

Mud Hole: A Unique Warm-Water Submarine Spring, Located Offshore Southwestern Florida

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ABSTRACT

Mud Hole Submarine Spring is an unusual warm-water submarine discharge of water offshore of the southwestern Gulf Coast of Florida, located at latitude 26°15'48"N longitude 82°01'06"W, or about 18.5 km due south of the Sanibel Island lighthouse, Lee County, Florida. This warm-water submarine spring oftentimes has a surface appearance of discolored turbid warm-water which is very attractive to large fish, sharks, turtles, sport fisherman, and scuba divers. The spring discharges warm water from many vents in a sinkhole depression about 61 m in diameter at about 19 m below NGVD. The bottom sediment consists of gray silt and mud atop sand and limestone gravel which, when disturbed, causes clouds of mud to be thrown into suspension, giving the spring the name "Mud Hole". Warm water flowing from several orifices has a constant temperature of 35.31°C, pH of 7.25, and a salinity of 34.6 ppt (averaged hourly measurements during the period May 5 through June 17, 1998). The plume extends about 1.5 m around the main orifice, about 1 m long by 0.3 m wide, with a velocity estimated at 0.6 m/s and a discharge of about 0.17 m³/s (4 million gallons/day). The total discharge from the whole depression is however considerably much larger. This study mapped the spring and measured physical water quality. The results indicated that the discharge movement is fault-related to the basement Sunniland Fracture Zone, based on the geology of southern Florida. The saline-water temperature of 35.3°C indicates that the water comes from a considerable depth, as the surrounding seawater only averages 21°C and onshore Upper Floridan aquifer water only ranges from 26.6°C to 29.4°C. The temperature profile in the oil-exploration well, State Lease #224B-1, located offshore north of Sanibel Island indicates that this temperature exists only at a depth greater than 500 m, that is, in the Boulder Zone of the Lower Floridan aquifer. This study concludes that the source is saline water migrating through faults extending from the basement Sunniland Fracture Zone and moving upwards through the section, mixing with the brackish cooler Floridan Aquifer, and eventually flowing from the spring. As no lithological gradient exists from east to west in southern Florida and higher water temperatures are found near major fault zones, the geothermally-activated convective flow cell hypothesis cannot be valid. Based on the data obtained in this study, the source is not considered the surficial aquifer as reported in the literature by some researchers.

INTRODUCTION

Mud Hole Submarine Spring is an unusual warm-water submarine discharge of water offshore of the southwestern Gulf Coast of Florida (Fig. 1). The general location of the spring is marked on some nautical charts, and has been recorded in the literature by Kohout (1965) and Smith and Griffin (1977), Fanning *et al.* (1981,

1982) and also is cited in a local diving videotape "Reefs in Motion" produced by Jaws Productions in 1994. The spring had been reported many years ago by local fishermen as a surface area of discolored turbid warm water (Fig. 2) that is very attractive to large fish, sharks, and turtles. The location of the spring (Fig. 1) is at latitude 26°15'48"N longitude 82°01'06"W (Loran 14097.1/43865.2) or about 19 km due south of the Sanibel Island lighthouse. This warm-water submarine spring is an important fishing spot for both local fishermen and scuba divers, and is visible as an anomaly on airborne infrared imagery and on satellite photography. The spring discharges warm water from many different-sized vents in a sinkhole depression about 300 m in diameter at about 19 m below NGVD (National Vertical Datum of 1929, formerly known as mean sea level). The bottom sediment consists of gray silt and mud atop sand and limestone gravel. Disturbance of the bottom sediment causes clouds of mud to be thrown into suspension, giving the spring the name "Mud Hole" (Munson, 1961). In 1998 this study investigated and mapped the Mud Hole Spring. The mapping (Fig. 3) and documenting of this offshore warm-water artesian is considered very important to the water resources assessment of southwestern Florida, especially if the spring is fault-related. As the Floridan Aquifer System (FAS) is presently undergoing Aquifer Storage Recovery (ASR) and is used for deep-well injection of waste contaminants in southern Florida, this project will provide important new insights concerning origin and water movement along faults and possible saline intrusion of overlying aquifers. A recorder was also installed during the investigation in the main vent that obtained hourly physical water-quality parameters of pH, dissolved oxygen, conductivity, salinity, temperature, and depth. Lithological rock and sediment analyses were conducted to determine the age and formation of the outcropping seabed rocks. Warm water flows from several orifices at a constant temperature of 35.31°C, a pH of 7.25, and a salinity of 34.6 ppt (this study). In October 1972, Smith and Griffin (1977), using a human fever-thermometer, recorded a temperature of 36°C from one vent. The apprehensive visual blurring reported by divers entering the plume may be due to a heat-mixing effect as vision becomes clearer within the plume itself. The velocity of water from the main vent, a fissure 1 m long by 0.3 m wide, was estimated at 0.5 m/s, while the discharge was measured at about 0.17 m³/s (Smith and Griffin, 1977), however, the total discharge from the whole depression is considerably larger.

In this study, our hypothesis proposes that the discharge is fault-related and sourced from deep saline water mixed with the fresher water of the Floridan aquifer, based on the subsurface water chemistry and temperature gradients. The temperature of the spring, measured at a constant 35.31°C (634 measurements), while the surrounding ocean only averages 21°C and onshore groundwater temperatures in the Upper Floridan aquifer range from only 26.6°C to 29.4°C (Sproul, 1977). Also, the temperature profile in the oil-exploration well, California Company, State Lease #224B-1, located offshore north of Sanibel Island along the Florida Plateau axis, indicates that this temperature exists at a depth greater than 500 m, that

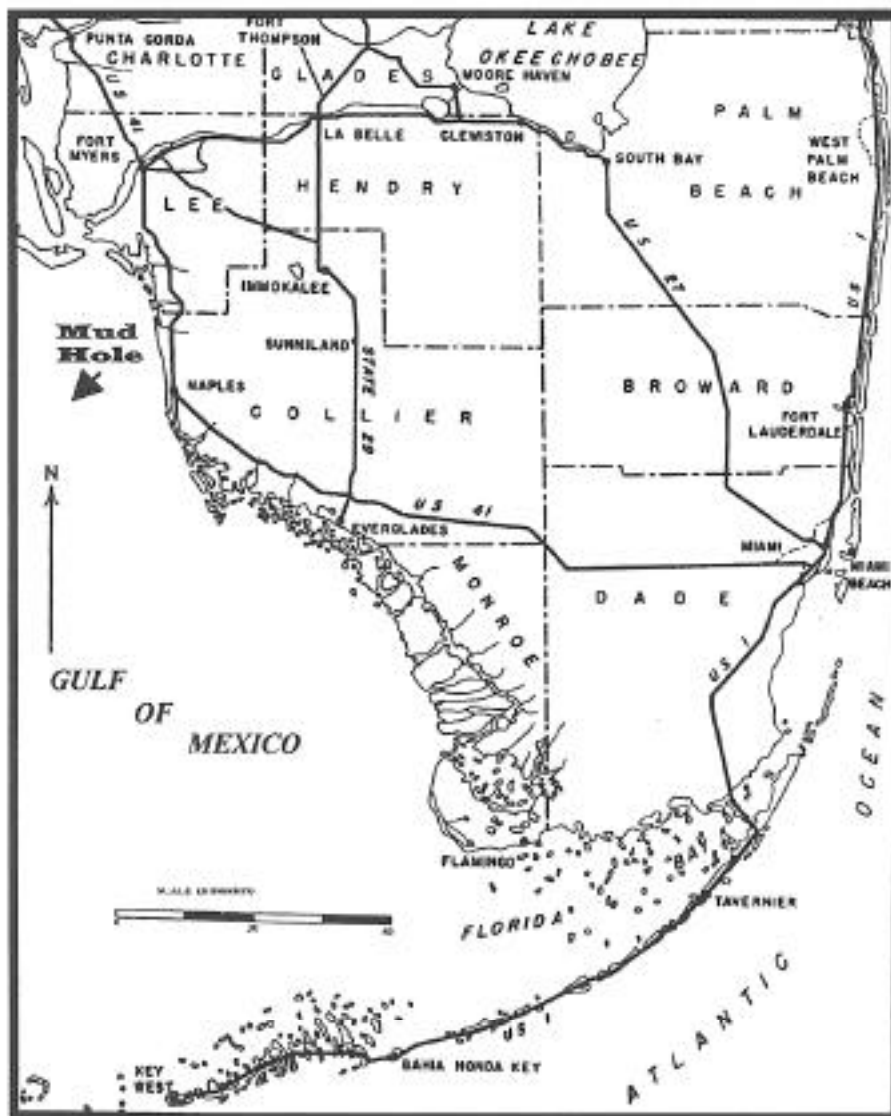


Figure 1. Location of Mud Hole spring in offshore southwestern Florida.

Table 1.
Mud Hole main vent physical water quality statistical records

	<i>Temp(degC)</i>	<i>pH units</i>	<i>SpCond (mS/cm)</i>	<i>Salinity (ppt)</i>	<i>Depth (meters)</i>
Maximum	35.32	7.34	53.2	35.2	19.5
Minimum	32.38	7.20	52.4	34.6	18.3
Average	35.29	7.27	52.5	34.7	19.0
Median	35.31	7.27	52.5	34.7	19.0
AvDev	0.04	0.03	0.1	0.1	<i>Tide effect</i>
# Samples	634	634	634	634	634

Table 1. Mud Hole main vent physical water quality statistical parameters.



Figure 2. Chief diver, Graham Woody, on the surface in the Mud Hole plume preparing to dive 18 m to the main vent (photo: Mitchell-Tapping).

is, below the Boulder Zone of the Floridan aquifer and the Cedar Keys Anhydrite Formation. It is thought that artesian saline water from a deep source is upconing and mixing with the cooler brackish-saline water of the Floridan Aquifer while migrating through a fault to the spring. In order to comprehend our hypothesis it is necessary to understand previous investigations, southern Florida basement features, the Floridan Aquifer System, well temperature gradients, and the chemistry of these subsurface waters.

PREVIOUS INVESTIGATIONS

Mud-Hole Submarine Spring is also occasionally referred to as the "Mud Boil". Kohout (1967) reported the spring as "*field evidence of a geothermally activated convective flow cell in saline groundwater underlying the Florida Plateau.*" Kohout (1965, 1967) recorded that the spring was discharging from a sink-like depression about 20 m below sea level where the surrounding water depth is about 15 m. He measured a water temperature of 36°C and concluded that the high temperature indicated that water is upwelling from the Floridan Aquifer. Other researchers (Kohout et al., 1977; Sproul, 1977; Meyer, 1989) also hypothesized inland flow of seawater through the lower part of the FAS on the basis of a temperature anomaly (reversed geothermal gradient) found in several deep wells in southern Florida (Fig. 4). The driving force, according to Kohout et al. (1977), was geothermal heat that produced a convection flow cell wherein the cold seawater was heated as it flowed inland from the Straits of Florida through the Lower Floridan Boulder Zone and then upward through vertical paths (such as ancient sinkholes) in the overlying confining units and then mixed with the seaward-flowing water in the upper part of the Floridan Aquifer. Opposing views were expressed by Vernon (1970), who suggested that the temperature only was due only to heat conduction (supported by this study), while Sproul (1977) concluded that the then existing data was insufficient to support either hypothesis.

Regional aspects of the hydrogeology of the Floridan Aquifer System (FAS) (also referred to as the "Vicksburg artesian lime-stones," the "principal artesian formation," the "principal artesian aquifer," the "Floridan aquifer," and "Tertiary limestone aquifer system" in southern Florida were first reported by Sellards and Gunter (1913), and later by Stringfield (1936, 1953, 1966), Parker et al. (1955), Kohout (1965, 1967), Vernon (1970, 1973), and Miller

(1982a, 1982b, 1986). Hydrogeologic studies of a local were reported by Schroeder et al. (1954), Bishop (1956), Lichtler (1960), McCoy (1962), Klein et al. (1964), Meyer (1971, 1974, 1989), Sproul et al. (1972), Boggess (1974), Sutcliffe (1975, 1979), Cram et al. (1975), Wilson (1977), Reece et al. (1980), Smith et al. (1977), and Wedderburn et al. (1982). Potentiometric surface maps, which indicate the direction of ground-water movement in the upper part of the aquifer system, were compiled by Stringfield (1936), Parker et al. (1955), Healy (1975a, 1975b, 1982), and Johnson et al. (1980, 1981, 1988). Smith and Griffin (1977) also reported the chloride concentration ranging from 19,000 to 20,000 mg/l, that is, about the same as seawater. This study, however, emphasizes a deeper source and the relationship of the Sunniland Fracture Zone, major fault patterns, and solution features as a conduit for the Mud Hole spring.

SOUTHERN FLORIDA BASEMENT FEATURES

The present day southeastern Gulf of Mexico covers an area of about 210,000 km² onshore and offshore southern Florida. The offshore western shelf is a major shelf area of southern Florida characterized by gentle dips with only minor structural deformation which consists of tensional faulting, related to normal basin subsidence. This western sub-basin depocenter in the Gulf of Mexico lies offshore to the northwest of the Keys. Seismic interpretation of the sub-surface section offshore indicates this area contains more than 8,000 m of Mesozoic and Tertiary clastics, carbonates and evaporites (Lord, 1987). The most significant clastic lithology in the basin is Triassic and Jurassic basal non-marine sands and Pleistocene to Recent sands and sandstones at or near the land surface (Fig. 5). Basement Paleozoic structural features have controlled sedimenta-

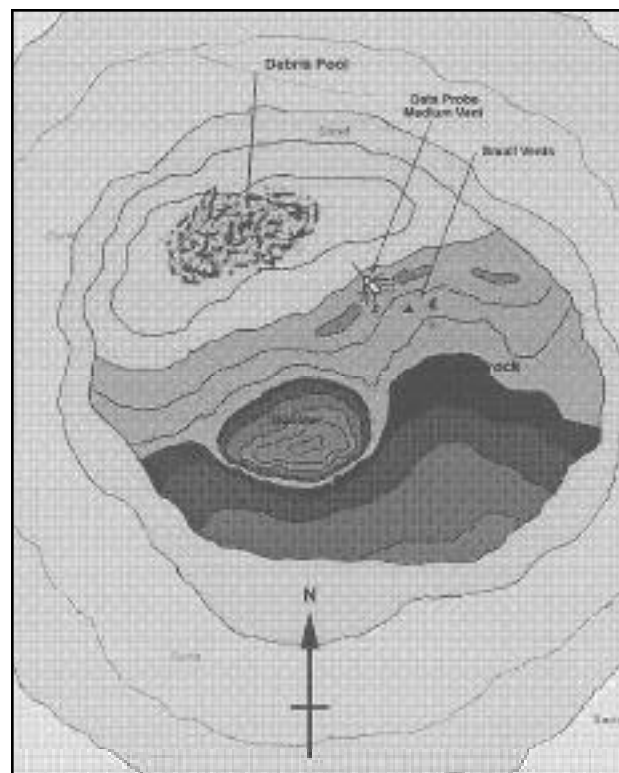


Figure 3. A map of the Mud Hole, drawn by G. Woody, showing the various vents and the location of the deployed Hydrolab Datasonde3 water quality instrument in the main vent. (scale: width of map is 300m, 1 m contour interval)

Table 2.
Physical water quality measured at various depths above Mud Hole

Depth (m)	Temp (degC)	pH	Spcond (mS/cm)	Date	Time
0.70	18.01	7.3	55.40	2/01/96	12:33:17
5.00	18.10	7.3	55.30	2/01/96	12:34:48
8.70	20.59	7.3	54.30	2/01/96	12:35:46

Table 2. Physical water quality parameters measured at various depths above Mud Hole plume.

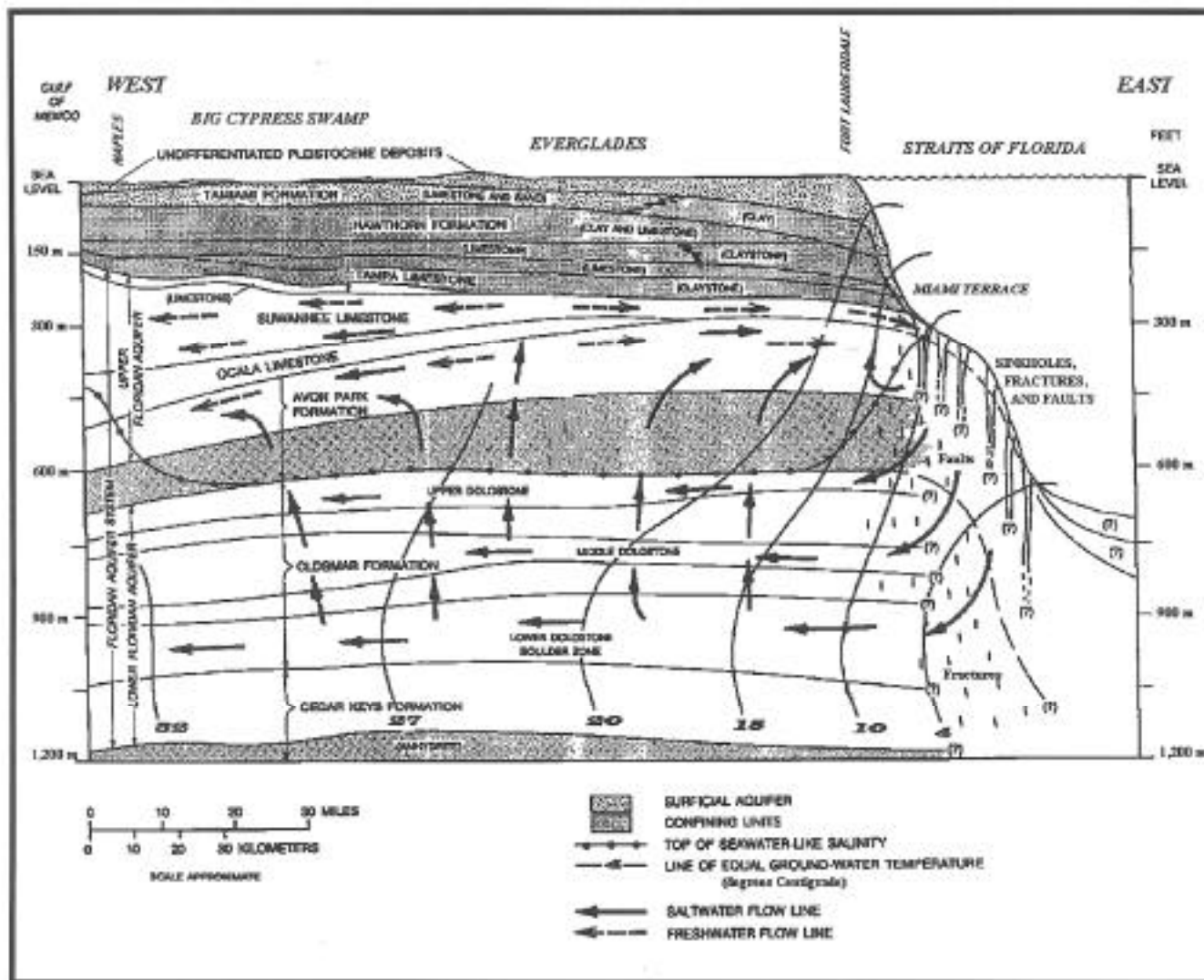


Figure 4. Generalized section from Naples (west coast) through Fort Lauderdale (east coast) showing isotherms, top of the Floridan, and the seawater cyclic flow induced by geothermal heating (Meyer, 1989).

SYSTEM	SERIES	LITHOSTRATIGRAPHIC UNIT	HYDROSTRATIGRAPHIC UNIT
QUATERNARY	HOLOCENE	UNDIFFERENTIATED PLEISTOCENE SEDIMENTS	SURFICIAL AQUIFER SYSTEM
	PLEISTOCENE		
TERTIARY	PLIOCENE	TAMIAMI FORMATION	INTERMEDIATE CONFINING UNIT OR AQUIFER SYSTEM
	MIOCENE	HAWTHORN GROUP	
	OLIGOCENE	SUWANEE LIMESTONE	FLORIDAN AQUIFER SYSTEM
	Eocene	UPPER OCALA LIMESTONE	UPPER FLORIDAN AQUIFER SYSTEM
		MIDDLE AVON PARK FORMATION	
		LOWER OLDSMAR FORMATION	
	PALEOCENE	CEDAR KEYS FORMATION	LOWER FLORIDAN AQUIFER SYSTEM
CRETACEOUS AND OLDER		UNDIFFERENTIATED	SUB-FLORIDIAN CONFINING UNIT

Figure 5. Hydrostratigraphic column of southern Florida (after Meyer, 1989)

tion. There have been several tectonic episodes causing major fracturing of the Florida plateau as evidenced from drill cores and seismic sections. Definition of these basement fracture-zones is crucial to understanding of the location of these up-section faults and their effect on aquifer water movement, especially in carbonate sequences that are already prone to fracturing. The tectonic and stratigraphic evolutions of the platform are essentially known through seismic profiles calibrated with wells. Triassic and Jurassic rifting of the area does not seem to be preceded by any uplift since the shallow water environments change during the Jurassic time into a deeper basin and shoal marine environments (Mitchell-Tapping, 1982, 1994a, 1994b). A long period of rifting is evident since the sediments reflect episodic movements on faults indicated by sedimentary onlap and slight platform tilting and fracturing. The long rifting period, about 40 my duration, and the episodic discontinuous movements can also be justified by seismic signatures indicating rapid deepening of the basinal area, or initial subsidence, resulting from eustatic and tectonic factors (Mitchell-Tapping, 1994a). Smith (1982) has comprehensively summarized the general geology of western Africa and reviewed the similarities to the Florida basement, noting belts of rocks with radiometric ages between 500 mybp and 650 mybp and a Pan-African deformation thermotectonic event. The reconstructions by Smith (1982), Sheridan *et al.* (1969), and Bullard *et al.* (1965) each show a strong affinity of west Africa to Florida in the Paleozoic, based on seismic refraction data off the coast of north-western Africa, age-dating, and composition of the basement rocks. Paleozoic grabens, formed before the Proto-Atlantic, were influenced by the Atlantic rifting, major fracture zones (Fig. 6), and the initial spreading of the Gulf of Mexico. On the western shelf of southern Florida horsts and grabens are present during the Paleozoic, such as, the Paleozoic Tampa-Sarasota Arch; Pulley Ridge Arch, and the Pine Key Arch under the Florida Keys. While the area was still part of the proto-Atlantic and the grabens being

infilled by continental clastic sediments, at the same time southern Florida was also rifting northward away from the Yucatan while the Gulf of Mexico expanded. During the upper Jurassic, while initial Atlantic rifting was occurring, this southern Florida area was an updip rim of an enlarging Gulf of Mexico as well as the updip part of the Bahamas shallow marine basin (Meyerhoff and Halten, 1974; Tator and Hatfield, 1975; Mitchell-Tapping, 1984).

One of the first documented descriptions of the basement Paleozoic rocks of Florida was made by Applin (1951) and included a discussion of granite and diorite provinces. Subsequent granitic cores have been described by Bass (1969), Barnett (1975) and Smith (1982), who have proposed a general distribution or province of granitic basement rocks in Florida. The most predominant igneous rocks in southern Florida are rhyolitic ignimbrites, tuffs, and agglomerates (Bass, 1969). A subsequent report by Barnett (1975) confirmed the presence of rhyolitic rocks throughout the southern half of the Florida peninsula. An analyses of a rhyolite penetrated in a well about subsea 6,000 m depth in Collier County, onshore east of Mud Hole, yielded an age of 189 mybp (Applegate *et al.*, 1981).

In seismic studies of the deep Gulf and the Florida Escarpment by Lord (1987) and Schlager *et al.* (1987), the lowermost sedimentary unit that can be identified by seismic stratigraphy is interpreted to be graben clastic and carbonate infill. The overlying marine sequences are interpreted to be the seaward portion of a transgressive sequence over a subsiding shallow-water margin. This is a period of cooling, faulting, fracturing, and subsidence of the crust coupled with the buildup of an extensive carbonate platform, which followed the cessation of sea-floor spreading (Manspeizer, 1985). Some seismic reflections show deformation by block-faulting that correlates with the northern Gulf Coast fault motion. The Shell well OCS-G-4950 drilled offshore Charlotte Harbor in 1986 (TD 3,187.25 m) indicates that the Tampa-Sarasota Horst or Arch and Pulley Ridge were in place before the Jurassic. Therefore, it can be inferred from

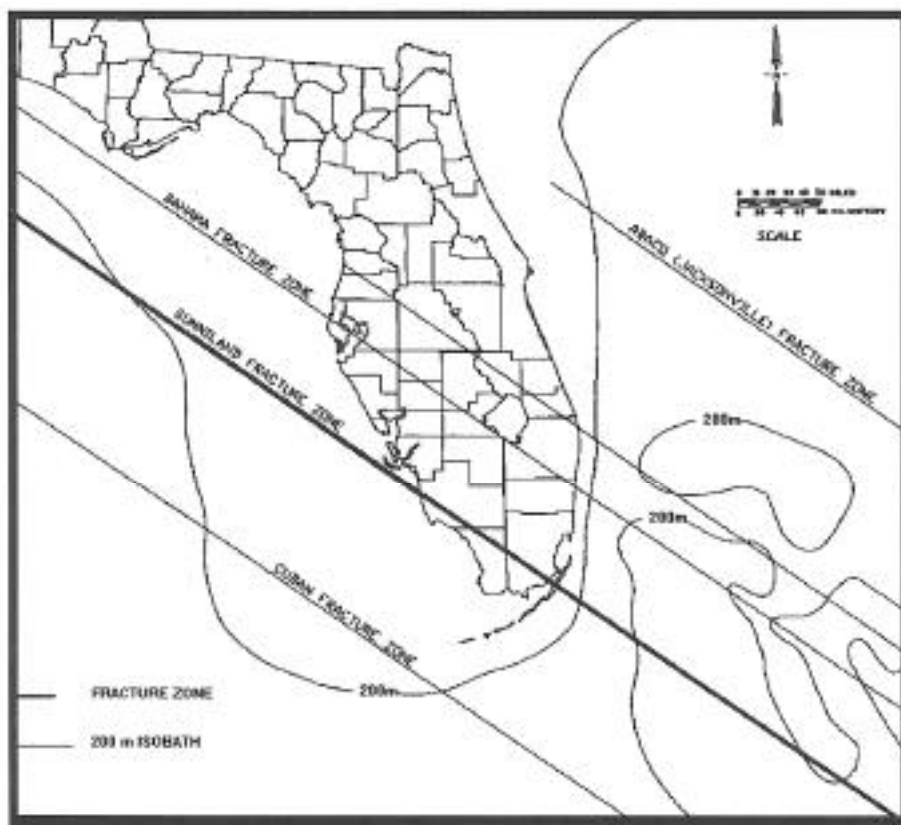


Figure 6. Major basement fracture zones crossing the Peninsular Florida – Bahamas region (Duncan et al., 1992). The Sunniland Fracture Zone crosses the State northwards passing near Key Largo, Felda oilfields, and Naples. The Sunniland Fracture Zone crosses through the Mud Hole area, while a northeastern-southwestern fault branching from the Sunniland Fracture Zone passes nearby Mineral Springs area.

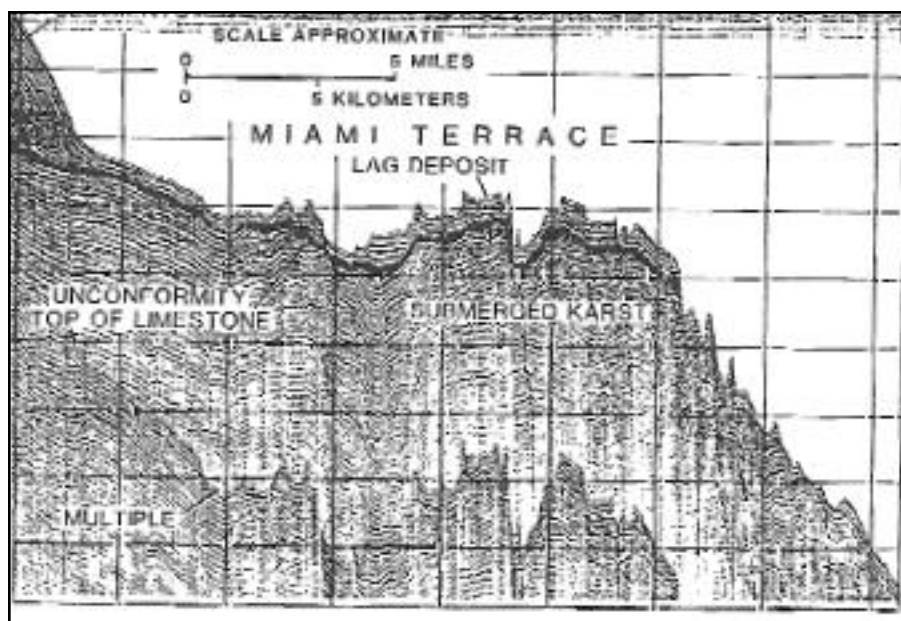


Figure 7. Seismic reflection profile in the western Straits of Florida showing faulting and the sinkhole features in the Suwannee Limestone of the Floridan Aquifer (Meyer, 1989).

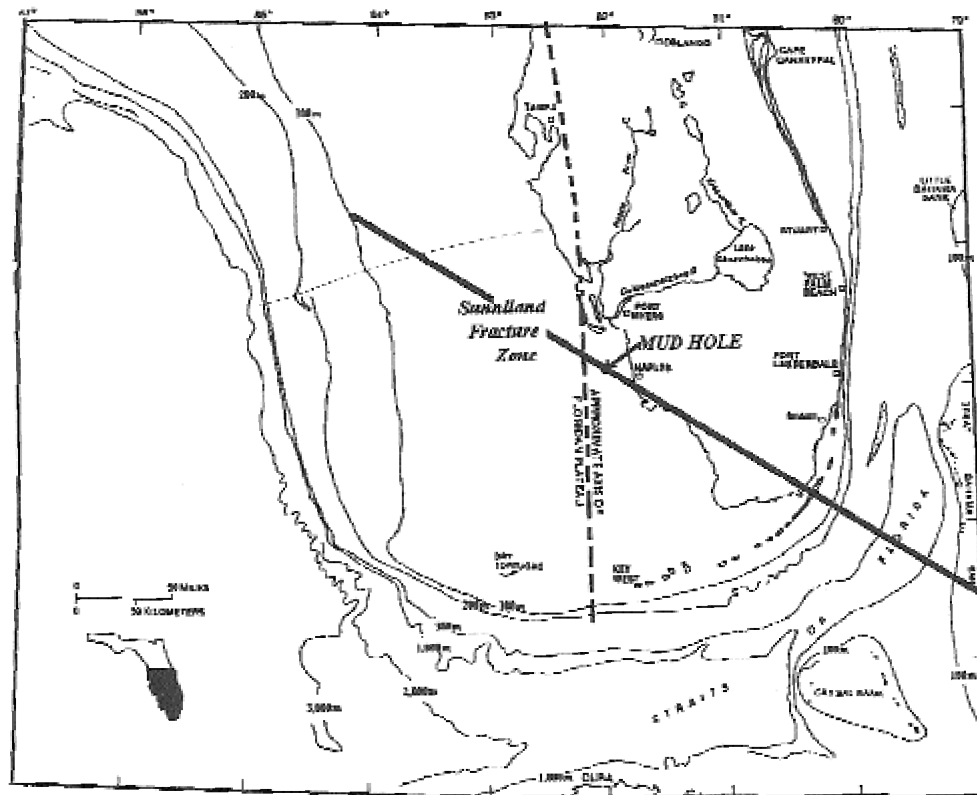


Figure 8. The relationship of the basement Sunniland Fracture Zone passing through Key Largo, Sunniland oilfields, and the Mud Hole location (after Duncan et al, 1992).

seismic not only that the thickest Triassic and Jurassic sediments are only present in the grabens (Mitchell-Tapping, 1994a), but also that deposition is controlled by major basement faulting (Fig. 6).

FLORIDAN AQUIFER SYSTEM (FAS) OF SOUTHERN FLORIDA

Southern Florida is underlain by about 2,000 m of Cenozoic age sediments with about 1,000 m of Mesozoic sediments overlying a rhyolitic basement. The Triassic continental sediments (Mitchell-Tapping, 1994a) are overlain by Cenozoic sediments composed of are marine limestones, dolostones, and evaporites with clastics (sand and clay) in the uppermost section of the Cenozoic. The FAS (Fig. 5) of southern Florida is composed chiefly of rocks that range in age from early Miocene to Paleocene. The top of the system in southern Florida ranges from depths of 150 m to 400 m with an average thickness of about 300 m. The Paleocene Cedar Keys Formation evaporites are the lowermost confining unit of the FAS. Overlying these evaporites are the limestones of the Cedar Keys, Oldsmar, Avon Park, Ocala, and Suwannee Formations (Fig. 5). Part of FAS was once called the "Floridan aquifer" (Parker et al., 1955) and all of which was once called the "Tertiary limestone aquifer system" (Johnston et al., 1980). In southwest Florida, the lowermost part of the Tampa Limestone is also included in the FAS. Now-a-days, the Floridan Aquifer System is defined (Miller, 1986) "as a vertically continuous sequence of permeable carbonate rocks of Tertiary age that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than that of the rocks that bound the system above and below."

In northern and central Florida, the FAS includes rocks ranging from Paleocene to early Miocene age, and locally in southeast Georgia, it includes rocks of Late Cretaceous age. Overlying the Floridan are alternating beds of sandstones, clay, marl, and limestone in the Miocene Tampa Limestone of the Hawthorn Group. These sediments contain the intermediate artesian aquifers and make up the upper confining unit. Overlying these deposits are limestones, clays, and sandstones of the Tamiami and Caloosahatchee Formations and undifferentiated Pleistocene Pamlico clastic deposits that make up the unconfined surficial aquifer. The system is divided into three general hydrogeologic units: Upper, middle confining, and Lower units.

The Lower Floridan aquifer is used for injected liquid wastes, while the Upper Floridan aquifer contains brackish to saline water and is chiefly used for limited industrial and agricultural supply, surplus freshwater storage (ASR), and for feedstock for desalination or reverse-osmosis desalting plants. Some saline Miocene limestone aquifers within the upper confining unit are also an important local source of groundwater for reverse-osmosis supply in certain areas of southwestern Florida. The surficial aquifer generally is the major source of potable water in southern Florida.

Upper Floridan Aquifer

In southern Florida, the aquifer interval consists of the permeable carbonate zones of the Tampa, Suwannee, Ocala, and the upper section of the Avon Park Formations (Fig. 5). Aquifer performance tests (APT's) indicate that the transmissivity of the aquifer to be as great as 5,570 m²/d (Meyer, 1989). The groundwater is saline.

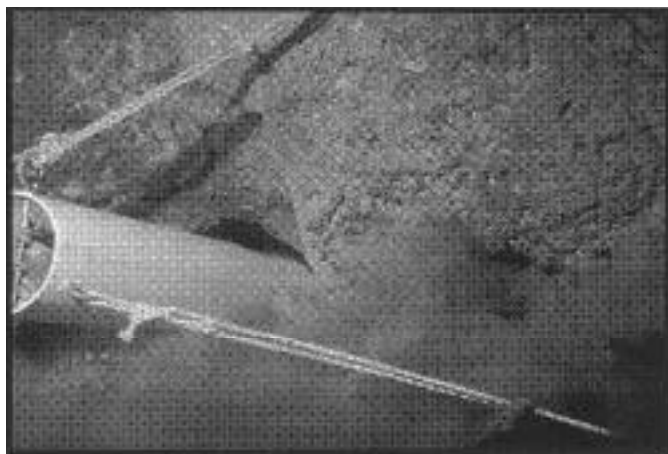


Figure 9. The Hydrolab Datasonde3, recording hourly physical water quality data, installed in a perforated protective housing and deployed in the main vent of Mud Hole at 18m depth. The instrument was deployed on the 19th May 1998 and removed by a fishing party-boat on 16th June 1998 (photo: G.Woody). The hourly data of 634 samples of each parameter was constant (standard deviation <0.1) except for tidal depth measurements.

Salinity and temperature both increase with depth. As temperatures along the southeastern coast are anomalously cooler (at about 21°C) possibly resulting from both seawater intrusion causing heat transfer to the Atlantic Ocean Straits of Florida (Sproul, 1977) as well as heat transfer to the cooler Lower Floridan aquifer (Kohout, 1965). Many researchers consider that water movement is lateral through highly permeable zones of dissolution at or near the top of each formation. A seismic reflection profile (Fig. 7) across the offshore Miami Terrace shows the pinnacles and troughs associated with the submerged karst and the northward-prograding sediments of Miocene through Pleistocene age unconformably overlying the Suwannee Limestone (Institute of Marine Science, 1962). The rugged topography of the submarine terrace was formed by the collapse of solution features (sinkholes) in the underlying limestone. Malloy and Hurley (1970) identified the surface rock as Suwannee and Hawthorn based on the foraminifers present. Sinkholes in the Miami Terrace (Fig. 7) are both filled and unfilled: those that are unfilled are thought to be active springs (Meyer, 1989). The large filled sinkhole in the center profile (Fig. 7) is about 3 km wide and is probably a collapse of the highly cavernous Boulder Zone in the lower part of the Oldsmar Formation (Miller, 1986). Sinkholes generally are present throughout southern Florida but are obscured by Miocene and younger sediment. These sinkholes are chiefly in Tertiary limestone along joints or fractures that trend northwestward to southeastward. Their presence, however, is often indicated by seismic, drilling, changes in local salinity, and temperature anomalies.

Middle Confining Unit

This unit consists of the lower part of the Avon Park Formation and the upper part of the Oldsmar Formation (Fig. 5). The unit has relatively low permeability, and it generally separates the less-saline Upper Floridan aquifer from saline Lower Floridan aquifer. Hydraulic connection between the upper and lower aquifer is inferred from sinkholes and fractures observed from seismic. Ground-water movement in southern Florida is artesian and estimated to be upward flow from the Lower Floridan aquifer through the

middle confining unit, then through the Upper Floridan aquifer. Temperature anomalies and salinities can vary greatly at the top of the unit, indicating upwelling of water from the Lower Floridan.

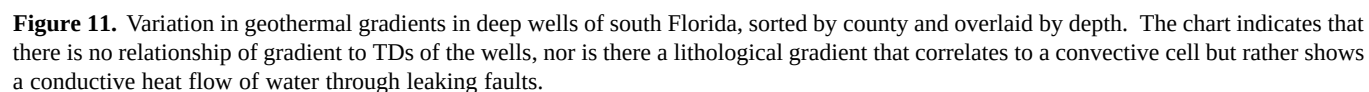
Lower Floridan Aquifer

This aquifer consists of the Oldsmar and the upper part of the Cedar Keys Formations (Fig. 5). In the Oldsmar Formation there are three permeable dolostones separated by less permeable limestones. The high transmissivity of the lowermost dolostone, called the Boulder Zone (Miller, 1986), ranges from 3×10^5 m²/d to 2.3×10^6 m²/d (Singh et al., 1983, 1983; Meyer, 1975), whereas that for the overlying dolostones is considerably smaller and the hydraulic connection between the permeable dolostones is poor (Meyer, 1989). In a similar study by Mitchell-Tapping (1995), it was proposed that upward movement of Floridan freshwater along faults in the Suwannee and Ocala Limestones may be recharging two large lenses or bubbles in the deep saline artesian Floridan Aquifer in the coastal areas of southern Brevard and Indian River Counties of Florida.

A pronounced temperature anomaly is usually present in the Lower Floridan Boulder Zone, with the lowest temperature measured at 10.3°C in the deep disposal well G-2334, located in Fort Lauderdale. Based on limited data, it appears that the Boulder Zone water temperature increases from the Straits of Florida westwards toward the axis of the Floridan Plateau. Based on a few well data values and Mud Hole temperature, Kohout (1965) hypothesized the circulation of cold seawater inland from the Straits of Florida through the lower part of the Floridan aquifer driven by geothermal heat flow, while Meyer (1989) thought that measurements of head,



Figure 10. A nurse shark resting in a small vent in a rock cavity. The spring area is littered with man-made debris, but also is teeming with marine life, such as, Loggerhead turtles, Jewfish, groupers, skates, rays, a variety of mollusks, and many other fish were observed. The presence of skate eggs and Lightning-welk egg cases might indicate that the area is attractive for breeding. The bottom was sandy and devoid of live plant or benthic life, but fish were abundant, mostly large snapper and some grouper. A large stingray was resting at the lowest point of the vent area, while a medium-sized Yellow Wrass occupied the major vent, while two large Nurse sharks resting in a rock crevasse in one of the smaller vents. The bottom area was covered with organic matter, mostly Whelk egg casings and Angel Wing proboscis sheaths, along with an old crab trap, with rope and buoy, in the middle of the depression (photo: G.Woody).



Parameter	Open Ocean	Mud Hole*	Injection Well+
Calcium	411	660	
Magnesium	1,290	1,300	
Sodium	10,760	12,000	10,454
Potassium	399	470	
Silica	0.1	5.8	
Bicarbonate	142	135	
Sulphate	2,710	4,000	3,188
Chloride	19,350	20,000	19,744
Dissolved Solids	38,700	37,600	29,200
Specific Conductance (mS/cm)	55.6	54.3	
pH	8.3	7.2	7.64
Temperature (degC)	26	35.3	38.67
Depth (m)	surface	18	915

Table 3. Chemical analyses of Mud Hole, FAS, and oceanic waters.

temperature, and carbon-14 activity in the water of the Boulder Zone, as recorded in wells G-2334 and G-2296 in eastern and western Broward County, supported the Kohout hypothesis (Fig. 4). No previous researchers have considered the effects of fracture zones as a conduit for upconing of deep hotter water (Fig. 8) or that much hotter water must be mixing in the Floridan Aquifer to maintain the Mud Hole water temperature.

MUD HOLE EXPLORATION

During this study, three surveys were conducted: the first scouted the site, the second was unsuccessful in locating the spring due to rough seas, while the third successfully mapped the spring (Fig. 3), determined the location of the number of vents, obtained rock samples, and deployed a physical water-quality recording device.

The first survey of Mud Hole was conducted on 1st February 1996. At that time, two dives were conducted to a depths of 19 m (65 ft) but visibility was poor at only 1.5 m horizontally to 3 m vertically. Air temperature was approximately 25°C with ambient seawater temperature at 19 m measured at 17°C. The site was difficult to find and is marked at the surface (Fig. 2) only by very slight differences in water color due to sediment up-welling from the spring. While the surrounding bottom depths are generally at 12 m, the spring sits in a sink-hole type depression at approximately 19 m, with the slope of the sides more gradual than the expected cone-shape. The spring does not flow out only from one or two "holes" in the bottom, but in some cases actually percolates up through the bottom sediment. The spring water was quite warm, measured at 35°C using a fever thermometer, and can be seen coming up out of the seafloor like heat waves on a summer highway. Silt is easily stirred-up, but the spring flow clears it up rapidly, taking some sediment to the surface. The spring area is littered with man-made debris, but also is teeming with marine life, such as, Loggerhead turtles, Jewfish, groupers, skates, rays, a variety of mollusks, and many other fish were observed. The presence of skate eggs and Lightning-welk egg cases might indicate that the area is attractive for breeding. The water column above the spring was also measured (Table 2).

The third visit to the site was made on a sunny clear and calm morning of Tuesday 19th May 1998 from a harbor on Sanibel Island. The objectives of the dive were to install a physical water quality measuring device in the mouth of the main spring (Fig. 9), and to map the submarine spring (Fig. 3). The water quality instrument (Hydrolab Datasonde3) was programmed to record data hourly for 3 months. As the water visibility was good, the Mud Hole thermal vent was easily located, as the transition from the surrounding flat bottom to the deeper water of the Mud Hole sinkhole was clearly visible on the graphical depth-sounder display, and the surface had been also marked by two small foam ball buoys by party fishing boats. The dive started in warm, clear water near the surface with about 10 m horizontal visibility with a surface temperature about 30°C, until encountering a thermocline about 6 m down from the surface the temperature dropped to about 23°C, and the visibility decreased. On the bottom of the sinkhole at 19 m, the surface was sandy and devoid of live plant or benthic life, but fish were abundant, mostly large snapper and some grouper. A large stingray was resting at the lowermost point of the sinkhole, while a medium-sized Yellow Wrass occupied the major vent area. A survey of the area was made, noting two large Nurse sharks resting in a rock crevasse near the main vent (Fig. 10). The bottom area of the mud hole was covered with organic matter, mostly Whelk egg casings and Angel Wing proboscis sheaths, along with an old crab trap, with rope and buoy, in the mid-

dle of the depression. After completing the survey, the perforated protective housing holding the recording instrument fitted neatly into the main vent hole of the spring was secured with steel cables. Unfortunately, the instrument was torn out of the seabed vent by the anchor of a fishing party boat on 16th June 1998. Table 1 shows the statistical record of the physical water quality parameters recorded by a Hydrolab Datasonde3 programmed to record data every hour during the period May 19 to June 16, 1998 (28 days). No indication of variation in water parameters due to tidal flow or change in clarity after heavy rains was recorded. The values (Table 1) agree closely with the findings of Kohout (1965) and Fanning et al (1981, 1982).

SOUTH FLORIDA TEMPERATURE GRADIENTS AND WATER CHEMISTRY

The FAS is thought to have a strong cooling influence on the geothermal gradient of southern Florida (Smith and Fuller, 1977; Meyer, 1989). Kahout has proposed that a cyclic convective flow of seawater is responsible for this influence and the water is heated as it passes through the FAS Boulder Zone. This hypothesis requires that there is a landward gradient, however, this is very questionable as the geology does not appear to support it (Fig. 4). Sproul (1977) reported a negative geothermal gradient in a well in coastal Martin County (-4.13°C/km) while Meyers (1989) reported other wells in Miami, Fort Lauderdale, and the Florida Keys also showed a reverse temperature. Sproul (1977) also examined many wells drilled in McGregor Isles, Lee County, and showed a strong relationship of anomalous warm-water temperatures to faulting. These wells lie very near to faults extending from a basement fracture zone.

An example of sudden change in temperature was recorded in an injection well drilled in coastal Lee County in 1998 near to documented McGregor Isles and Caloosahatchee river faults. The temperature log recorded 30.4°C at 76.25 m, remained constant until 167.8 m, then rose to 32.3°C until 735 m then rapidly rising to 37.5°C within 2 m. The log recorded 37.5°C with a steady rise until 38.3°C at 823.5 m, then remained steady at 38.67°C until TD 915 m (Lindsey J. Sampson, Lee County Environmental Services Division, personal communication via email, 25 February 1999).

Smith and Fuller (1977) calculated the average gradient in 13 wells in southern Florida as 13.5°C/km, however, a range of 14.8°C/km to 25.8°C/km, with an average of 17.3°C/km, was calculated in this study (Table 4). This study investigated the bottom-hole temperature (BHT) recorded in 64 deep wells in Hendry Lee, Collier, Monroe and Dade counties and calculated a geothermal gradient, using a surface temperature of 23.9°C, for each well. The results (Table 4) indicate a variation in gradient that depends on nearness to major fault or fracture zone (Fig. 6). Plotting the gradients indicated that anomalous high values were an indication of near proximity to faults usually falling on a line with a major basement fracture zone (Fig. 11).

On the west coast, there are other major warm-water springs in the onshore, such as, Warm Mineral Springs, also known as *Warm Salt*, *Salt*, and *Big Salt* springs, located at lat. 27°03'33"N., long. 82°15'40"W, about 3 km southeast of Venice in Sarasota County. The water is currently used in an outdoor bathing pool and recreation spa. This spring was surveyed and the source identified by a vent on the northern wall of the sink at a depth of 65 m from the surface (Rupert, 1994). The hot saline sulfurous spring is emerging from a 53 m long and 1 m high conduit in a collapsed cavern in the Tamiami Limestone, about 75 m in width at the surface, funneling down to a depth of 70 m. Water flow rates increase and clarity appears to

Table 4
South Florida Deep Well Temperature Gradients

County	Operator	well #	TD (m)	BHT (°C)	Corr °C	°C/km
Charlotte	Gulf	#1 Stevens	3794.8	82.2	68.3	18.00
Charlotte	Exchange	#1 Babcock	3950.4	97.2	73.3	18.56
Charlotte	Mobil	#1a Babcock	3808.8	88.9	65.0	17.06
Charlotte	Mobil	#1a Babcock	3510.9	85.1	62.2	17.72
Collier	ANG	#1 Collier 6-4	3625.2	79.4	55.5	15.32
Collier	Bass	#12-2	5693.1	122.2	98.3	17.27
Collier	Bass	#5-2 Oleum	3663.7	85.7	62.8	17.13
Collier	Chambers & Kennedy	#1 Anchor	3585.9	75.6	51.7	14.41
Collier	Gulf	#1 S/L 340	3462.4	113.3	89.4	25.83
Collier	HOR	#1 Collier	3843.0	106.7	82.8	21.54
Collier	HOR	#31-3 Collier	3585.6	82.2	58.3	16.27
Collier	HOR	#26 GCR	3571.6	76.7	52.8	14.77
Collier	HOR	#20 GCR	3567.0	77.8	53.9	15.10
Collier	HOR	#2 Miles Collier	3943.7	87.8	63.9	16.20
Collier	HOR	#22	3554.8	100.0	76.1	21.41
Collier	HOR	#24-4	3659.1	83.3	59.4	16.24
Collier	HOR	#25 GCR	3568.2	81.1	57.2	16.03
Collier	HOR	#1 Price	3623.7	66.7	42.8	11.80
Collier	HOR	#21	3553.6	99.4	75.5	21.26
Collier	LL&E	#6 S/L	3591.1	90.0	66.1	18.41
Collier	McCulloch	#7-2 Collier	3538.6	73.9	50.0	14.13
Collier	Mobil	#1 Trien	5019.7	108.3	84.4	16.82
Collier	NRM	#1-3 Lee	3568.2	75.7	52.8	14.78
Collier	Phillips	#1 Gerry A	3612.7	79.4	55.5	15.37
Collier	Tribal/Exxon	#2-6 GCR	3541.7	87.2	63.3	17.88
Collier	Weiner	#1 Collier Read	3873.8	88.9	65.0	16.78
Dade	Barnett Fario	#1-SL	3542.9	77.8	53.9	15.21
Dade	RK Petroleum	#2-S/L 1938S	3505.1	75.6	51.7	14.74
Dade	RK Petroleum	#2-S/L 1939	3538.9	74.4	50.5	14.28
Hendry	Clayton-Williams/Dart	#27-1 Collier	3560.9	71.1	47.2	13.26
Hendry	Exxon	#6-3 Turner	3528.9	76.1	52.2	14.80
Hendry	Exxon	#8-1 Turner	3561.8	93.9	70.0	19.65
Hendry	HOR	#30-3 Lee Cypress	3579.2	85.1	62.2	17.38
Hendry	LL&E	#1 S/L 164	3724.1	92.2	68.3	18.35
Hendry	LL&E	#1 S/L 165	3481.3	87.2	63.3	18.19
Hendry	Mobil	#1 SeminoleB	3552.3	89.4	65.5	18.45
Hendry	Mossbacher	#1 Collier	3570.3	88.3	64.4	18.05
Hendry	Phillips	#A1 Duda	3539.8	88.3	64.4	18.20
Hendry	Phillips/Mobil	#1 Seminole C	5187.4	113.3	89.4	17.24
Hendry	Sun	#1-RC-b	3562.7	88.3	64.4	18.09
Hendry	Sun	#21-2 Red Cattle	3534.6	88.9	65.0	18.39
Hendry	Sun	#19-2 Red Cattle B	3531.6	87.8	63.9	18.09
Hendry	Sun	#33-3 Red Cattle B	3560.0	89.4	65.5	18.41
Hendry	Tribal	#2-1 CNS	3603.3	87.8	63.9	17.73
Hendry	Tribal	#1 Duda	3511.8	90.0	66.1	18.82
Hendry	Tribal	#2 Duda	3484.0	93.3	69.4	19.93
Hendry	Tribal	#1 Duda	3512.7	85.6	61.7	17.55
Hendry	Tribal/HOR	#5-3 Oleum	3528.9	87.8	63.9	18.10
Hendry	Weiner	#1 Oleum	3555.1	88.9	65.0	18.28
Lee	Lee County	#1 Injection Pine Ridge	915.0	38.7	14.8	16.14
Lee	Calco	#1 S/L 224B	4261.2	114.4	90.5	21.25
Lee	HOR	#2-1 LeHigh Acres	3573.1	92.2	68.3	19.12
Lee	HOR	#20-2 Consolidated	3553.6	88.9	65.0	18.29
Lee	Hughes Oil	#1 Hunter	3547.2	87.8	63.9	18.01
Lee	NRM	#34-1 Chapman	3601.7	85.6	61.7	17.12
Lee	Tribal	#29-1 Osbourne	3603.0	88.9	65.0	18.04
Monroe	Calco-Gulf	S/L #1-46	4663.5	73.3	49.4	10.60
Monroe	Gulf	S/L 826Y	3989.4	87.8	63.9	16.01
Palm Beach	HOR	S/L #1-1004	3906.4	83.3	59.4	15.21
Palm Beach	Hughes & Hughes	S/L #1-B3	3355.6	93.3	69.4	20.69

Table 4. Variation in geothermal gradients in deep wells of south Florida, sorted by county and depth.

improve after heavy rainfall, while changes in temperature indicate mixing of Floridan and surficial waters (Rupert, 1994).

Warm Springs Spa located at lat. 26°28'31"N., long. 81°50'14"W, about 18 km south of Fort Myers in Bonita Springs. The spring is an artesian well 1309.5 m deep with a 0.23 m diameter casing. The water temperature has been measured at 32°C and the chloride concentration is 1,000 mg/L. The water is currently used in an outdoor bathing pool and health spa (Rosenau et al, 1977).

Hot Springs is located at lat. 26°49'23"N, long. 82°01'37"W on Burnt Store Road (State Highway 765) about 13 km south of Punta Gorda, in Charlotte County. This artesian well was drilled to a depth of 481.2 m adjacent to an oil test that was drilled much deeper and is now apparently discharging through the water well. The well was discharging about 175 m³/min to a swimming pool when sampled on November 18, 1965: water temperature 35.6°C, specific conductance 52.5 mS/cm, and chloride 19,200 mg/L (Rosenau et al, 1977). Humble Oil #1-Lownes-Treadwell, an abandoned wildcat developed into a spa, is located in Charlotte County south of the Peace River, about 37 km southeast of Warm Mineral Spring. The well flowed at the rate of 500 m³/min, chloride was recorded as 18,700 mg/L, and a temperature of 35.6°C (Kohout, 1977). Another wildcat drilled by Gulf Oil #1-Stevens, located 3 km due east recorded a temperature of 37.8°C in the Floridan Boulder Zone (Meyer, 1989).

In the chemical analysis of the Mud Hole water, the values appear at first glance to be similar to the surrounding seawater (Table 3). However, the sulfate content is very high indicating that the water has been in the presence of anhydrite. The SO₄/Cl ratio is 0.2, indicating brine water from a deeper source than the Floridan. Some of the values are similar to those of oil field brines and even though they are similar in some parameters, they indicate a mixing of hot brine with saline aquifer water.

CONCLUSIONS

In southern Florida deep well temperature measurements have shown that the geothermal gradients are affected by cooler brackish and saline water from the Floridan aquifer (Duncan et al., 1992). At depths between 300 m and 1,000 m the water in the Floridan aquifer (Fig. 5) suddenly becomes anomalously cooler by about 2°C (Meyer, 1989). The average temperature of the aquifer appears to increase from the eastern coast towards the central axis of the Florida Plateau, upon which lies the Mud Hole spring. The temperature distribution, both horizontally and vertically, are thought by some researchers to indicate that cold dense seawater flows inland through the Boulder Zone where it becomes warmer by geothermal heat (Fig. 4). However, no convective lithological gradient exists in southern Florida.

Based on then existing well data values and the Mud Hole temperature, Kohout (1965) hypothesized the circulation of cold seawater inland from the Straits of Florida through the lower part of the Floridan aquifer driven by geothermal heat flow. Later, Meyer (1989) thought that measurements of head, temperature, and carbon-14 activity in the water supported the Kohout hypothesis (Fig. 4). However, no previous researchers have considered the effects of fracture zones as a conduit for upconing of deep hotter water (Fig. 8) or that much hotter water must be mixing in the Floridan Aquifer to maintain the Mud Hole water temperature. This study considers that the origin is not seawater but hotter brine and saline water upconing from a deeper zone that moves upward via fault zones. Therefore, assessment of south Florida water resources should seriously consider the effects of faulting on aquifers.

ACKNOWLEDGMENTS

We would like to acknowledge the help of the Ostego Bay Foundation and Steve Brown of Sanibel Island, the owner of the diving vessel, for their help and kindness. The chief diver, an outstanding academic ECC student and co-author of this paper, Graham Woody, died in January 1999 after a parasailing accident in California which left him in a comma for 9 weeks. Graham performed and directed the underwater survey and the water chemistry analysis of Mud Hole. This project is dedicated to his memory.

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