

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ABSTRACT

Differential subsidence of the Florida continental margin may have occurred as a result of inhomogenous heat production within the crustal rocks which compose the Peninsular Arch and the adjacent ocean basins. A two-dimensional heat conduction model was set up to investigate the magnitude of such an effect. The results showed that, as a result of thermal contraction alone, elevation differences of greater than 200 m are likely. The coupled effects of differential sedimentation and isostatic adjustment are likely to significantly enhance the elevation differences.

Inhomogenous heat production, together with differential sedimentation, may partially explain the observed trend of decreasing conductive heat flow from north to south along the Florida peninsula.

INTRODUCTION

The development of the plate tectonics hypothesis over the past decade has provided a conceptual framework which accommodates not only the large-scale horizontal motions of the lithosphere but also contemporary movement as indicated by the associated earthquake activity at plate margins. In plate interiors, however, vertical movements and some earthquakes are not so easily accommodated by the simple plate tectonics hypothesis. Of particular interest are the tectonic processes at continental margins such as the east and gulf coast of North America. These margins which are within a contemporary plate interior represent large-scale changes in crustal structure which had their origin at a plate margin. This paper deals with the tectonics of the continental margin after integration into the interior of a plate.

The principle tectonic activity of an Atlantic type continental margin is subsidence, and it has been suggested (Sleep, 1971) that the subsidence of such continental margins may be due primarily to thermal contraction as the continental boundaries move away from the ridge axis. The same mechanism of subsidence via thermal contraction has been shown to explain the variation of ocean ridge topography with age (Sclater et al., 1971) and may also partially explain the formation of mid-continent basins (Sleep and Snell, 1975).

The subsidence of continental margins is somewhat more complex than the subsidence of ocean floor. Local variations in heat production, variations in sedimentation rate, and isostatic effects may significantly affect vertical movements. The accumulation and release of elastic stresses associated with such differential movements may provide a mechanism for some earthquakes in the southeastern United States. For example, Long (1974) indicates that earthquakes in Florida may lie along extensions of the edges of crustal blocks where irregularities of the crustal structure can amplify stresses associated with differential vertical uplift.

The thermal nature of the Florida crust must, therefore, be investigated in terms of models involving subsidence of continental margins. A rather simple model, similar to that developed by Long and Lowell (1973) is presented below.

A MODEL OF SUBSIDENCE WITH INHOMOGENEOUS HEAT PRODUCTION

The gravity data of Krivoy and Pyle (1972) shows the landward protrusion of a large positive Bouguer gravity anomaly on the west Florida shelf. This anomaly suggests the existence of rocks with densities intermediate to typical continental and oceanic rocks. On the Atlantic side of the Florida peninsula, the crust consists of typical oceanic basaltic rocks, whereas the northern portion of the peninsula itself (the Peninsular Arch) (Applin and Applin, 1965) is underlain by relatively undisturbed continental rocks of Paleozoic age. Since continental rocks usually have a greater heat production than oceanic rocks, one would expect significant inhomogeneties in heat production along a traverse trending SW-NE across the Floridan platform (Figure 1). We constructed a simple two-dimensional model for conductive heat transport along this traverse in order to determine the uplift of the Peninsular Arch relative to the adjacent portions of the crust. The higher heat production in the continental rocks is expected to lead to differential subsidence of the Florida continental margin. The thermal model used for the heat transfer calculation is shown in Figure 2.

Within the central block, which is of width $2d$, heat is being produced at a constant rate A per unit mass relative to the adjacent blocks. It is assumed that upper surface is maintained at temperature $T = 0$ and that there are no heat losses through the ends of the system. A constant heat flux q_0 is assumed to enter the lower surface and the initial temperature distribution is assumed to be $q_0 z/k$ where k is the thermal conductivity and z is the depth. The horizontal coordinate x is measured from the center of the central block, being positive to the right. Due to the symmetry of the system, we need only solve for the region $0 \leq x \leq L$ and $0 \leq z \leq h$, the boundary condition at $x = 0$ being the absence of horizontal heat transfer. The pertinent heat diffusion equation for this system is then

$$\partial T / \partial t = a(\partial^2 T / \partial x^2 + \partial^2 T / \partial z^2) + A(x, z)/c \quad (1)$$

where a is the thermal diffusivity, c is the specific heat and

$$A(x, z) = \begin{cases} 0, & d < x \leq L \\ A, & 0 \leq x \leq d \end{cases}$$

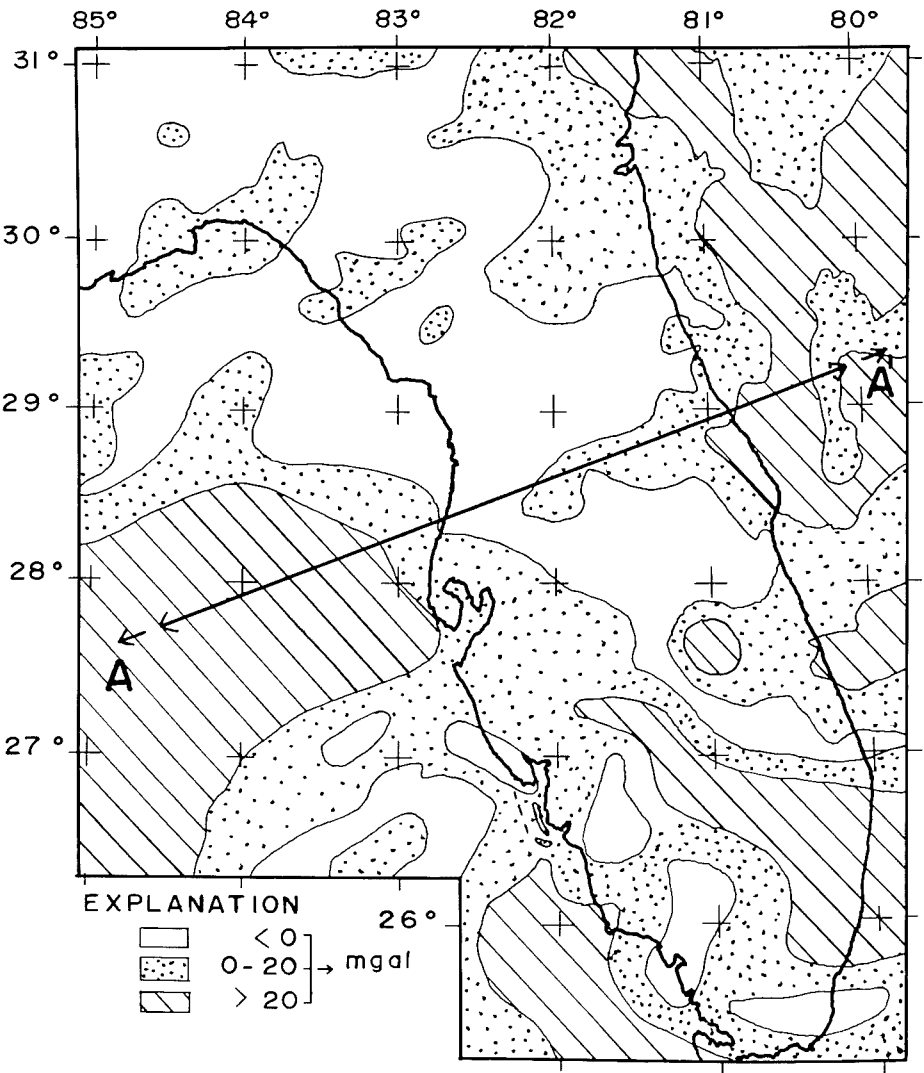
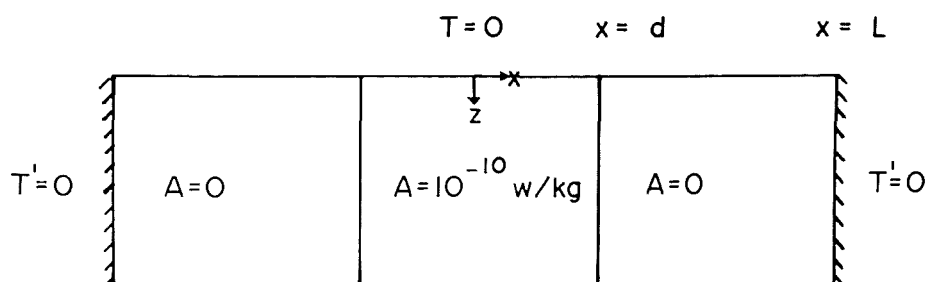


Figure 1. Regional map of Bouguer gravity anomalies on the Florida platform (after Krivoy and Pyle, 1972)



$$T' = q_o/k$$

Figure 2. Thermal model of Peninsular arch (continental crust) surrounded by oceanic crust

Along with boundary and initial conditions

$$T(x, 0, t) = 0$$

$$\frac{\partial T(0, z, t)}{\partial x} = \frac{\partial T(L, z, t)}{\partial x} = 0$$

$$\frac{\partial T(x, h, t)}{\partial z} = q_o/k$$

$$T(x, z, 0) = q_o z/k \quad (2)$$

Equation (1) with conditions (2) can be solved using Green's functions (Carslaw and Jaeger, 1959), the Green's function being determined by the method of eigenfunction expansion. The result is

$$T(x, z, t) = \frac{q_o z}{k} - \frac{2Adh^2}{Lac\pi^3} \sum_{n=0}^{\infty} \frac{\sin(n+1/2) \frac{\pi z}{h}}{(n+1/2)^3} \left\{ 1 - \exp\left(-\frac{a(n+1/2)^2 \pi^2 t}{h^2}\right) \right\} \\ + \frac{4A}{ac\pi^4} \sum_{\substack{n=0 \\ m=1}}^{\infty} \frac{\sin(n+1/2) \frac{\pi z}{h} \cos \frac{m\pi x}{L} \sin \frac{m\pi d}{L}}{m(n+1/2) \left\{ \frac{(n+1/2)^2}{h^2} + \frac{m^2}{L^2} \right\}} \left\{ 1 - \exp\left(-a\pi^2 t \left[\frac{(n+1/2)^2}{h^2} + \frac{m^2}{L^2} \right] \right) \right\} \quad (3)$$

the elevation of the crustal layer relative to the initial elevation is found from

$$E = \alpha \int_0^h T^*(x, z, t) dz \quad (4)$$

where α is the thermal expansion coefficient and $T^* = T - q_0 z/h$. Integrating (3) over z gives

$$E = \frac{-2Adh^3\alpha}{Lac\pi^4} \sum_{n=0}^{\infty} \left\{ \frac{1 - \exp\left(-\frac{a(n+1/2)^2\pi^2 t}{h^2}\right)}{(n+1/2)^4} \right\} \\ + \frac{4A\alpha h}{ac\pi^5} \sum_{\substack{n=0 \\ m=1}}^{\infty} \frac{\cos \frac{m\pi x}{L} \sin \frac{m\pi d}{L} \left\{ 1 - \exp\left[-\left\{\frac{(n+1/2)^2}{h^2} + \frac{m^2}{L^2}\right\}\pi^2 at\right] \right\}}{m(n+1/2)^2 \left\{ \frac{(n+1/2)^2}{h^2} + \frac{m^2}{L^2} \right\}} \quad (5)$$

Equation (3) and (5) may be simplified somewhat by realizing that in practice h and d are much less than L and that reasonable approximations can be made by taking only the first terms in the expansion. Thus we obtain

$$T(x, z, t) \approx \frac{q_0 z}{k} + \frac{16A dh^2}{Lac\pi^3} \sin \frac{\pi z}{2h} \left(2 \cos \frac{\pi x}{L} - 1\right) \left(1 - \exp\left\{\frac{-a\pi^2 t}{4h^2}\right\}\right) \quad (6)$$

and

$$E \approx \frac{32A dh^3\alpha}{Lac\pi^4} \left(2 \cos \frac{\pi x}{L} - 1\right) \left(1 - \exp\left\{\frac{-a\pi^2 t}{4h^2}\right\}\right) \quad (7)$$

This result suggests that the crust subsides with a time constant similar to that for ocean ridges as was pointed out by Sleep (1971). Due to the horizontal heat production differences; however, the elevation varies as the $\cos x$. Assuming a steady state situation and using reasonable values for the thermal parameters,

$A = 10^{-10}$ w/kg, $d = h = 10^5$ m, $\alpha = 2 \times 10^{-5}/^\circ\text{C}$, $L = 10^6$ m,

$a = 10^{-6}$ m²/sec, $c = 10^3$ j/kg- $^\circ\text{C}$, equation (7) gives a maximum

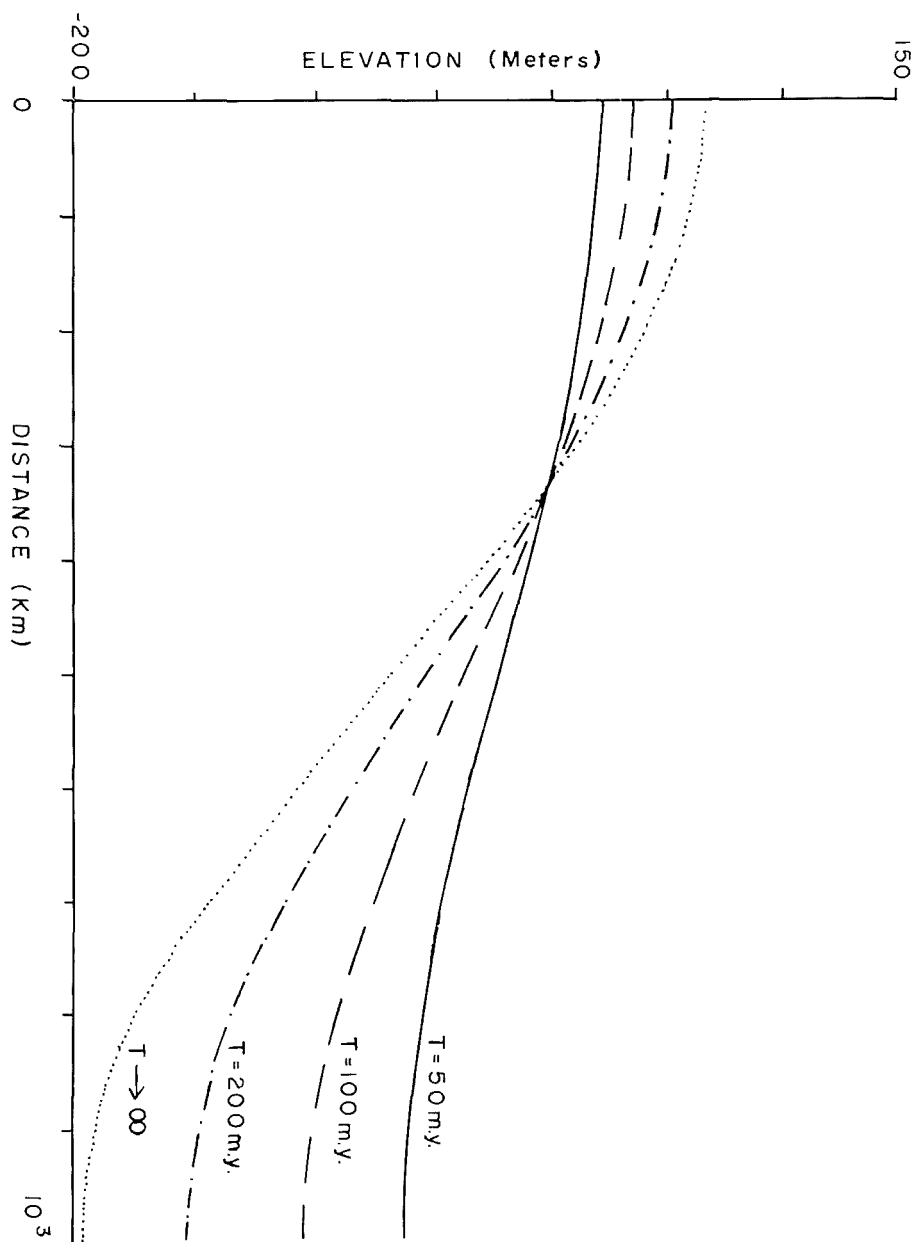


Figure 3. Profile of elevation change at selected times

elevation difference of about 250 m. between the Peninsular Arch and the adjacent ocean basins. Figure 3 shows the elevation as a function of horizontal distance at a few representative times.

On this model, the surface heat flow is also expected to be greater over the Peninsular Arch than in the adjacent basin. Based on equation (6) the heat flow should vary with horizontal distance as the $\cos x$ and the temperature gradient should be about $3^\circ/\text{km}$ greater over the Peninsular Arch than over the adjacent basins.

DISCUSSION

The simple thermal model presented above suggests that lateral inhomogeneities in heat production retards the subsidence of the Peninsular Arch and that the conductive heat flow should be greater over the arch than over the adjacent basins. A map of the pre-Cretaceous surface of the Florida platform (Kinney, 1967) shows the relative elevation of the Peninsular Arch above the adjacent basement. The thermal effects derived above certainly contribute to the differential subsidence of the continental margin. However, we have not included the effects of sediment loading on the amount of subsidence. This effect may be substantial (Rona, 1974). We point out, however, that the sediment loading may in fact be coupled to the thermal effect in that the differential sedimentation may partially result from the Peninsular Arch remaining above sea level during small scale sea water transgressions. It may also be that phase changes contribute to the subsidence (Sheridan, 1974). This effect is also coupled to the thermal and sediment loading effects, however. O'Connell and Wasserburg (1967, 1972) have performed extensive calculations on the thermal response of a phase change boundary to sediment loading. A complete model of the subsidence of the Atlantic continental margin would involve a treatment of these interrelated effects. This represents a rather formidable mathematical problem which is beyond the scope of this introductory paper.

The second effect of the thermal model presented here concerns the expected variation in surface heat flow. Unfortunately, there is insufficient heat-flow data on the continental shelf to compare with those on the Florida peninsula. Data on the Florida peninsula itself, however, indicates that the surface heat flow is somewhat low and that the heat flow tends to decrease from north to south along the peninsula (Douglas Smith, personal commun.). Bottom-hole temperature gradient measurements (Griffin et al., 1969) also support a southward trending decrease in the heat flow. Long and Lowell (1973) have constructed a N-S two-dimensional temperature model similar to the one we have presented here. This model (Long

and Lowell, 1973) is in reasonable agreement with the heat flow data; that is, the low heat flow measured on the southern portion of the peninsula may be because the southern portion is underlain by oceanic rather than continental crust.

The low mean of the heat-flow values may also arise from one or more of several regional processes. These may tend, also, to mask heat-flow differences between the Peninsular Arch and the adjacent ocean basin. The first of these regional effects is, again, sedimentation. It is well known that heat conduction is a slow process and that heat-flow measurements in an area of recent sediment slumping give low values. This is mainly because of the insulating effects of the sediment cover. In regions of fairly rapid long-term sedimentation such as in geosynclines, the insulating effect of the accumulating sediment also tends to lower the geothermal gradient in the upper layers. In Florida, where periods of erosion and sedimentation alternate, the situation is somewhat complicated. The greater thickness of sediment cover on the southern portion of the peninsula, however, may contribute to the lower heat-flow values measured there.

Another possible cause of the low surface heat flow may be the lateral cooling effect of sea water adjacent to peninsular Florida. Rather straight-forward calculations of this conductive cooling effect (Lowell, unpublished calculations) indicate that this effect is negligible except very near the edges of the peninsula.

Lastly, circulation of water in the shallow crustal formations may effectively remove heat. Kohout (1967) has suggested that this may have a significant effect on the thermal regime of the upper crustal layers on the Florida peninsula.

CONCLUSION

A two-dimensional E-W thermal model for the Peninsular Arch in northern Florida suggests that the Arch may be partially a result from lateral inhomogeneity in heat production between the continental basement rocks of northern Florida and the oceanic basement of the adjacent ocean basins. A similar model constructed along a N-S profile may also help explain the tendency surface heat flow to decrease toward the south. To construct a model which includes the coupled effects of differential sedimentation, thermal expansion, and possible phase changes would require a much more sophisticated mathematical analysis than the available data warrants.

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