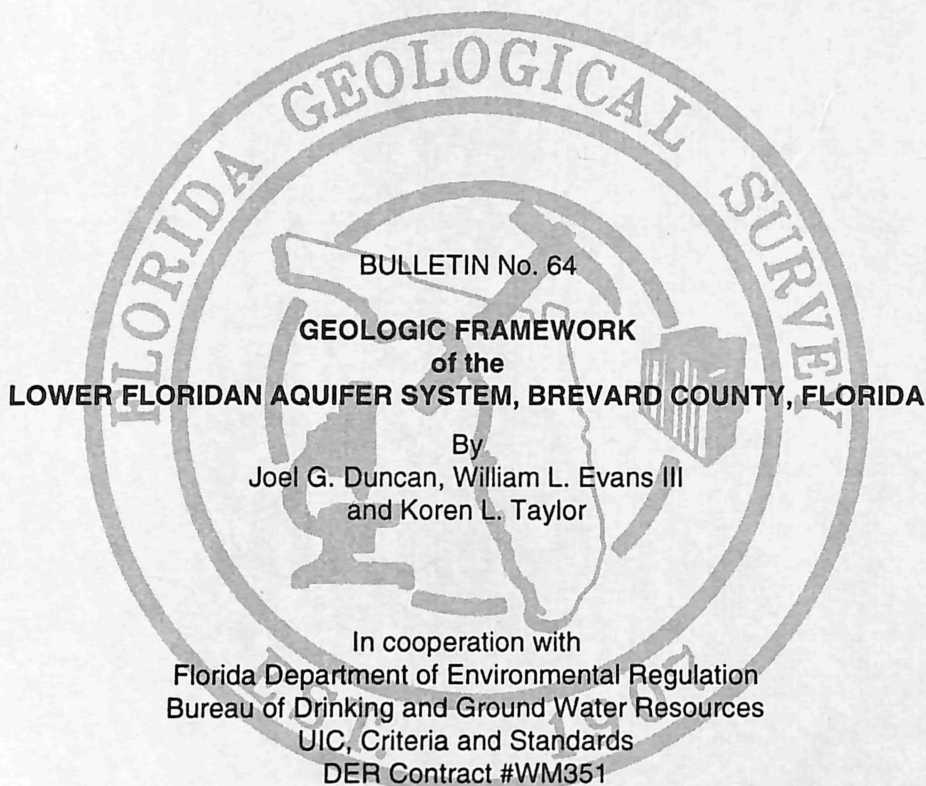


STATE OF FLORIDA
DEPARTMENT OF ENVIRONMENTAL PROTECTION
Virginia B. Wetherell, *Executive Director*

DIVISION OF RESOURCE MANAGEMENT
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CONVERSION FACTORS

The English units used in this report may be converted to metric (International System) units with the following factors:

MULTIPLY	BY	TO OBTAIN
feet	0.3048	meters
inches	2.540	centimeters
inches	0.0254	meters
miles	1.609	kilometers
sq. miles	2.590	sq. kilometers
Fahrenheit (F)	5/9 (F-32)	Centigrade
gallons	0.003785	cubic meters

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) - a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929" or "mean sea level (MSL)." Although the datum was derived from the average sea level over a period of many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific Coasts, it does not necessarily represent local mean sea level at any particular place.

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BULLETIN No. 64

GEOLOGIC FRAMEWORK
of the
LOWER FLORIDAN AQUIFER SYSTEM, BREVARD COUNTY, FLORIDA

By
Joel G. Duncan, William L. Evans III
and Koren L. Taylor

In cooperation with
Florida Department of Environmental Regulation
Bureau of Drinking and Ground Water Resources
UIC, Criteria and Standards
DER Contract #WM351

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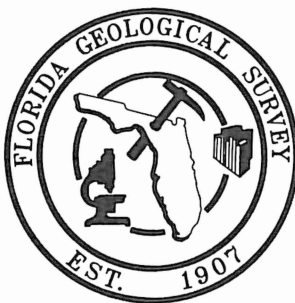
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LETTER OF TRANSMITTAL



FLORIDA GEOLOGICAL SURVEY
Tallahassee

April 1994

Governor Lawton Chiles, Chairman
Florida Department of Environmental Protection
Tallahassee, Florida 32301

Dear Governor Chiles:

The Florida Geological Survey, Division of Resource Management, Department of Environmental Protection, is publishing as Bulletin 64, *Geologic Framework of the Lower Floridan Aquifer System, Brevard County, Florida*, prepared by staff geologist Joel Duncan and research assistants William L. Evans III and Koren L. Taylor. This report presents data on the geology and hydrology of Brevard County. This report is timely because of its detailed examination of the lower Floridan aquifer system, which is used to receive liquid waste products. This information will be of significant value to local, county, and state planners, as well as to the private sector.

Respectfully,

Walter Schmidt, Ph.D.
State Geologist and Chief
Florida Geological Survey

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ABSTRACT

A common problem for coastal communities in Brevard County has been the disposal of liquid waste products. A favored solution utilizes injection-disposal wells whereby liquid waste is pumped underground into highly permeable rocks within the non-potable portion of the lower Floridan aquifer system. Ground-water chemistry data from monitor wells at several Brevard County injection sites suggest that the presence and/or lateral continuity of suitable confining rock above the injection zone is questionable and indicate that a better understanding of the lower Floridan aquifer system is needed. Thus, the purpose of this study is to detail the geologic framework of the lower Floridan aquifer system in Brevard County.

Strata of the lower Floridan aquifer system in Brevard County dip generally to the southeast with an average dip angle of 0.1 degree. Several lines of evidence suggest the possibility of faulting in Brevard County. The inferred faults strike north-south and are downthrown to the west.

Cores of lower Floridan aquifer system strata commonly exhibited some degree of fracturing. In general, fractures appear to be restricted to well indurated or highly cemented carbonates, principally dolostone. Slickensided surfaces, lacking well defined fracture planes, were observed in moderately to poorly indurated limestones.

Strata of the lower Floridan aquifer system in Brevard County are characterized by Paleocene to Middle Eocene, interbedded limestones and dolostones. Limestones are generally fossiliferous, moderately to poorly indurated, and have high primary porosity. Dolostones are typically well indurated and have fossil moldic and vugular porosity.

In Brevard County, the Floridan aquifer system generally consists of two major permeable zones separated by a middle confining unit of lower permeability. The middle confining unit in the study area consists of dense dolostone with interbedded limestones which act as a single leaky confining unit within the main body of the permeable carbonates of the Floridan aquifer system. Carbonates below the middle confining unit in the lower Floridan aquifer system are predominantly low permeability, interbedded dolostones and limestones with zones of moderate to high permeability.

The "Boulder Zone," a subzone of the lower Floridan aquifer system, is the primary injection horizon in Brevard County and consists of highly fractured and cavernous dolostones which exhibit high transmissivities. Above the Boulder Zone, there are layers of carbonates that have confining qualities. Evaluation of geophysical logs, lithologic samples and borehole videos from Brevard County injection wells indicate that numerous fractures exist throughout the lower Floridan aquifer system.

Analysis of monitor zone ground-water chemistry data showed that the majority of the wells in the study exhibit trends in water quality to some degree. These trends, barring wellbore mechanical problems, are attributed to the upward migration of injected waste waters along permeable conduits related to fractures, dissolution cavities, and vertical and lateral lithofacies variations. The middle confining unit of the Floridan aquifer system in Brevard County is probably best described as having a leaky confining character.

GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM, BREVARD COUNTY, FLORIDA

By

Joel G. Duncan, P.G. #396, William L. Evans III and
Koren L. Taylor

INTRODUCTION

Brevard County is located on the Atlantic coastline of eastern, central peninsular Florida (Figure 1). White (1970) places Brevard County in the Mid-Peninsular Zone which is "characterized by discontinuous highlands in the form of sub-parallel ridges separated by broad valleys." According to White (1970), the geomorphology of Brevard County consists of, on the east, the Atlantic Coastal Ridge and on the west, the Eastern Valley (Figure 2). Ten Mile Ridge is a discontinuous ridge trending northwest-southeast through the southeastern portion of the county (White, 1970).

Coastal communities in Brevard County, like many others in Florida, have experienced a substantial population increase over the past several decades. Rapid growth and development accompanying the population influx resulted in increased demands on the environment. A common problem has been the disposal of liquid waste products, principally treated municipal sewage and in some cases, industrial waste by-products. A favored solution utilizes injection-disposal wells whereby liquid waste is pumped underground into highly permeable rocks of the lower Floridan aquifer system. In Brevard County, ground water within the lower Floridan is highly mineralized and unsuitable as a potable water source. Thus, disposal of injected waste water in this portion of the aquifer system was not considered a problem. Ideally, upward migration of liquid waste into potable portions of the aquifer system is prevented by a confining sequence of impermeable strata overlying the injection zone.

Monitor well data from several injection sites in Brevard County suggest that the presence

and/or lateral continuity of suitable confining rock above the lower Floridan injection zone is questionable. These data indicate that a better understanding of the lower Floridan aquifer system is necessary in formulating protective criteria for future injection projects. The purpose of this study is to detail the geologic framework of the lower Floridan aquifer system in Brevard County. This will contribute to a better understanding of the local aquifer hydrogeology and thus support future injection well practices that maximize resource protection.

This investigation summarizes the geology, hydrogeology, and ground-water chemistry of the lower Floridan aquifer system based on data from seven injection wells in Brevard County and one in Indian River County. Data employed in the study included well cuttings, cores, injection well tests, borehole videos, geophysical logs, and monitor well water chemistry information.

The report focuses on the following aspects of the lower Floridan aquifer system:

1. Structural Geology
2. Lithostratigraphy
3. Depositional environments
4. Dolomitization
5. Geophysical character
6. Hydrogeology
7. Ground-water chemistry analysis

The greatest concentration of injection wells occurs in the Melbourne-Palm Bay area (Figure 3). Merritt Island, approximately 25 miles north of Melbourne, is the northern-most injection site of the study. The Hercules injection site, in Indian River County, is the southern-most injection well included in the study and was chosen as a control well outside the primary study area for comparison purposes.

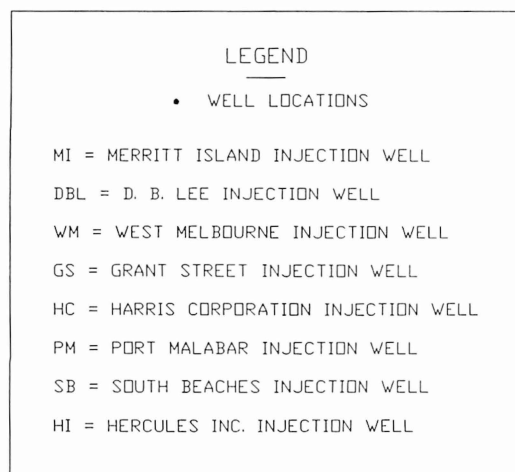
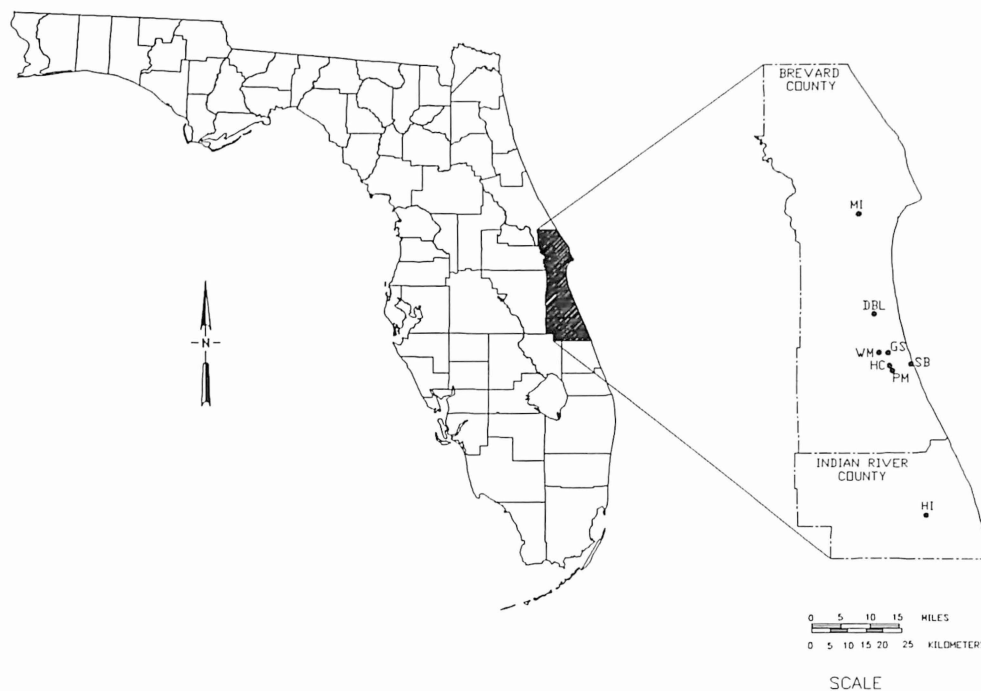


Figure 1. Map of peninsular Florida showing the location of the study area and the injection wells.

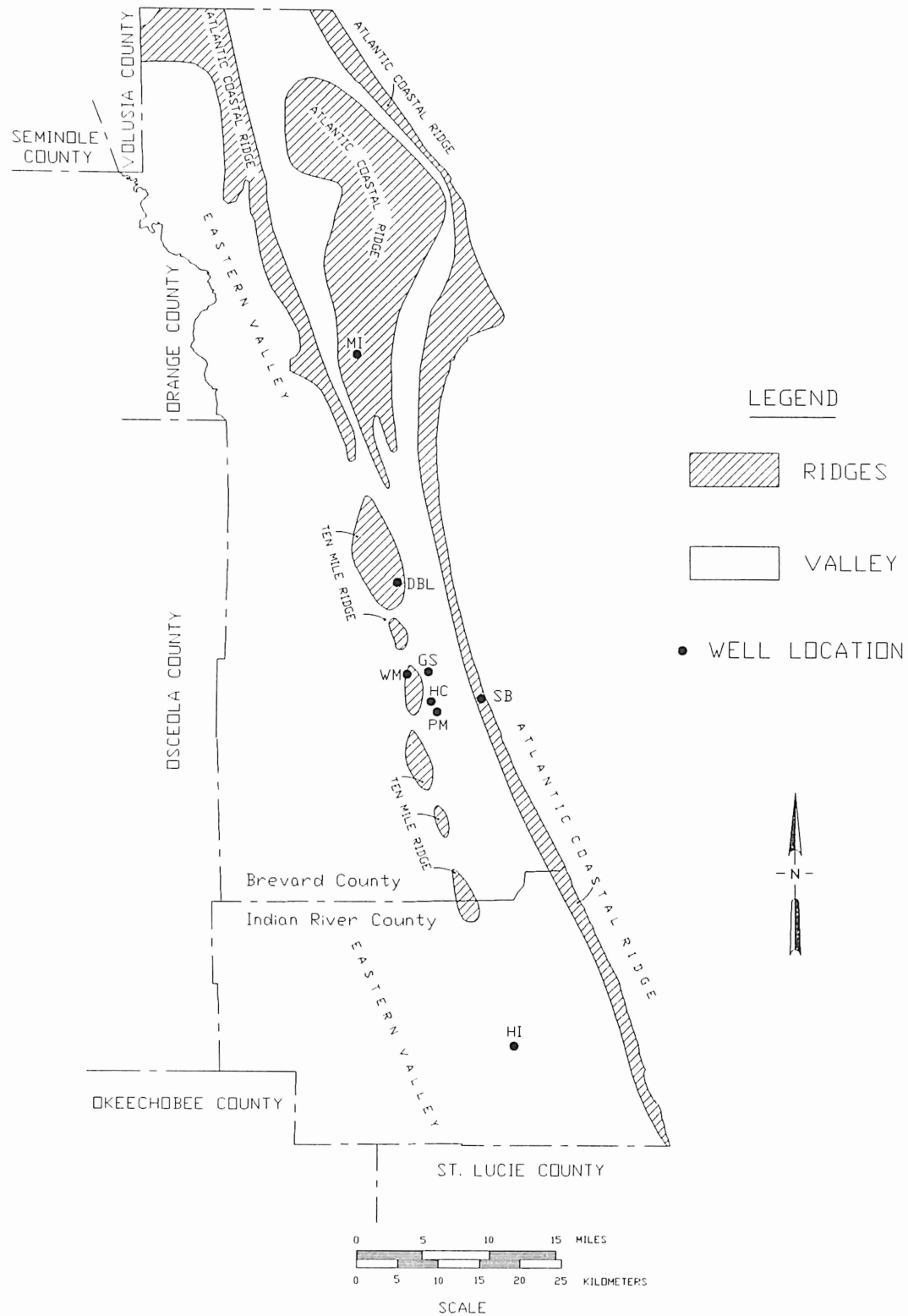


Figure 2. Geomorphologic features of Brevard and Indian River counties (modified from White, 1970).

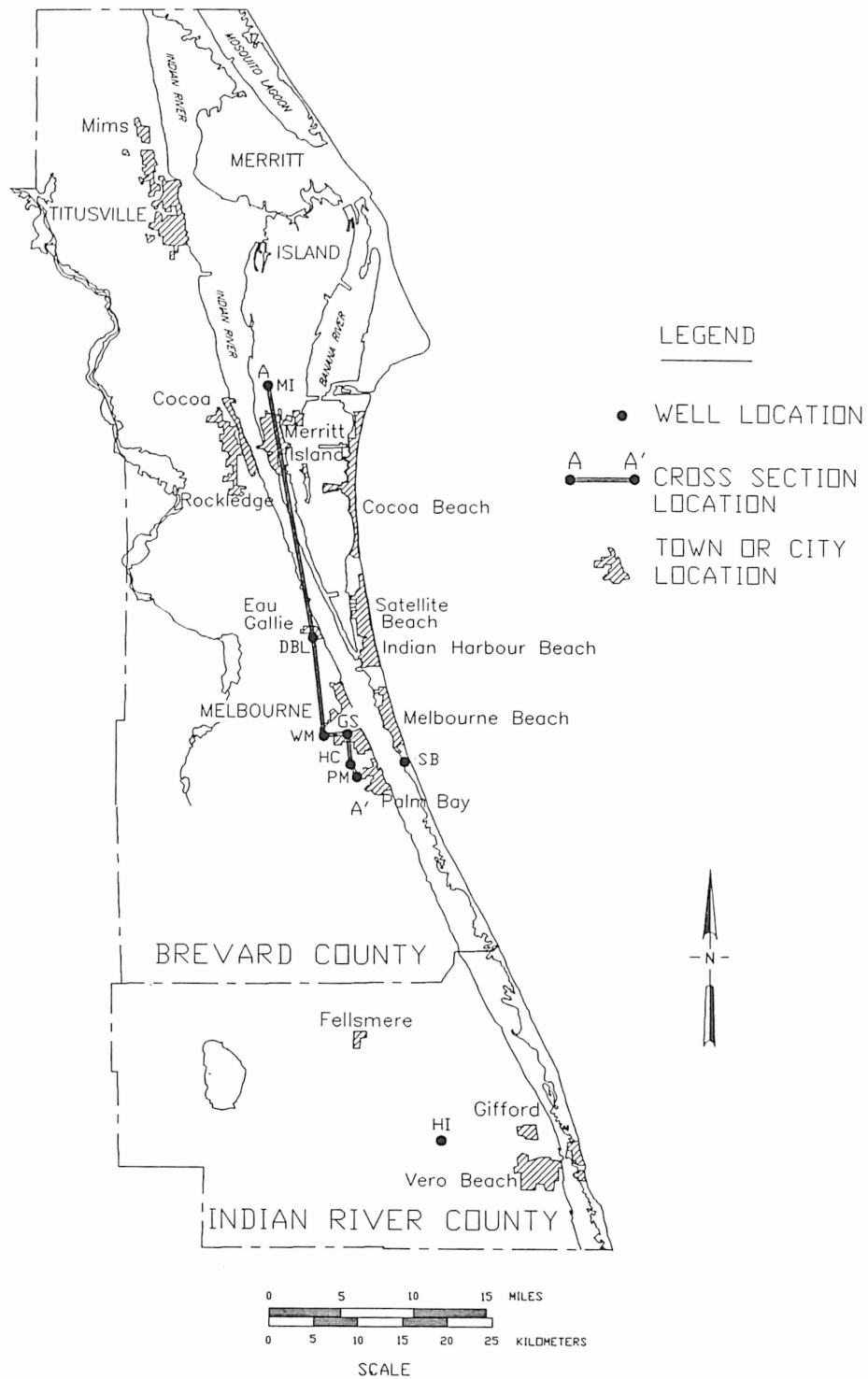


Figure 3. Map showing the location of the A-A' cross section (Plates 1-3) and the injection wells.

STRUCTURAL GEOLOGY

Regional Structural Framework

In Florida, Mesozoic and Cenozoic sediments overlie an eroded basement rock complex ranging from Precambrian to Jurassic (Barnett, 1975). The Peninsular Arch (Figure 4), the dominant structural feature of Florida, is a north-west-southeast trending positive basement element cored by a large block of Precambrian rock covered by Paleozoic strata (Barnett, 1975). The Peninsular Arch has been a positive feature affecting sedimentation from the Jurassic into the early Cenozoic (Miller, 1986).

Structural Framework of Brevard County

Brevard County lies on the eastern flank of the Peninsular Arch. Depth to basement ranges from approximately -7500 feet in the northwest to -11,000 feet National Geodetic Vertical Datum (NGVD) in the southeast portion of the county (Barnett, 1975). Barnett's (1975) sub-Zuni subcrop map shows that basement rock in Brevard County consists of Middle Cambrian Osceola Granite with possible Jurassic volcanics in the extreme southern portion of the county. An apparently significant subsurface basement fault trends northwest-southeast from near the Florida-Georgia border down through the central portion of Brevard County according to Barnett's (1975) basement structure map (Figure 5). The interpreted normal fault is down-thrown to the east.

The most prominent structural feature influencing the lower Floridan aquifer system in Brevard County is the Brevard Platform, described originally by Riggs (1979). Scott (1988) characterized the Brevard Platform as a low relief ridge or platform that plunges gently to the south-southeast and southeast (Figure 6). Both the Ocala Limestone and Hawthorn Group sediments erosionally thin across the Brevard Platform and have erosional upper surfaces (Brown et al., 1962; Scott, 1988). The observed

degree of thinning increases to the north into Seminole and Volusia Counties where both the Ocala Limestone and Hawthorn Group are missing after erosionally wedging out along the flanks of the Sanford High (Vernon, 1951). Riggs (1979) considered the Brevard Platform a southern extension of the Sanford High.

West of the Brevard Platform is the Osceola Low, described by Vernon (1951) as a fault-bounded low with a significant thickness of Miocene sediments. Vernon's postulated fault that forms the eastern boundary of the Osceola Low trends north-northwest roughly following the Brevard - Osceola County line and is upthrown to the east. Subsurface structure maps constructed on top of the Ocala Limestone for this area indicate anomalous apparent dip directions with possible dip reversals in the vicinity of Vernon's proposed fault. Scott (personal communication, 1991) interpreted the feature as "a possible flexure or perhaps a zone of displacement with 'up' on the east and 'down' on the west."

Strata of the lower Floridan aquifer system in Brevard County dip generally to the southeast away from the Brevard Platform axis at an average angle of 0.1 degree (Figure 7). Apparent dip angles are greater in the Melbourne - Port Malabar vicinity ranging from 0.2 to 0.5 degrees locally. Several apparent dip reversals occur along a southeasterly trend from the West Melbourne site to the Port Malabar site.

Several lines of evidence indicate the possibility of normal faulting in Brevard County. The concentration, amount and quality of data in the Melbourne vicinity is much greater than that available in other areas making fault identification more confident. However, faulting is probably not restricted to this area. After detailed correlation of injection well geophysical logs (gamma-ray and sonic), a sequence of correlative marker horizons can be recognized and the thickness of specific stratigraphic intervals relative to the marker horizons can be determined

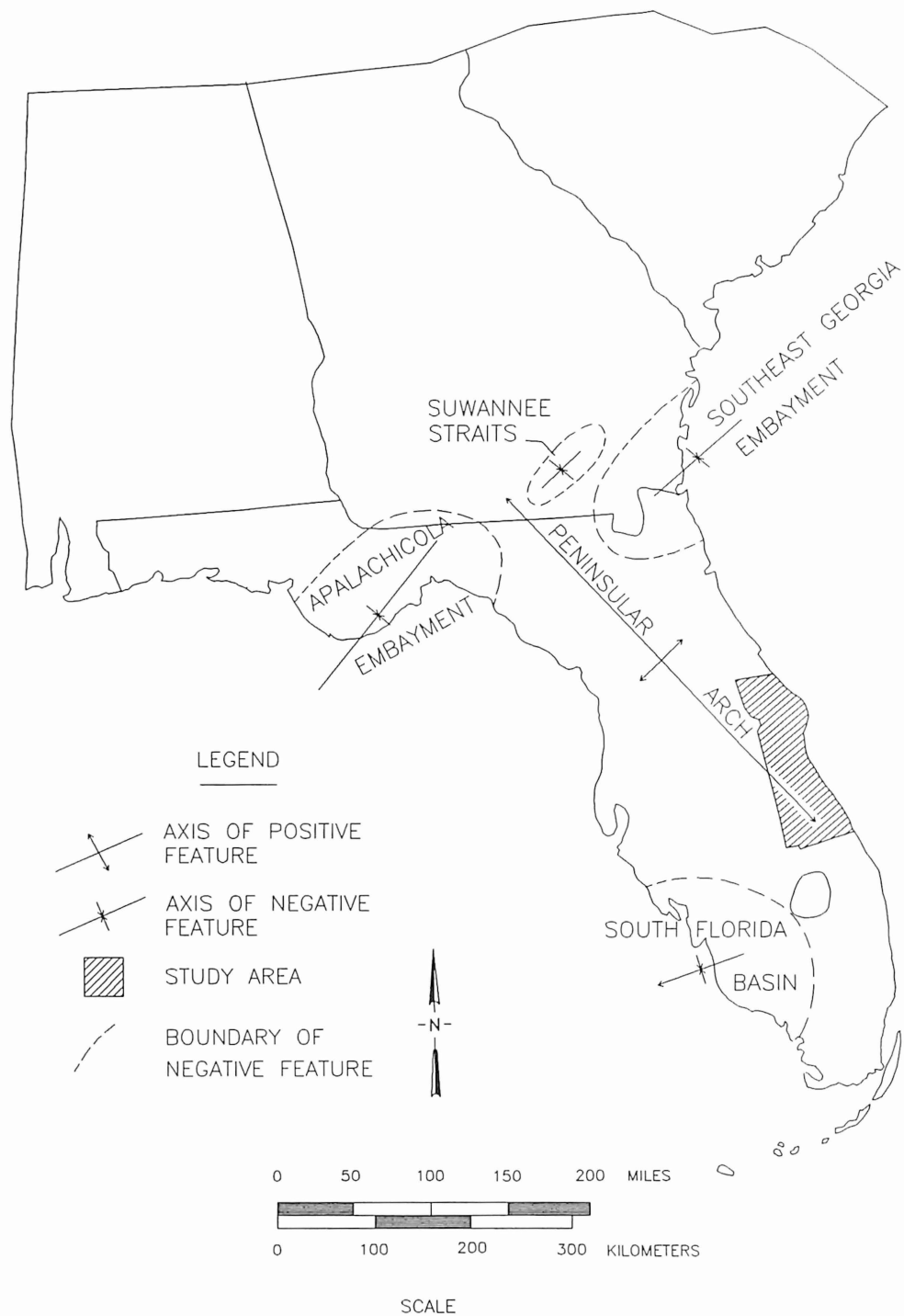


Figure 4. Pre-Cenozoic structural features of Florida and south Georgia (from Miller, 1986).

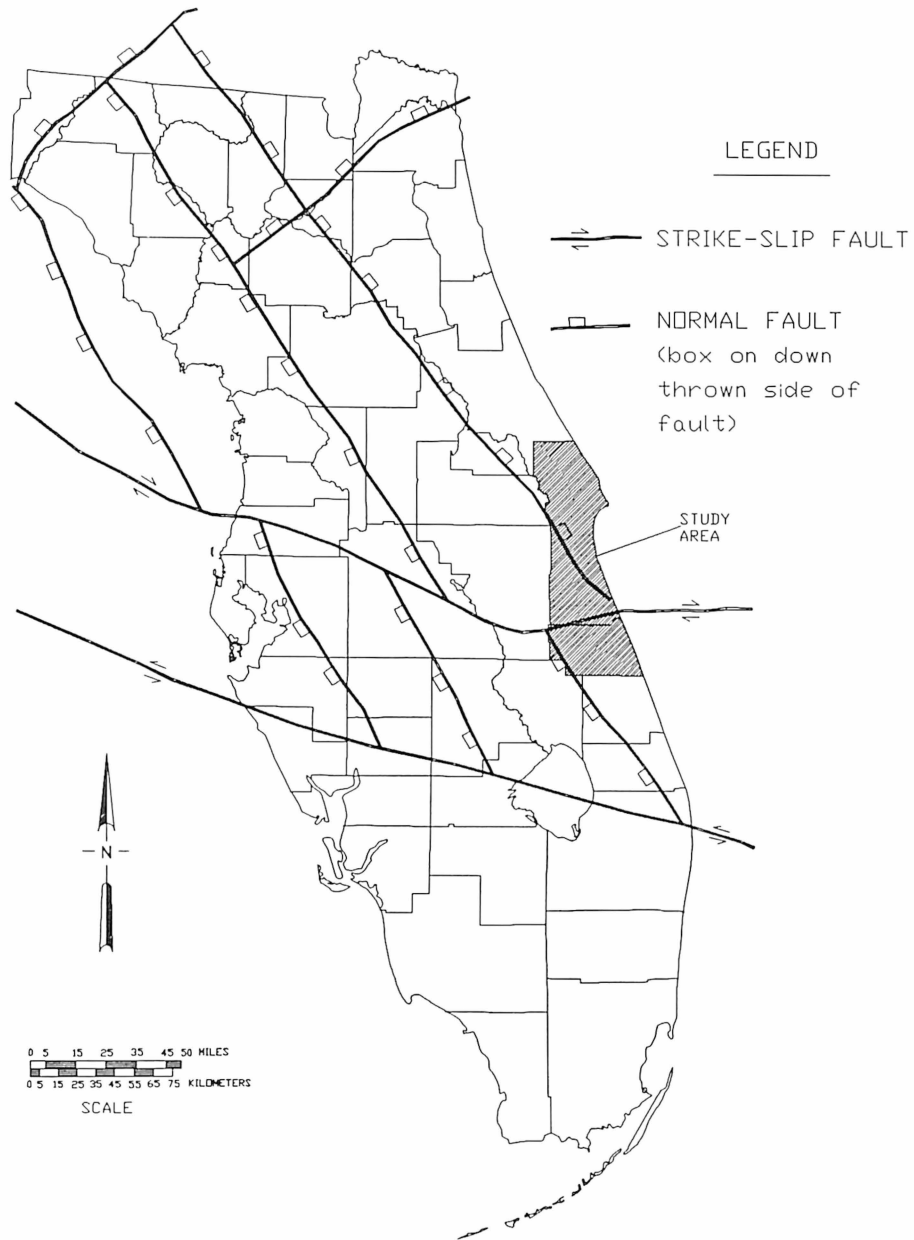


Figure 5. Basement faults of Peninsular Florida (modified from Barnett, 1975).

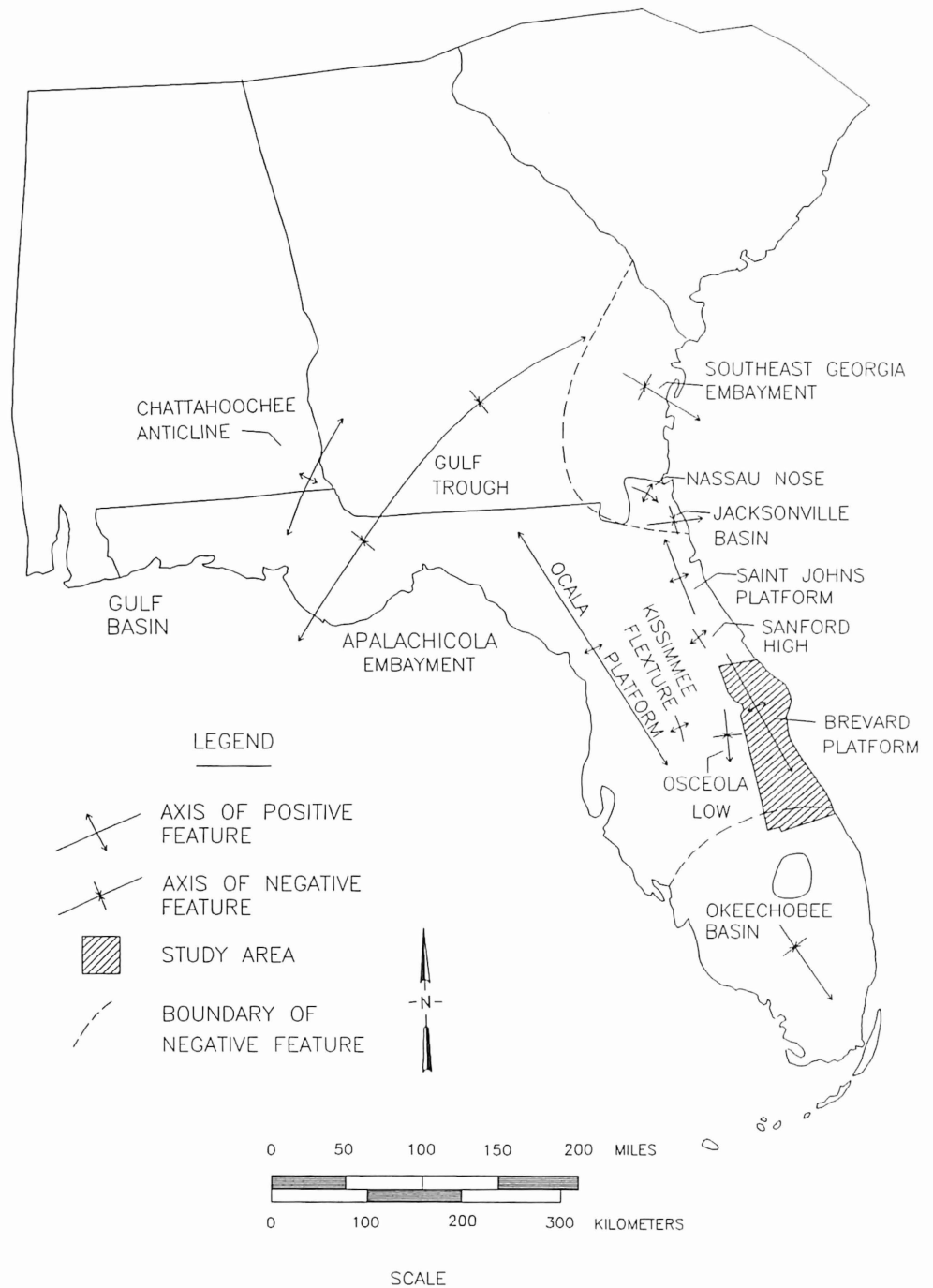


Figure 6. Mid-Cenozoic structures affecting the lower Floridan aquifer system (modified from Scott et al., 1991)

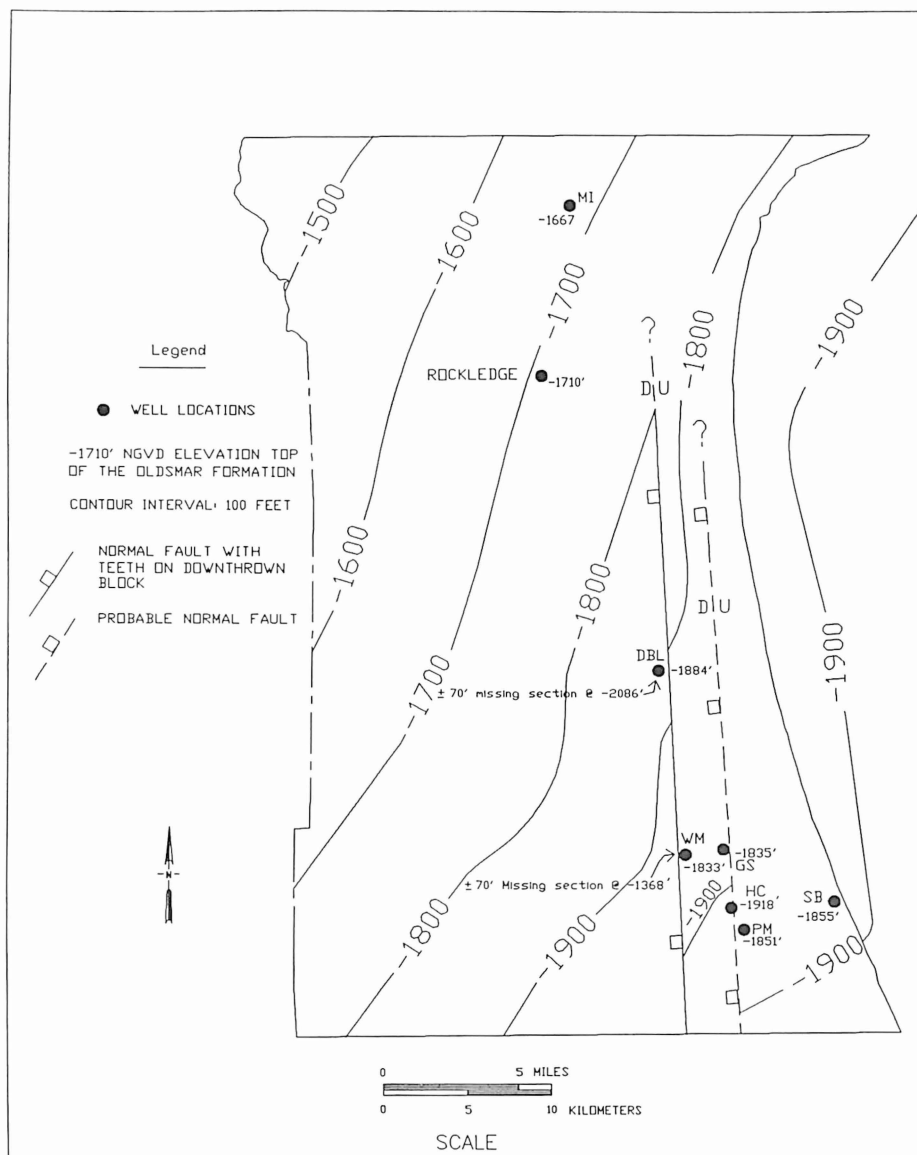


Figure 7. Structure top of the Oldsmar Formation (glauconite marker bed).

(Plate 1). Marker-bed constrained stratigraphic intervals can then be compared on a well-to-well basis. Any significant variations in thickness within a particular stratigraphic interval can then be evaluated in terms of a possible fault, unconformity, or other geological mechanism.

Anomalously shortened stratigraphic sections are evident in the D. B. Lee and West Melbourne boreholes (Plates 1 and 2). Approximately 70 feet of strata are missing in both wells at two different stratigraphic levels. The omitted section occurs at a depth of approximately -2,086 feet NGVD in the D. B. Lee and -1,368 feet NGVD in the West Melbourne well. The structure top of the Oldsmar Formation (glauconite marker bed) based on geophysical logs shows that the West Melbourne well is 51 feet higher compared to the D. B. Lee well (Figure 7) which is consistent with the appropriate footwall/hanging wall geometric relationship of a possible normal fault cutting both wellbores where the omitted sections occur (Plate 2). The West Melbourne and Grant Street wells are both located on the footwall or "upthrown" block of the fault and are on strike with respect to the Oldsmar Formation top. Marker beds above the fault cut in the West Melbourne well are structurally lower than the equivalent intervals in the Grant Street well indicating their position on the "downthrown" block of the fault (Plate 2). The fault apparently "dies out" upward above the Ocala Limestone in the Hawthorn Group somewhere between the West Melbourne and Grant Street wells (Plate 2). The similarity in the amount of shortened stratigraphic section or "throw" occurring in the D. B. Lee and the West Melbourne wells and the structural relationships between the West Melbourne and Grant Street wells suggest that the probable fault strikes north-south and is downthrown to the west.

Difficulties encountered during drilling operations, and unusual pump test results in the D. B. Lee injection well, could be a reflection of anomalous structural conditions in this vicinity. Extremely poor recovery on several attempts to

core could be an indication of highly fractured rock that may be associated with faulting in this wellbore. Pump tests (see Figure 33, Hydrogeology Section) conducted on the D. B. Lee injection well showed an almost immediate response in all three surrounding monitor wells (Knapp, 1989) indicating an unexpected high degree of vertical communication within the Floridan aquifer system at this location. This could be the result of a highly fractured injection and confining sequence, direct communication along a fault plane, or injection well mechanical problems. Sonic log cycle skipping and an erratic caliper log observed from approximately 1,150 feet below land surface (BLS) to 2,185 feet BLS could be explained by the presence of fractured rock (Plates 1, 2 and 3). Fracturing is also apparent on borehole videos beginning at a depth of 1,100 feet BLS down to 2,176 feet BLS.

Alternatively, the shortened stratigraphic sections in the D. B. Lee and West Melbourne wells could be interpreted in terms of two unconformities rather than a single fault. However, as the missing sections occur at significantly different stratigraphic levels in the two wells, such an interpretation would have to involve two separate unconformities representing two unique episodes of uplift. This interpretation appears less likely, over such a small stratigraphic interval, than one involving faulting given that the amount of missing section is approximately the same in both wells and the unique circumstances of the D. B. Lee.

Shortened stratigraphic sections in Brevard County wells could be an artifact of karst collapse structures. Conceptually this explanation would entail a sinkhole-like collapse and sediment in-fill with subsequent differential compaction and subsidence across the karst feature (Figure 8). A shortened section could occur between the hypothesized subsided sediment and the karst depression floor. However, the sediment package overlying the karst feature should be thicker overall relative to non-karst well locations. Detailed correlation of marker beds indi-

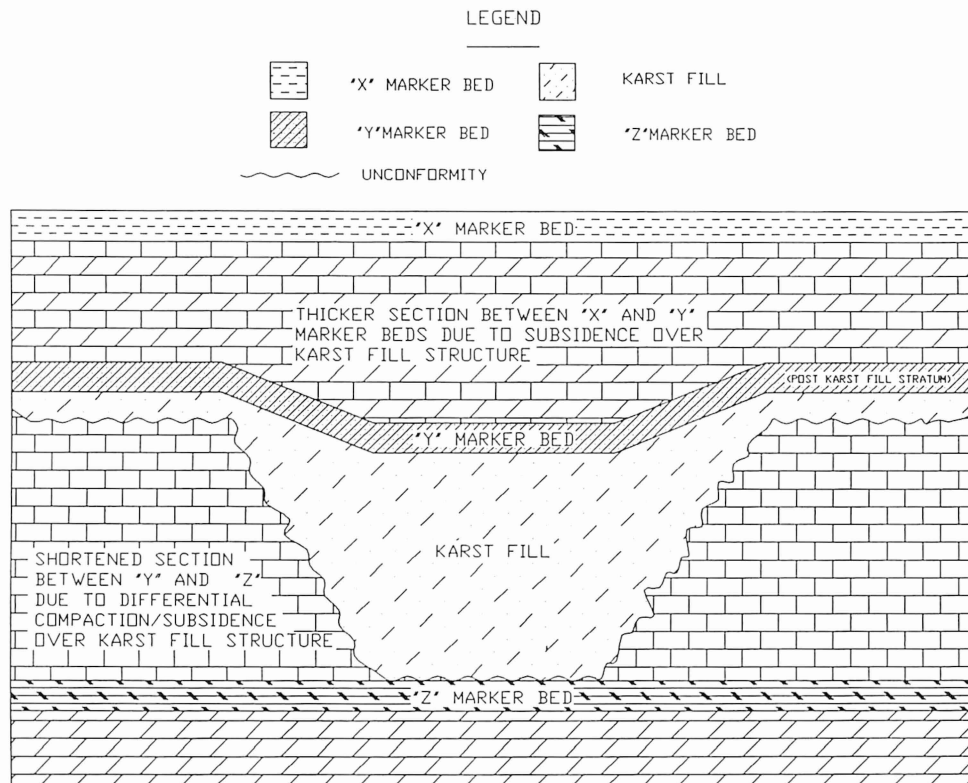


Figure 8. Hypothetical model of karst fill structure. Note the apparent thickness between marker beds "X" and "Z" remains constant even over the karst structure.

cates that such stratigraphic relationships are not apparent between boreholes in Brevard County and a karst collapse origin for the shortened sections in the D. B. Lee and West Melbourne wells is unlikely.

Core from each of the four wells for which core was available exhibited some degree of fracturing. In general, fractures appear to be restricted to well-indurated or highly cemented carbonates of the Floridan aquifer system in Brevard County. Consequently, fractures are more prevalent in dolostones due to their consistently highly indurated nature than in limestones. Moderately- to poorly-indurated mudstones, wackestones, packstones and grainstones may act as mechanical boundary layers preventing the vertical propagation of fractures from dolostone beds. However, several core samples of poorly to moderately-indurated carbonates did have slickensided surfaces but lacked well defined fracture planes. The slickensides may be the unique expression of fracture-related strain consistent with the mechanical properties of the less indurated carbonate rocks.

The majority of observed fractures are high angle, approaching vertical and are probably tensional in origin. What appear to be shear fractures were observed in core recovered in the Harris #2 within the interval from 1,903 to 1,912 feet BLS. These fractures occur in a moderately-indurated mudstone sequence and have dip angles of approximately 50 degrees. The fractures have well developed, polished slickensided surfaces and could be related to faulting. Other data, such as anomalous differences in marker bed structural elevations between the Harris #2 and the Port Malabar well and shortened stratigraphic sections in the Harris #2 (between 2,000 and 2,130 feet BLS) and the Merritt Island (between 510 and 900 feet BLS) are also suggestive of possible small displacement faulting (<50 feet of throw). A second possible fault, downthrown to the west with north-south strike, is suggested by the apparent dip

reversal occurring between the Harris #2 and Port Malabar wells (Figure 7 and Plate 2).

Tensional fractures in Brevard County could be related to several different processes in terms of their origin. These processes may include release fracturing as a result of sea level changes, fracturing associated with possible uplift of the Brevard Platform, and tension gash fracturing in proximity to fault planes.

The origin of faulting here is less clear given the apparent passive nature of the North American Atlantic coastal margin and the absence of salt-related tectonics that is typical of Gulf Coastal Plain regions. The most recent major tectonic event involving the Florida-Bahama Platform region was the Late Cretaceous through Eocene convergence of the Caribbean plate with the North American plate in the northern Cuba and southern Bahama platform region (Sheridan et al., 1981). Sheridan et al. (1988) explained the present configuration of deep channels and shallow platforms of the Bahamas and Eocene faulting along the Abaco Canyon as the result of north-south compression associated with Caribbean-North American plate convergence. Convergence-related stresses reactivated old (Jurassic) planes of crustal weakness (Sheridan et al., 1988) such as the Abaco and Bahama Fracture Zones of Klitgord, et al. (1984) with possible left lateral shear displacement (Sheridan et al., 1981, 1988). The effect of these stresses along the projected trend of the Bahama Fracture Zone across the Florida peninsula (Figure 9) (and the Florida Atlantic Coastal Margin) has not been addressed, and the possibility of deformation similar to that proposed in the Bahamas cannot be ruled out.

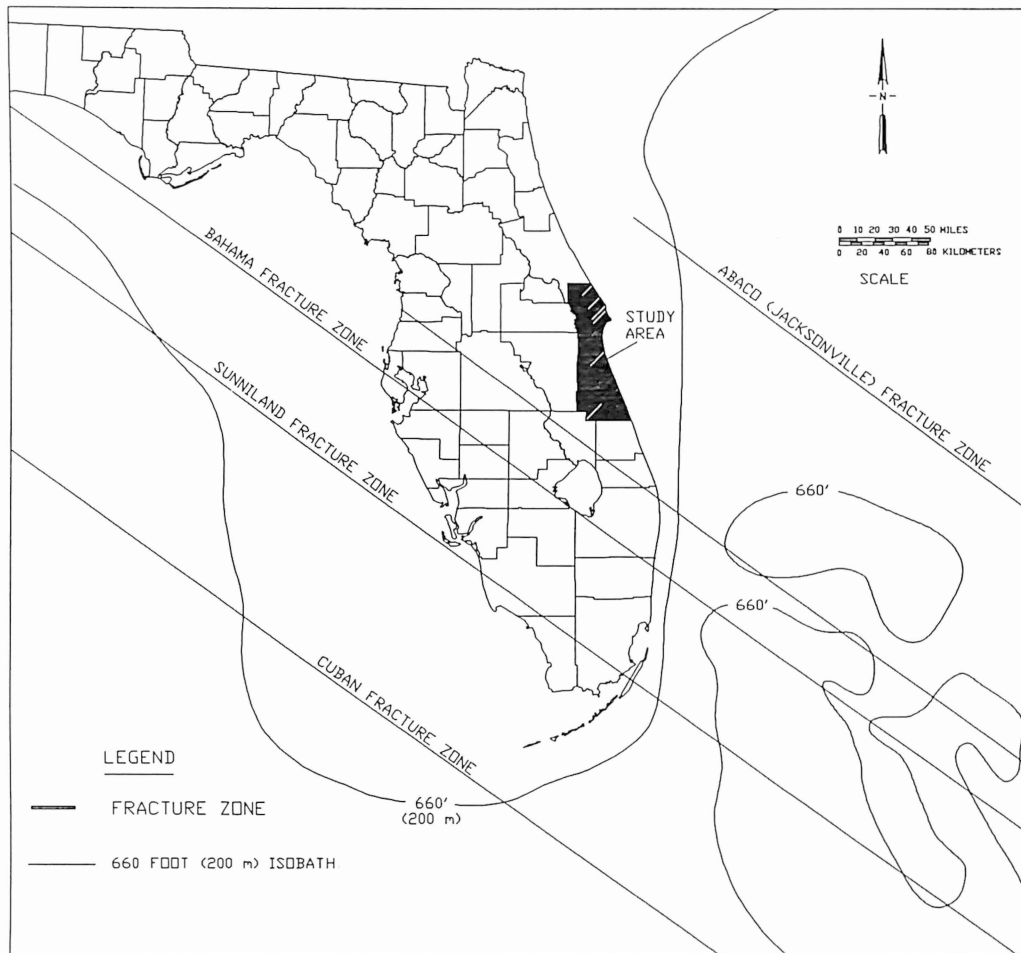


Figure 9. Basement (Jurassic) Fracture Zones of the Florida/Bahama Region (after Klitgord et. al., 1984).

LITHOSTRATIGRAPHY

General Stratigraphy

Cretaceous to Holocene strata in Brevard County consist of a thick sequence of interbedded limestone and dolostone overlain by a veneer of siliciclastic sediment. The Floridan aquifer system is characterized by Paleocene to Upper Eocene limestones and dolostones (Figure 10) that form part of an extensive carbonate platform that existed from late Cretaceous through Late Oligocene.

Dunham's (1962) carbonate classification system is utilized in the following discussion of the Floridan aquifer system lithostratigraphy. Carbonate rocks, based on Dunham's method, are classified according to depositional texture with the primary emphasis on the presence or absence of carbonate mud and the abundance of carbonate grains (allochems). The classification system also distinguishes between mud-supported and grain-supported rocks which is the criteria used to separate wackestone from packstone and grainstone.

Paleocene - Cedar Keys Formation

The Cedar Keys Formation is a sequence of interbedded dolostones and evaporites unconformably overlying the undifferentiated Cretaceous Lawson Formation and conformably underlying the Lower Eocene Oldsmar Formation (Chen, 1965). The top of the Cedar Keys Formation was described by Chen (1965) as a "distinct lithology consisting of a gray, microcrystalline, slightly gypsiferous and rarely fossiliferous dolomite (dolostone)." Anhydrite with "chicken wire" texture is commonly interbedded with gray to tan dolostone in the lower two-thirds of the Cedar Keys Formation (Miller, 1986). The formation commonly contains the foraminifera species *Borelis gunteri* except in the highly recrystallized dolostones of the upper Cedar Keys section (Miller, 1986).

The top of the Cedar Keys Formation according to Miller (1986) ranges from approximately -2,200 feet NGVD in northern Brevard County to -3,000 feet NGVD in southern Brevard County. The Merritt Island, Harris #2, South Beaches, and Port Malabar wells were drilled within this depth range and could have penetrated the upper Cedar Keys Formation. Examination of cuttings over these intervals show a change from grayish and yellowish-brown dolostones characteristic of the lower Oldsmar to a gray dolostone that could be interpreted as Cedar Keys Formation. However, a definitive Cedar Keys Formation top was not identified in these wellbores.

Lower Eocene - Oldsmar Formation

Miller (1986) defined the Oldsmar Formation as "the sequence of white to gray limestone and interbedded tan to light-brown dolomite (dolostone) that lies between the pelletal, predominantly brown limestone and brown dolomite (dolostone) of the Middle Eocene and the gray, coarsely crystalline dolomite (dolostone) of the Cedar Keys Formation." The contacts with both the underlying Cedar Keys Formation and the overlying Avon Park Formation are unconformable (Braunstein, et al, 1988). In Brevard County, the Oldsmar Formation top is indicated by a white to light gray, glauconitic, moderately indurated wackestone or packstone which contrasts with the cherty, brown dolostones of the overlying Avon Park Formation. The glauconitic zone has a characteristic gamma-ray and sonic log signature that is correlative between all the injection wells (Plates 1 and 2) and serves as an excellent datum for stratigraphic and structural analyses. *Helicostegina gyralis* is a common faunal constituent of the glauconitic interval. The top of the Oldsmar Formation ranges from -1,667 feet NGVD at the Merritt Island site to -1,918 feet NGVD at the Harris #2 site (Figure 7).

Overall, the Oldsmar Formation consists of an upper section of interbedded packstone, wacke-

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

Figure 10. Lithostratigraphic/hydrostratigraphic nomenclature for southern Florida (modified from Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, Southeastern Geological Society (SEGS), 1986).

stone, mudstone, and dolostone and a lower section of predominantly well-indurated, crystalline dolostone. Benthic foraminifera and echinoderm fragments are the principle allochems composing the packstones and wackestones of the upper interbedded sequence. Clay is a common, but minor accessory mineral in the glauconitic wackestones of the upper Oldsmar Formation. Limestones are moderately cemented with a grain-fringing rim of microspar cement; however a pore-occluding, fresh-water, phreatic-spar cement was observed in a well-indurated packstone in the Merritt Island core at 1,720 to 1,723 feet BLS and the West Melbourne core at 1,967 feet BLS. Limestone porosity is generally high (20 to 30 percent) and permeability, based on visual estimates, is moderate to high.

Dolostones of the upper Oldsmar Formation are microcrystalline to finely crystalline and fossils are typically not preserved. Laminations, burrows, mottles, and spar-filled root traces are common in dolostones of the upper interbedded sequence. Porosity is generally five percent or less and permeability is low. Matrix-selective dolomitization is apparent in some Oldsmar Formation dolostones where unaltered calcitic allochems appear to "float" in a finer grained dolostone matrix. Partial replacement imparts a speckled nature to some dolostones in this interval. Cores and geophysical logs indicate the dolostone beds range from approximately five to ten feet thick.

The lower Oldsmar Formation is characterized by grayish-brown, microcrystalline, dense, and generally non-fossiliferous dolostone. The top of this sequence is a distinctive marker horizon ("C" marker bed) on gamma-ray and sonic logs and is correlative throughout the study area (Plates 1 and 2). The gamma-ray log shows increased radioactivity below this horizon relative to the overlying section. The sonic log shows a marked decrease in interval transit time at this point, which is indicative of the low porosities (less than five percent) and permeabilities prevalent throughout much of this interval.

Middle Eocene - Avon Park Formation

Miller (1986) defined the Avon Park Formation as "the sequence of predominantly brown limestones and dolomites (dolostones) of various textures that lies between the gray, largely micritic limestones and gray dolomites (dolostones) of the Oldsmar Formation and the white foraminiferal coquina or fossiliferous micrite of the Ocala Limestone." In Brevard County, the Avon Park Formation is characterized by white limestones ranging from grainstone to mudstone interbedded with grayish-brown to grayish-orange dolostones commonly containing organics. Cherty dolostones are typical of the lowermost Avon Park Formation.

In Brevard County, the top of the Avon Park Formation is marked by a slight radioactive peak on the gamma-ray log which characteristically coincides with the first occurrence of Dictyoconus sp. foraminifers (Plates 1 and 2). The top of the Avon Park Formation varies from -232 feet NGVD in the Merritt Island well to -443 feet NGVD in the Harris Corporation well. Formation thickness averages approximately 1,500 feet across the study area.

The uppermost Avon Park Formation consists of very light orange to white, moderately indurated wackestones and packstones containing abundant Dictyoconus sp. foraminifers. Below this interval, the Avon Park Formation is characterized by interbedded dolostones and limestones. The principal allochems are whole foraminiferal tests and echinoderm skeletal fragments. Organic flecks are common throughout much of the formation. Ooids were present in a middle Avon Park "oolite" in the West Melbourne well. The range of allochemical and textural alteration in dolostones varies from complete preservation to total destruction depending on the particular diagenetic mechanism. A gamma-ray marker bed, designated the "B" marker bed (Plates 1 and 2), occurs approximately midway through the Avon Park Formation and serves as an excellent reference datum for correlation

throughout Brevard County. In general, the "B" marker separates more thinly-bedded strata of the upper Avon Park Formation from more thickly-bedded and massive units of the lower Avon Park Formation.

Grain-supported limestones are only moderately indurated with generally high interparticle porosity and high permeability. Minimal amounts of pore-occluding cements are present and most of the porosity is primary in origin. Thin section analysis of middle Avon Park grainstones and packstones shows an isopachous fringing rim of cement surrounding individual grains, indicating possible marine phreatic cementation at the site of deposition (Harris et al., 1985). Possibly early marine cementation provided a rigid framework, thereby limiting the effects of compaction-related porosity reduction in these sediments.

Avon Park Formation dolostones exhibit a wide range of textural diversity due to varying types and degrees of diagenesis. Dolostones have generally subhedral to euhedral crystalline texture and have equigranular to inequigranular crystal fabric (Friedman and Sanders, 1967). Crystal size ranges from microcrystalline to fine. Burrows and vugs commonly contain coarser-grained dolomite crystals than the surrounding matrix. Sucrosic texture is common in very fine- to fine-grained dolostones.

Induration is generally high in all the Avon Park dolostones. Pore type, porosity, and permeability are extremely variable throughout the formation. Porosity types include intercrystalline, moldic, intergranular, vugular, and fracture. Moldic porosity is probably the product of matrix selective dolomitization whereby unaltered calcitic allochems remain in the rock and are later dissolved, possibly during periods of subaerial exposure (Murray, 1960). Dolostones speckled with white calcitic allochems (chiefly foraminifera), alternating with moldic dolostones, throughout much of the Avon Park Formation indicate that partial- or matrix-selective dolomitization was an important diagenetic process affecting these rocks.

The lowermost Avon Park Formation is characterized by intervals of nodular chert and cherty dolostones. Silicified burrows encased in dolostone were present in the West Melbourne core from 1,700 to 1,705 feet BLS. Also, fracture-filling chert was apparent in cores from several injection wells (Harris #2, South Beaches). The chert is typically black to gray and highly brittle.

An apparent microfaunal marker horizon occurs within the lower Avon Park Formation in a majority of injection wells. Abundant Operculina cookei occurred at the same approximate stratigraphic level (based on correlation with geophysical log markers) in each well except for the D. B. Lee and West Melbourne sites (Plate 1). The Operculina cookei zone was encountered in the West Melbourne well approximately 80 feet below the equivalent stratigraphic position observed in other wells. The difference in stratigraphic position could be related to inadequate sampling procedures during drilling or poor preservation related to diagenesis. The presence (or absence) of this horizon in the D. B. Lee well was not determined due to limited access to samples.

Upper Eocene - Ocala Limestone

The Ocala Limestone, as described by Applin and Applin (1944), consists of an upper member of white, poorly-indurated, porous coquina composed chiefly of foraminifera, bryzoan and echinoid fragments and a lower member of cream to white, fine-grained, poorly to moderately indurated, micritic, miliolid-rich limestone. The contacts between the underlying Avon Park Formation and the overlying Hawthorn Group are unconformable (Chen, 1965). In Brevard County, the Ocala consists of white to very light orange, medium grained, poorly to rarely moderately indurated, interbedded packstone and wackestone with occasional grainstone and mudstone. The principal allochems are foraminifera and echinoderm fragments. The Ocala Limestone micro-fauna commonly includes Lepidocyclina ocalana, Amphistegina pinarensis, and various

miliolids. The top of the Ocala Limestone is identifiable on gamma-ray logs as a sharp decrease in radioactivity relative to the overlying phosphatic Hawthorn Group sediments (Plates 1 and 2).

The top of the Ocala Limestone marks the top of the Floridan aquifer system in Brevard County (Miller, 1986). Porosity and permeability are generally high throughout the formation since most primary pore space remains open and well connected. Porosity is both intergranular and moldic, with intergranular as the dominant form. The top of the Ocala Limestone ranges from -104 feet NGVD at the Merritt Island site to -308 feet NGVD at the Harris Corporation site. Ocala Limestone thickness averages 130 feet.

Miocene - Hawthorn Group

The Hawthorn Group in Brevard County overlies the Ocala Limestone and consists of interbedded olive to yellowish-gray, poorly indurated calcareous clay, quartz sand, wackestone and dolostone. Phosphatic sand- and gravel-sized grains are characteristic accessory minerals of the Hawthorn sediments in the study area. Clay beds of the Hawthorn Group function as the upper confining unit for the Floridan aquifer system in Brevard County (Brown et al., 1962).

Hawthorn Group thickness is highly variable ranging from 20 feet at the Merritt Island site to 235 feet at the Harris Corporation site. The Hawthorn Group thins to the north and west with closer proximity to the Brevard Platform and Sanford High (Scott, 1988). The top of Hawthorn Group ranges from -55 feet NGVD at the Grant Street site to -134 feet NGVD at the D. B. Lee site.

Pliocene - Holocene Undifferentiated

Overlying the Hawthorn Group is a sequence of unconsolidated shell beds, clays, and quartz sands that range from Pliocene to Holocene

(Brown et al., 1962). Constraining the age of these sediments is beyond the scope of this study. Total thickness of the Pliocene-Holocene section varies from 90 feet at the Harris Corporation site to 160 feet at the West Melbourne site.

DEPOSITIONAL ENVIRONMENTS

The thick sequence of limestones and dolostones comprising the Floridan aquifer system was deposited on an extensive carbonate platform that existed from Late Cretaceous through Oligocene. Carbonate sediments are intrabasinal deposits and are primarily the product of carbonate-precipitating organisms that thrive in warm, shallow tropical seas. Depositional environments on carbonate platforms are highly variable and as a result vertical and lateral facies can change over very short distances.

Cores offer the optimum means for depositional environment interpretations in terms of subsurface studies. Cuttings are less useful because of their small size and because of the uncertainty associated with cavings. The lack of core in general, and the lack of stratigraphically-equivalent cored intervals in the available cores, poses severe limitations on the degree to which reasonable lower Floridan depositional environment interpretations can be made. Observations regarding depositional environments for the purposes of this study were based entirely on information derived from core and thin section examination. Core was available for the Merritt Island, West Melbourne, Harris, and South Beaches injection wells and, consequently, environmental interpretive efforts focused on these sites. Depositional environment interpretations focus on the Oldsmar and Avon Park Formations due to the availability of core and emphasis of this study on the geologic framework of the lower Floridan aquifer system.

Oldsmar Formation

Much of the interbedded mudstones, wackestones, packstones and dolostones of the upper Oldsmar have sedimentary structures and vertical facies variations that are indicative of tidal flat deposition (Shinn, 1983). The most representative sequence of probable tidal flat origin was cored in the Merritt Island well from 1,820 to 1,830 feet BLS. This section consists of interbedded dolostones, mudstones, wackestones, and packstones (Appendix A). Common allochems include peloids, foraminifera, high-spired gastropods (molds and casts) and echinoderm fragments. The dolostones are laminated and contain root molds filled with dolospar. Some laminations have been partially disturbed by burrowing. Contacts between the dolostones and limestones vary from extremely sharp and unconformable to gradational. One unconformable contact in this interval has a highly porous and permeable packstone overlying a dense, laminated dolostone containing dolospar-filled root molds. The upper surface of the dolostone is irregular with curved to domal algal laminated structures ("tepee" structures). Deposition of the packstone on top of the tidal flat sequence probably occurred during a brief transgressive phase. The gradational contacts are diagenetic in nature and are the result of either increasing or decreasing degrees of dolomitization. At 1,821 feet BLS, irregular masses or clumps of wackestone with abundant root traces floating in a matrix of dolomite may represent a caliche horizon developed during subaerial exposure.

Andros Island tidal flats serve as an excellent modern analog for the depositional environment of upper Oldsmar carbonates. Many of the sedimentary structures and sequences found in tidal flat sediments on Andros Island (Shinn et al., 1969) are present in upper Oldsmar Formation core. Laminated dolostones of the Oldsmar Formation may be comparable to recent supratidal dolomitic crusts that occur on Andros Island tidal flats (Shinn et al., 1969). Wackestones and

packstones containing root casts, peloids, and high-spired gastropods are similar to intertidal zone sediments of western Andros Island (Shinn et al., 1969). Stratigraphically equivalent intervals of the upper Oldsmar Formation in other injection wells in Brevard County have lithologic sequences very similar to that of the Merritt Island well. This similarity gives some indication of the tidal flats' potential areal extent, which, at a minimum, would range from the Merritt Island well south to the South Beaches well.

Core at 2,138 feet BLS in the South Beaches well (Appendix A7) has a brecciated texture with angular clasts of grayish-brown dolostone floating in a matrix of yellowish-brown dolostone. This zone may represent a caliche similar to that found at 1,821 feet BLS in the Merritt Island well or perhaps the angular nature of the fragments may be more indicative of a collapse breccia related to karstification.

The uppermost Oldsmar (upper 40 feet of the formation) lacks key sedimentary structures that might be indicative of a specific depositional environment. However, the observed mineralogical suite of this interval that includes glauconite, pyrite, collophane and clay is associated with unique chemical and depositional environmental conditions. Glauconite occurs in the form of well rounded, dark green, sand-sized peloids with concentrations ranging from one to as much as ten percent of the total rock (South Beaches and Port Malabar wells). Glauconitization occurs at the sediment seawater interface at depths of 195 feet down to 3,250 feet in open marine waters with temperatures of 59 degrees F (15 degrees C) or less (Odin and Fullagar, 1988). Low sedimentation rates and bottom turbulence are also necessary for glauconitization and as a result glauconitic sediments represent depositional hiatuses in the sedimentary record (Odin and Fullagar, 1988). Assuming glauconitization proceeds at a minimum water depth of 195 feet, then the uppermost Oldsmar glauconitic carbonates may record a significant, and possibly rapid, sea level rise since tidal flat deposits con-

taining subaerial exposure features occur immediately below this interval.

Collophane, in the form of rounded peloids, was identified in thin section from the upper Oldsmar glauconitic interval in the South Beaches well (1,881-1,889 feet BLS). Phosphates such as collophane apparently form where phosphate-rich water upwells adjacent to shallow shelves or platforms that border deep marine basins (Friedman and Sanders, 1978). Collophane forms at the sediment-water interface under similar conditions to that of glauconite and consequently is common in glauconitic sediments.

Pyrite occurs as subhedral to euhedral crystals in combination with glauconite. Pyrite crystals are commonly found within or form rims around glauconite peloids. Pyrite forms in organic, muddy sediments under reducing conditions (Miall, 1984) similar to those required for glauconitization which occurs at the oxidation-reduction boundary (Odin and Fullagar, 1988).

The origin of the clay is somewhat problematic given the apparent isolation of the carbonate platform from any potential siliciclastic source during this time. Possibly the clay is altered volcanic ash blown northward from erupting volcanoes associated with subduction along the Caribbean and North American plate boundary.

The lower Oldsmar Formation is characterized by highly recrystallized, unfossiliferous dolostones. Original depositional textures that may have been present have been totally obliterated by dolomitization, making environmental interpretations impractical.

Avon Park Formation

A diversity of carbonate depositional environments are represented over the approximately 1,500 feet of vertical sequence that comprises the Avon Park Formation in Brevard County.

Sedimentary structures range from those indicative of low energy tidal flat to high energy shoaling conditions. Most environmental information for the Avon Park Formation is derived from limestones that have undergone low degrees of dolomitization. Much of the dolostone is highly recrystallized with poor preservation of primary textural features.

A sequence of grainstone, packstone, and wackestone in the middle Avon Park Formation (approximately 200 feet below the "B" marker) contains sedimentary structures indicative of beach deposition. A complete vertical beach sequence from offshore at the base to shoreface and foreshore at the top (Benard et al., 1962) can be recognized. The best example of this sequence occurs in the Merritt Island well in the interval from 1,180 feet to 1,250 feet BLS. The lithofacies grades upward from a low-energy wackestone at the base to high-energy grainstones at the top (Appendix A5). High angle cross beds are common in grainstones and packstones. Some zones of coarse to gravel-sized "lag" were noted at the base of cross-bedded strata. Allochemical grains are dominantly skeletal.

The top of the beach sequence is capped by a peloidal grainstone (at 1,174 feet BLS) containing abundant tabular to spherical cavities known as "keystone vugs" which are commonly found in uppermost accretion beds of beach foreshore deposits (Dunham, 1970; Scholle et al., 1983). Keystone vugs are indicative of swash-zone deposition and represent cavities formed by trapped air bubbles that develop immediately above sediment which is flushed by onlapping wave action during daily tidal cycles (Scholle et al., 1983). The flushing action forces air out of the underlying sediment's intergranular pore space and upward into the overlying sediment where it can be preserved by early marine cementation (Scholle et al., 1983).

Core below the keystone vug zone consists of peloidal grainstones and packstones much of

which is cross-bedded. Coarse to gravel-sized "lag" zones are common at the base of cross-bedded intervals. The cross-bedded sequence probably represents shoreface sedimentation by currents flowing parallel to the shoreline (Scholle et al., 1983). A transition from offshore to shoreface sedimentation is reflected by decreasing amounts of mud in the sediments as wackestone grades upward into packstone and grainstone.

The beach sequence has a geophysical character that is generally correlative throughout the study area. The carbonates here have an extremely low gamma-ray signal and abnormally high sonic-log porosities due to borehole wash-out in the moderately indurated limestones relative to the overlying and underlying well indurated dolostones.

The equivalent section cored in the West Melbourne well (1,396-1,404 feet BLS) consists of interbedded grainstone, packstone, and wackestone similar to that in the Merritt Island well with the exception of sedimentary structures. No bedding features of any kind were evident as the section is apparently highly bioturbated. Bioturbation typically signifies lower-energy conditions and slower sedimentation rates (Friedman and Sanders, 1978). At approximately 1,400 feet BLS a one-foot-thick interval of burrowed, oolitic grainstone (oolite) is present suggesting high energy, shoaling conditions were nearby.

Core from 985 to 995 feet BLS in the Merritt Island well consists of laminated, moldic, to vuggy dolostone. At 992 feet BLS in this interval, an approximately six-inch-thick section of irregular to wavy algal laminated and moderately indurated dolostone (dolomudstone) may be indicative of tidal flat deposition. Randazzo and Cook (1987) studied approximately 450 feet of upper Avon Park Formation core from west central Florida and concluded that except for a 10-foot section, all of the cored interval was "characterized by tidal mudflat sedimentation."

Sedimentary structures indicative of tidal flat sedimentation included micritic crusts, rip-up clasts, contorted algal laminations, burrows, mottles and thin peat lenses.

GEOPHYSICAL CHARACTER OF THE LOWER FLORIDAN AQUIFER SYSTEM

The typical suite of borehole geophysical logs run as part of injection well-evaluation procedures includes gamma-ray, sonic, caliper, and induction resistivity. Lower Floridan aquifer system carbonates have characteristic responses to each geophysical tool which depend primarily on lithofacies type, mineralogy, porosity, water chemistry, and borehole conditions. The following discussion focuses on the general geophysical characteristics of representative lithofacies and certain key intervals within the lower Floridan aquifer system of Brevard County.

Poorly- to moderately-indurated limestones can be in many cases distinguished from interbedded, highly-indurated dolostones by using borehole geophysical criteria. Boreholes commonly enlarge or "wash-out" across poorly- to moderately-indurated lithologies and remain in gauge across highly-indurated zones during drilling operations. The effect is most apparent on caliper logs where relative borehole size variations can be readily noted. Sonic logs can record erroneously long travel times (i.e., high porosity) across wash-outs due to increased sound wave travel distances making porosity determinations invalid (Gulf Research and Development Company, 1978). A slight effect on the gamma-ray log in terms of reduced radioactivity across these zones can also be recognized. Induction resistivities are typically low in moderately- to poorly-indurated limestones due to abundant saltwater-saturated pore space in the rock.

A unique mineralogical assemblage within the uppermost Oldsmar Formation imparts a distinctive geophysical property to the interval resulting in a highly correlative marker horizon (Plates 1,

2 and 3). Glauconite, clay, and collophane are common accessory minerals within an interbedded sequence of wackestone and dolostone of the uppermost Oldsmar. The gamma-ray log, in response to this mineralogy, shows a distinct increase of gamma-ray activity across the zone which is correlative throughout the study area. The sonic log response across this interval, although not directly related to this mineralogy, is correlative to a lesser degree among all the injection wells. Sonic log interval transit times are highly variable through the uppermost Oldsmar, apparently reflecting porosity differences between the more porous limestones (approximately 30 percent porosity) and less porous dolostones (approximately 15 percent porosity) of this interbedded interval.

Sonic log response corresponds well to actual lithology in sequences consisting of lower porosity dolostones interbedded with higher porosity limestones. Dolostones in such cases have sonic log curves that peak in the low porosity direction (generally 20 percent or less porosity). Sonic log curves in limestones, on the other hand, peak in the high porosity direction (30 percent or greater). This relationship is especially true of upper Avon Park Formation sections in Brevard County. The Merritt Island sonic log and lithostratigraphic section from 400 to 800 feet (BLS) in the upper Avon Park Formation offers the best example of this property (Figure 11).

Induction resistivity logs can be useful in distinguishing relatively low porosity zones from relatively high porosity zones within the lower Floridan aquifer system. Low porosity, saltwater saturated carbonates are highly resistive and are typically indicative of dense dolostones or possibly calcite spar cemented limestones. Highly porous, saltwater-saturated carbonates have low resistivities and are generally indicative of porous dolostone or moderately to poorly-indurated limestone. Induction log resistivities across cavernous zones are extremely low and approach, if not equal, that of the formation water alone.

Several sections of the Floridan aquifer system have gamma-ray signatures that are correlative throughout Brevard County and serve as excellent datums for stratigraphic and structural analyses. In addition to the uppermost Oldsmar glauconitic zone, the lower Oldsmar Formation contains several correlative gamma-ray marker horizons including the "C" marker bed (Plates 1 and 2). The "B" marker bed (Plates 1 and 2) roughly divides the Avon Park Formation into upper and lower sections. The uppermost Avon Park, from the top down to the "A" marker bed (Plates 1 and 2), has highly correlative gamma-ray character.

DOLOMITIZATION IN THE LOWER FLORIDAN AQUIFER SYSTEM

Several investigations into the nature of dolomitization within the Floridan aquifer system have been conducted. Studies done by Hanshaw et al., (1971), Cander (1991), Randazzo and Hickey, (1978), Randazzo and Cook, (1987) and Randazzo et al., (1977), focused on the lower Floridan aquifer system and are summarized in the following discussion.

Hanshaw et al., (1971) hypothesized a mixing zone dolomitization model for Floridan aquifer system dolostones of regional extent. In their model, dolomitization occurs in brackish waters formed where freshwater mixes with seawater along coastal areas or subsurface brines further inland (Hanshaw et al., 1971). Circulating ground water having a Mg/Ca ratio > 1 is the driving force for dolomitization in the mixing zone (Hanshaw et al., 1971). Thermal convection of saltwater within the Florida Platform, as proposed by Kohout (1965), could provide the circulation and mixing mechanism for dolomitization of much of the Floridan aquifer system carbonates (Hanshaw et al., 1971). The lateral and vertical movement of the saltwater-freshwater interface due to sea-level variations, climatic changes, and/or platform uplift or subsidence has also facilitated dolomitization within much of

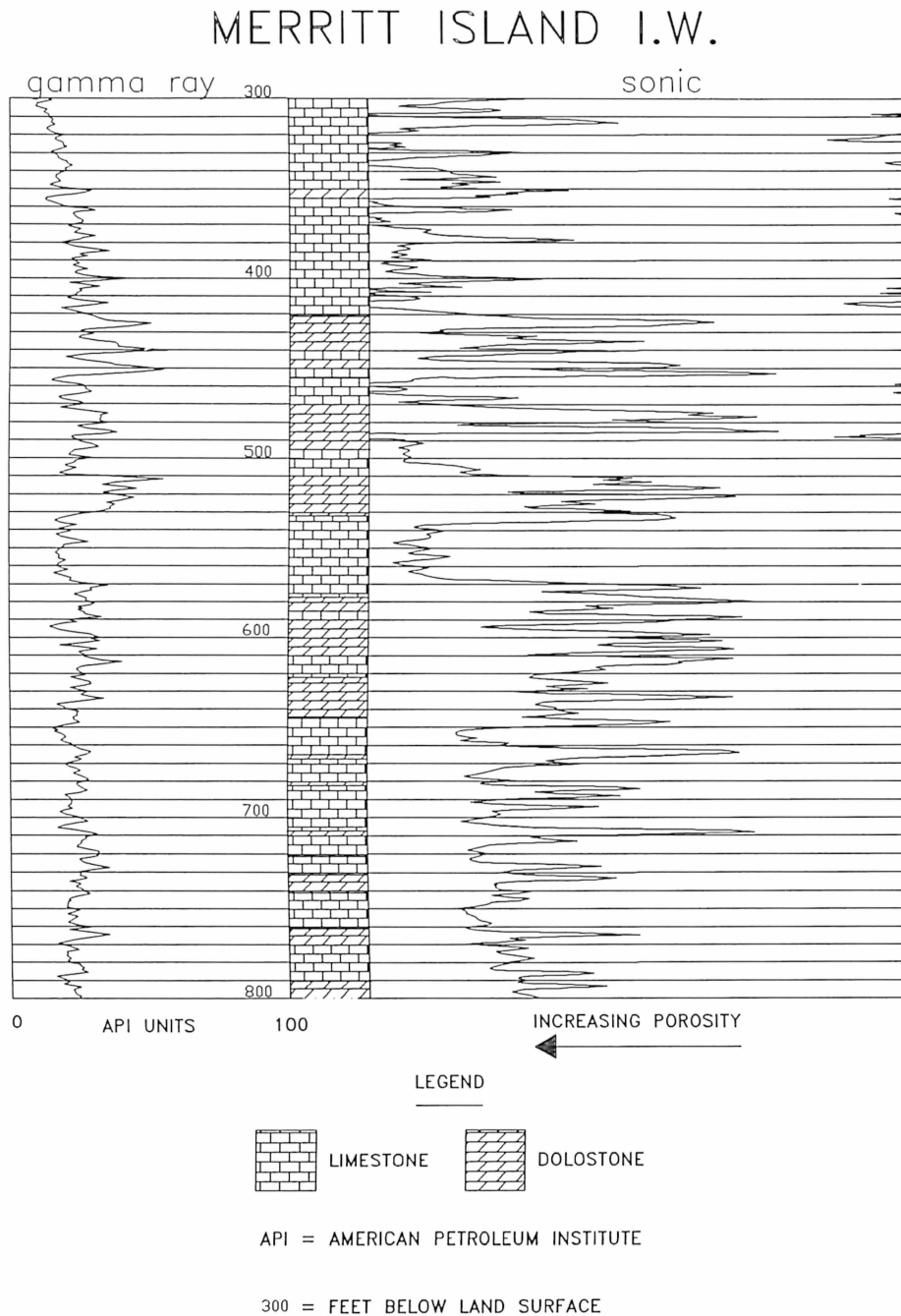


Figure 11. Detailed lithostratigraphic column with gamma-ray and sonic log for the upper portion of the Avon Park Formation in the Merritt Island injection well.

the Floridan aquifer system (Hanshaw et al., 1971).

A recent isotopic study by Cander (1991) argues against a mixing-zone origin for pervasive dolostones of the Avon Park Formation. Cander (1991) found that Avon Park Formation dolostones "have heavy oxygen and carbon isotopic compositions and coeval Middle Eocene $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions, indicating that the Avon Park Formation underwent massive dolomitization by normal to hypersaline seawater during the Middle Eocene, essentially contemporaneous with deposition." He concluded that the Avon Park Formation in central peninsular Florida was deposited in a tidal flat environment under arid climatic conditions analagous to the modern Persian Gulf (Cander, 1991).

Cander (1991), based on stable carbon and oxygen isotope compositions in the Avon Park Formation, recognized a late-stage of mixing-zone dolomite that is present locally in areas near the present coastline. The mixing-zone dolomite nucleated on and overgrew earlier marine-stage dolomite and does not replace limestone (Cander, 1991). Mixing-zone dolostones of the Avon Park Formation are dark brown, dense, hard, non-porous, and highly crystalline in contrast to the generally highly porous, relatively soft, chalky, and poorly crystalline marine dolostones elsewhere in the Avon Park Formation (Cander, 1991). Dolostones having similar texture and color to mixing-zone dolostones described by Cander (1991) are present in the Avon Park Formation of Brevard County.

Randazzo et al., (1977) in their study of upper Avon Park dolostones of west-central Florida recognized three principal textures indicative of different dolomitization processes: 1) dolomitization by total replacement, 2) dolomitization by aggrading porphyroid and coalescive neomorphism, and 3) dolomitization by selective replacement. Original depositional texture is preserved in total replacement dolostones

(Randazzo et al., 1977). Porphyroid dolomitization is characterized by scattered, euhedral dolomite rhombs distributed throughout the rock (Randazzo et al., 1977). The amount of dolomite present is dependent on how long dolomitization has been taking place (Randazzo et al., 1977). Selective dolomite replacement texture occurs as a result of partial dolomitization of allochems or matrix (Randazzo et al., 1977).

Randazzo and Hickey (1978) acknowledged the mixing-zone model's role in dolomitization of Avon Park carbonates in west-central Florida. They concluded that some Avon Park supratidal carbonates were partially dolomitized penecontemporaneously with sedimentation. After burial, the supratidal sediments along with those from other depositional environments were exposed to multiple periods of dolomitization resulting from a laterally and vertically migrating saltwater-freshwater interface and a ground-water mixing zone (Randazzo and Hickey, 1978).

Current dolomitization models, such as the mixing-zone and sabkha, remain highly controversial. Hardie (1987) questioned the validity of mixing-zone and sabkha models based on several lines of evidence. Hardie's objections to the mixing-zone model included the following: 1) thermodynamic problems associated with using calculations based on ordered dolomite formation rather than the more appropriate and realistic disordered dolomite; 2) lack of replacement dolomite in known modern coastal mixing zones; 3) the lack of dissolution in calcitic limestones underlying dolostones of alleged mixing zone origin. Hardie (1987) favored a direct precipitation origin for contemporaneous sabkha dolomite instead of a replacement origin. Hardie based his hypothesis on the generalization that contemporaneous dolomite only forms at low temperatures by direct precipitation since replacement dolomite apparently requires much longer reaction times on the order of 10,000 years or greater (Hardie, 1987).

Both penecontemporaneous and diagenetic dolomitization processes have apparently affected lower Floridan aquifer system carbonates in Brevard County. Dolostones associated with algal laminations and subaerial exposure surfaces are likely supratidal and at least partly penecontemporaneous in origin. Partial, matrix selective dolomitization is common in many of the lower Floridan aquifer system dolostones and may be an important factor in the development of moldic porosity (Murray, 1960). Murray (1960) suggested that where only partial dolomitization occurs, porosity can be created by the dissolution of non-replaced calcium carbonate remaining in the rock, possibly during periods of subaerial exposure. The origin of massive, regionally pervasive dolostone sequences within the lower Floridan is best explained by marine dolomitization, probably penecontemporaneous with deposition in a tidal flat environment.

HYDROGEOLOGY

General Hydrogeologic Summary of the Floridan Aquifer System

Four major hydrogeologic units occur in peninsular Florida (SEGS, 1986). These are the surficial aquifer system, the intermediate confining unit or intermediate aquifer system, the Floridan aquifer system and the sub-Floridan confining unit (Figure 10). The Floridan aquifer system consists of the upper Floridan aquifer system, the middle confining unit and the lower Floridan aquifer system. The hydrogeology for only the middle confining unit and lower Floridan aquifer system will be discussed in detail.

The upper-most hydrologic unit in the study area is the surficial aquifer system which is comprised of a thin blanket of terrace and fluvial sands, shell beds and sandy limestones of Pliocene, Pleistocene and Holocene age. In Brevard County, the surficial aquifer system is a permeable unit contiguous with land surface which varies in thickness from 90 to 150 feet (Plate 3). The surficial aquifer system is an

unconfined aquifer under water table conditions and is an important source of drinking water for more than half of Brevard and Indian River counties (Scott et al., 1991) (Figure 12).

The intermediate confining unit in the study area is associated with the Hawthorn Group. The Hawthorn Group sediments separate the overlying surficial aquifer system and the underlying Floridan aquifer system. These sediments consist of a low-permeability sequence of siliclastic sediments and carbonates which effectively confine the Floridan aquifer system throughout most of the study area (Plate 3). The intermediate aquifer system is not well developed in eastern central Florida and is not an important source of drinking water. Locally, the intermediate confining unit may be breached due to sinkhole activity or erosion; thus, the upper Floridan aquifer system may be under confined, semiconfined or unconfined conditions.

The Floridan aquifer system, as defined by Miller (1986), is a vertically continuous sequence of carbonate rocks of generally high permeability. These middle to upper Tertiary carbonates are hydraulically connected to varying degrees. Permeability is typically several orders of magnitude greater than those rocks that bound the system above and below.

In Brevard County, the Floridan aquifer system generally consists of two major permeable zones (Plate 3) separated by a middle confining unit of lower permeability (Miller, 1986). The upper and lower Floridan aquifer systems and the middle confining unit are comprised of a sequence of Paleocene to Eocene carbonates. These carbonates may be hydraulically connected or separated based upon highly variable local geologic conditions.

In the lower Floridan aquifer system of southern Florida, there is a subzone of highly fractured and cavernous dolostone which exhibits high transmissivities (Miller, 1986). The cav-

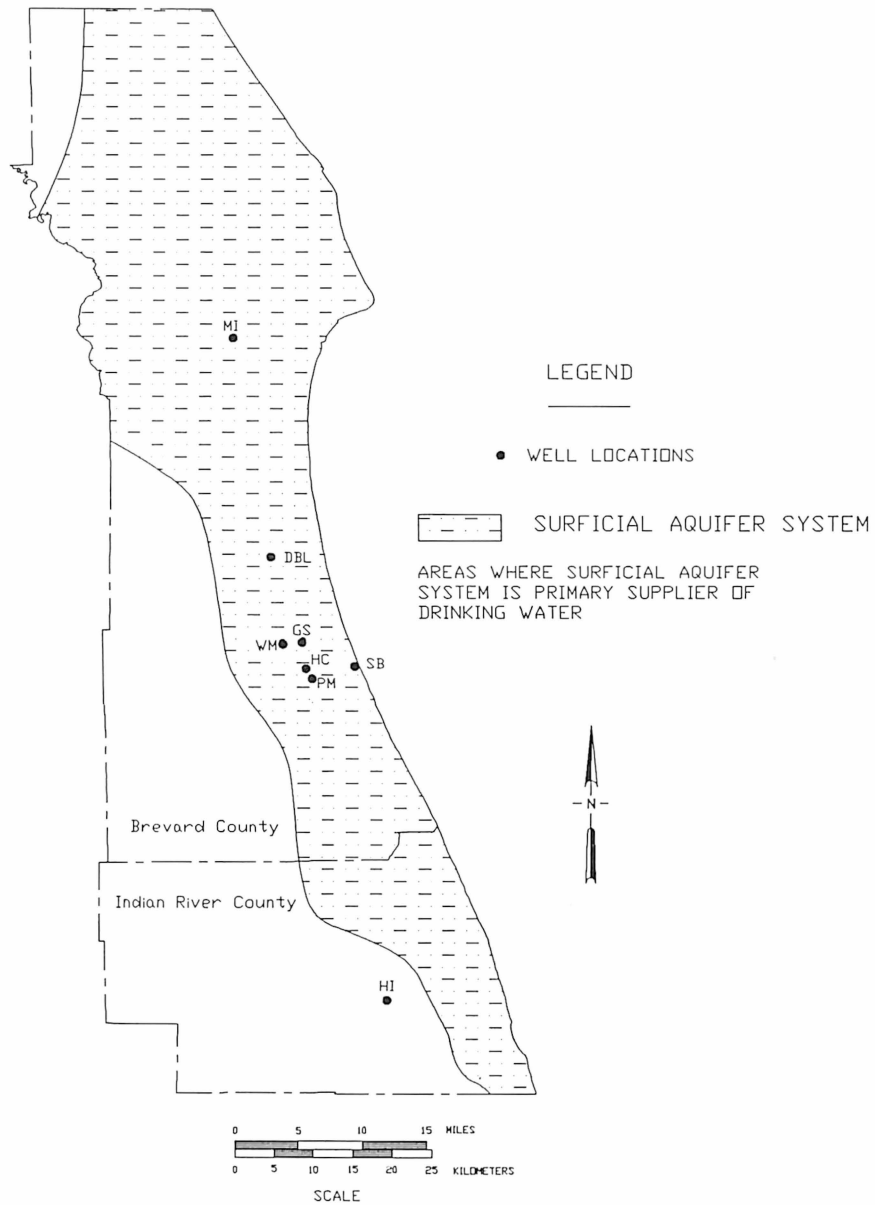


Figure 12. Areas of surficial aquifer system use, Brevard and Indian River counties (after Scott et al., 1991).

ernous and fractured nature of the dolostone commonly causes boulder size pieces of dolostone to be dislodged during the drilling process giving rise to the term "Boulder Zone" by drillers and subsequently adopted by Kohout (1965) and later authors. In areas where the salinity of the waters in the Boulder Zone is greater than 10,000 mg/L, the Boulder Zone is used as a receiving zone for underground injection of industrial wastes and treated effluent. A more detailed discussion of the hydrogeology of the middle confining unit, lower Floridan aquifer system and Boulder Zone is presented in subsequent sections of this report.

Numerous Tertiary regressive/transgressive sequences have produced a diverse carbonate lithology in the Floridan aquifer system (Plate 1). A typical sequence of deposition would vary from low energy, open platform, micritic sediments grading into progressively higher energy packstones or grainstones characteristic of a shoaling environment to low energy, tidal flat, fine-grained sediments. As a result of these numerous sea level fluctuations and subsequent diagenetic changes, locally variable, complex hydrogeologic conditions exist throughout the Floridan aquifer system.

The Floridan aquifer system does not necessarily conform to either lithostratigraphic or chronostratigraphic boundaries and therefore, the top of the Floridan aquifer system (Figure 10) coincides with the uppermost vertically-continuous, permeable, Eocene to Lower Miocene carbonate beds (SEGS, 1986). In the study area, the top of the Floridan aquifer system is contiguous with the top of the Eocene Ocala Limestone (Figure 10) and occurs at elevations ranging from -100 to deeper than -350 feet NGVD (Figure 13). The thickness of the Floridan aquifer system in the study area ranges between 2,300 to more than 2,900 feet and generally increases to the south (Figure 14) (Scott et al., 1991).

Recharge to the Floridan aquifer system is directly associated with the degree of hydraulic confinement of the system. The highest rates of recharge occurs in northern Brevard County where the Floridan aquifer system is unconfined or poorly confined (Figure 15). Sinkholes that breach the intermediate confining unit and provide hydraulic communication between the surficial aquifer system and the Floridan aquifer system can result in either recharge to or discharge from the Floridan aquifer system. In the study area recharge will occur in northern Brevard County and western Indian River County (Figure 15). Discharge to the surficial aquifer system will occur in areas of artesian flow (Figure 16).

The potentiometric surface and regional horizontal flow of the Floridan aquifer system are also related to the degree of confinement. The potentiometric surface of the upper Floridan aquifer system in the study area ranges from approximately 5 to 40 feet (Figure 17) and lateral flow is generally south. Where the potentiometric surface is higher than the surface elevation, artesian flow will occur (Figure 16). Artesian conditions are present over most of the study area. In areas where there is relatively poor or non-existent confinement, and where land surface is higher than the potentiometric surface, (i.e., western Indian River County) artesian conditions are absent (Figure 16) and recharge to the Floridan aquifer system may occur (Figure 15). Transmissivity of the upper Floridan aquifer system (Figure 18) is generally higher in the southern portion of the study area but is locally variable because of complex hydrogeologic heterogeneity.

Massively bedded anhydrite usually occurs in the lower two-thirds of Paleocene rocks (Miller, 1986). The top of the sub-Floridan confining unit (Figure 19) is defined in terms of a permeability contrast that limits the depth of active groundwater circulation and does not represent any particular stratigraphic or time unit (Figure 10). The injection and monitor wells in the study area are not deep enough to encounter the sub-Floridan confining unit.

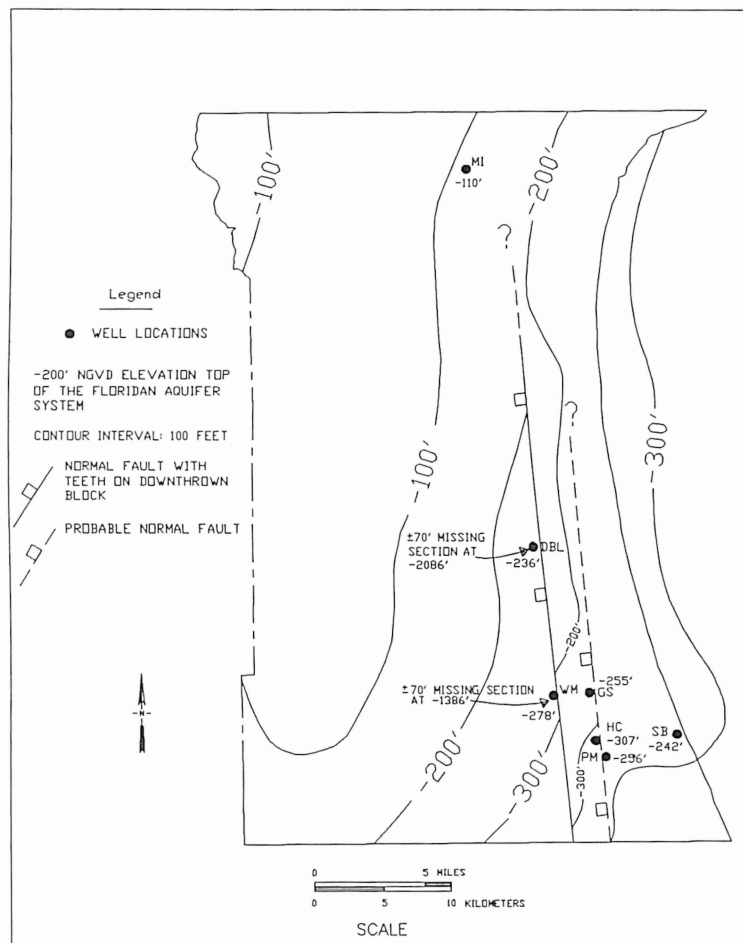


Figure 13. Top of the Floridan aquifer system (Ocala Limestone), Brevard County.

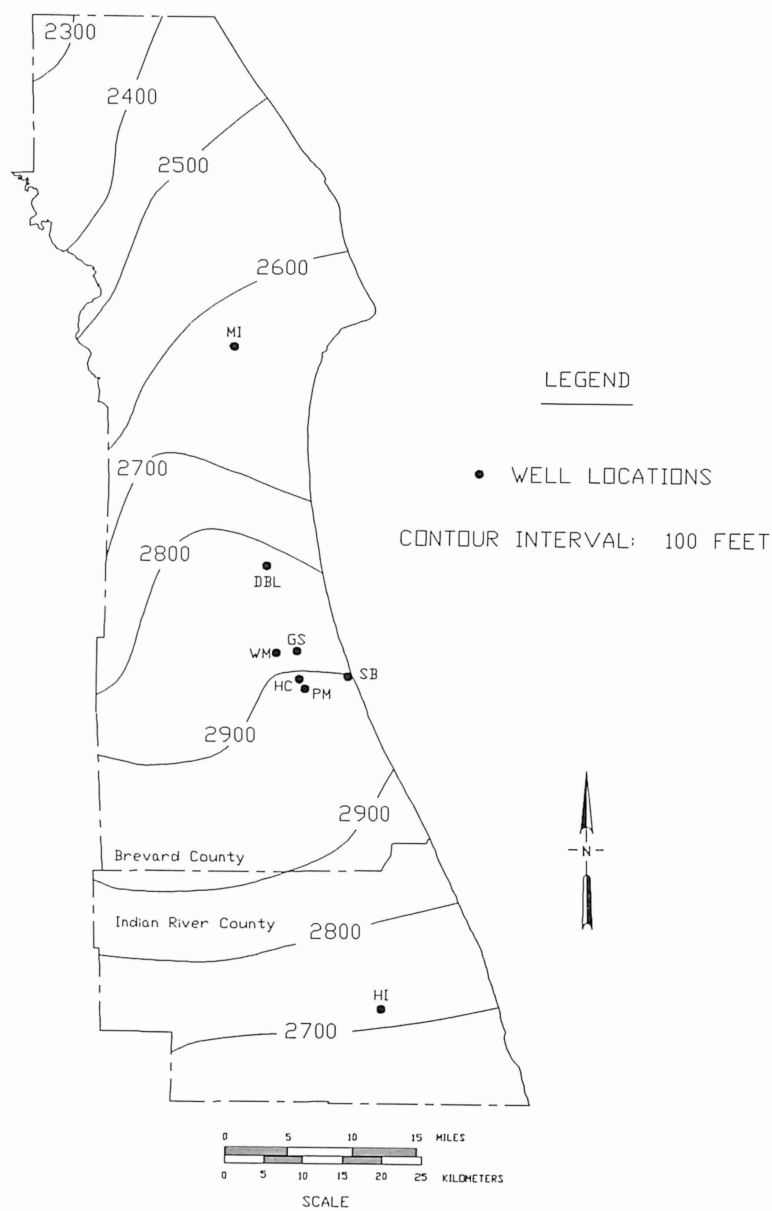


Figure 14. Thickness of the Floridan aquifer system, Brevard and Indian River counties (after Scott et al., 1991).

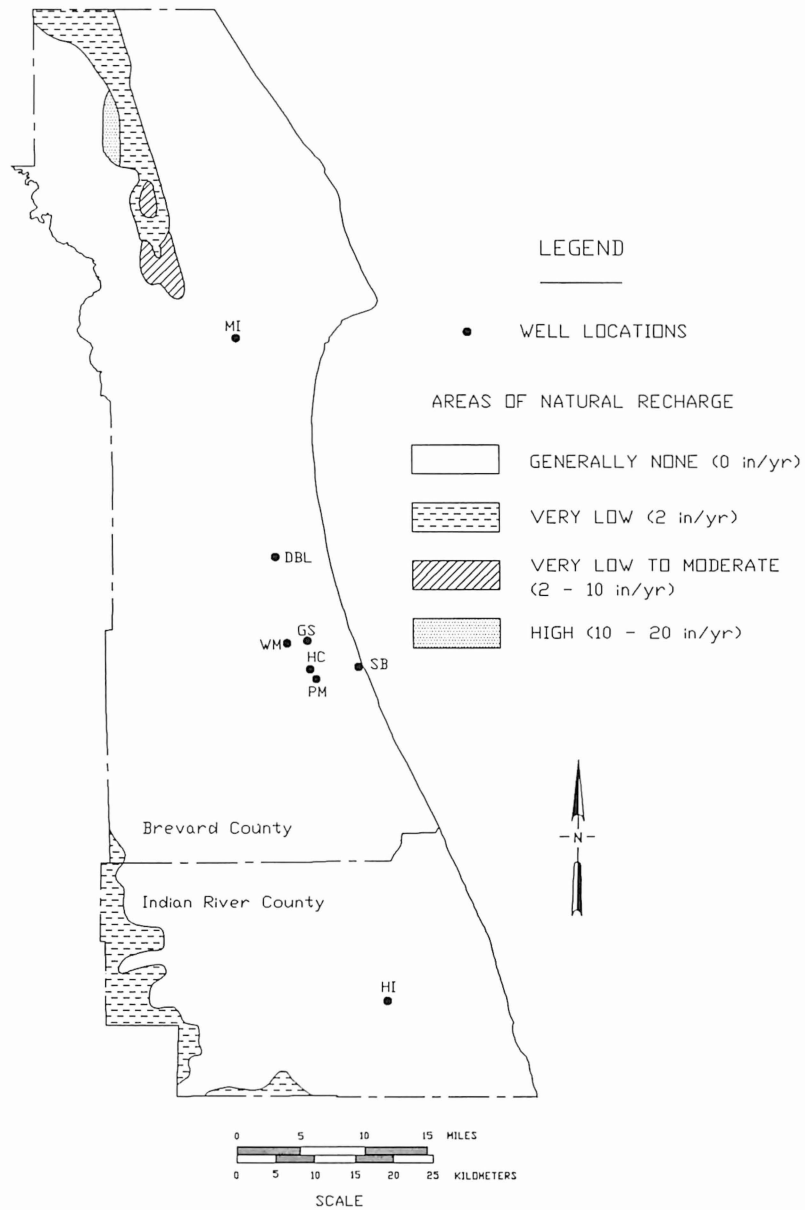


Figure 15. Floridan aquifer system recharge potential, Brevard and Indian River counties (after Scott et al., 1991).

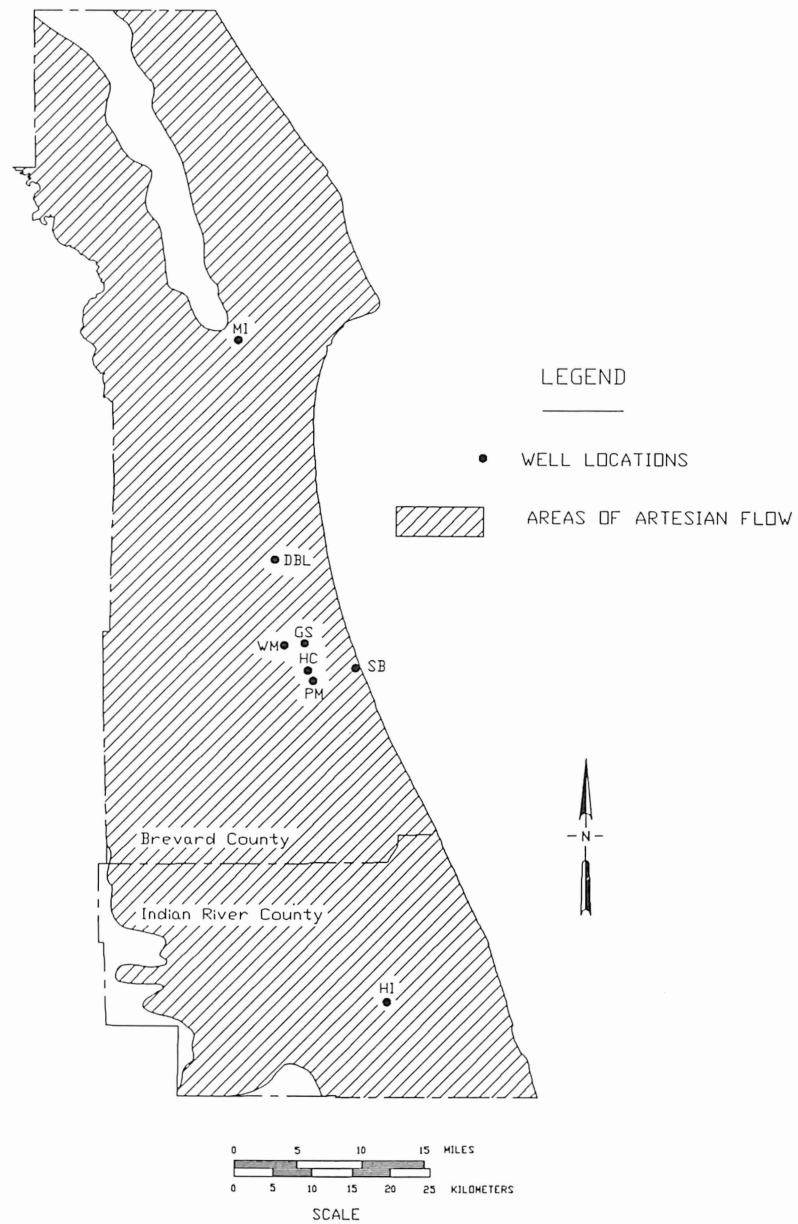


Figure 16. Areas of artesian flow from the Floridan aquifer system, Brevard and Indian River counties (after Scott et al., 1991).

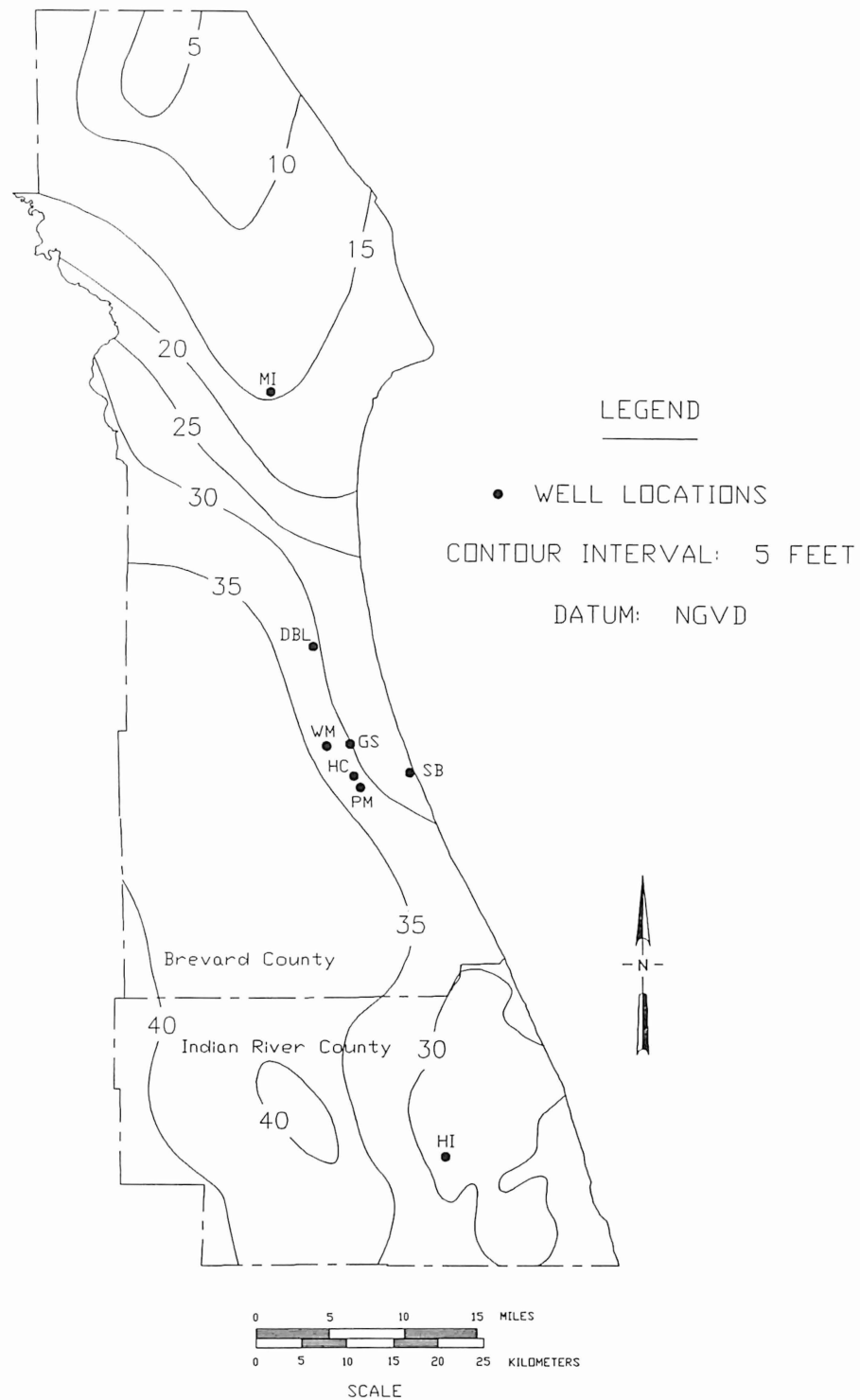


Figure 17. Floridan aquifer system potentiometric surface, Brevard and Indian River counties (after Scott et al., 1991).

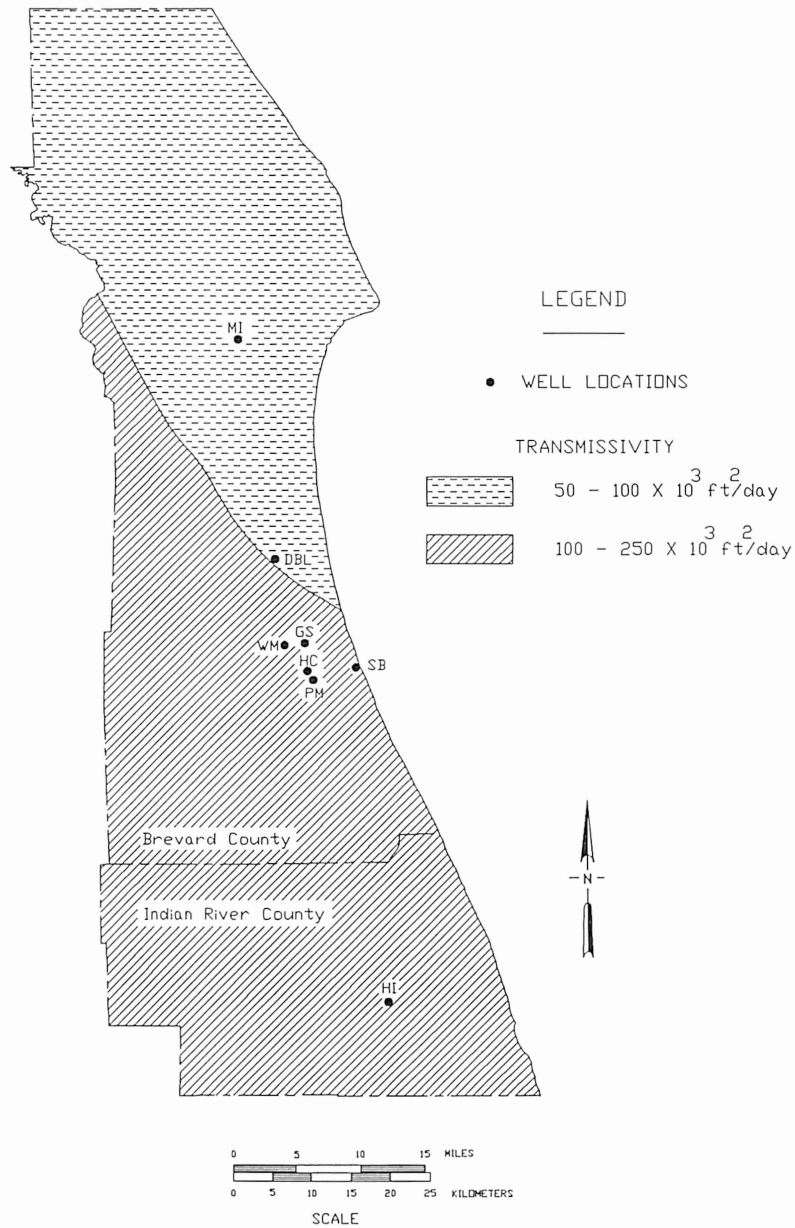


Figure 18. Estimated transmissivity of the upper Floridan aquifer system, Brevard and Indian River counties (after Miller, 1986).

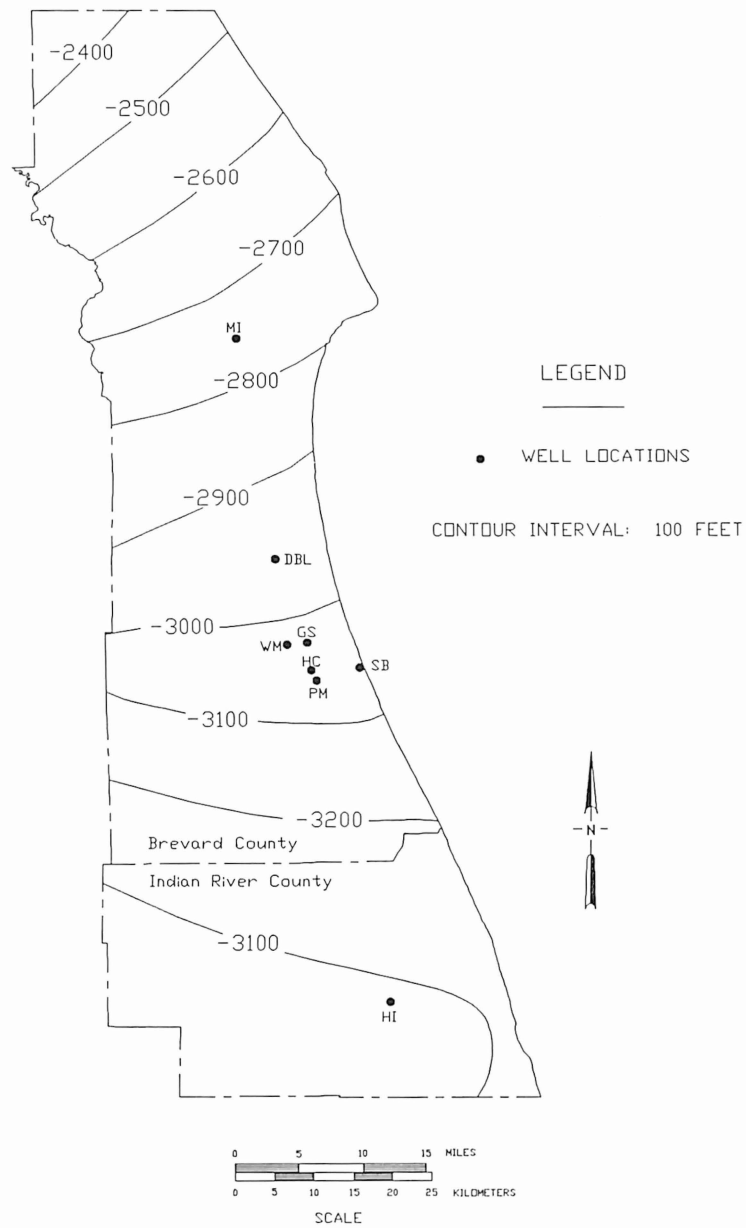


Figure 19. Top of the sub-Floridan confining unit, Brevard and Indian River counties (after Miller, 1986).

Hydrogeology of the Middle Confining Unit of the Floridan Aquifer System

The upper and lower Floridan aquifer systems are separated by a middle confining unit (Miller, 1986) (Plate 3). Locally this zone of confinement may contain thin zones of moderate to high permeability; however, as a whole, the unit acts as a single confining unit within the main body of the permeable carbonates of the Floridan aquifer system. The Middle Eocene sediments that make up the middle confining unit are (Miller, 1986) similar in composition to both the upper and lower Floridan aquifer systems. The middle confining unit is considered a leaky confining unit because of the lack of strong contrast in permeability between these three zones (Miller, 1986).

The middle confining unit in the study area consists of dense dolostone with interbedded limestones located immediately below the "B" marker bed of the Avon Park Formation (Plate 3). The middle confining unit in the study area is defined as a zone of slightly lower permeability separating two zones of higher permeability. This determination is based upon estimated porosities of less than 20 percent, and lithologic character determined from geophysical logs and sample descriptions (Plate 3).

The middle confining unit is recognized on geophysical logs by a slight increase in gamma ray activity and (when the carbonates are not fractured) a decrease in interval transit time on the sonic logs as the limestones of the upper Floridan aquifer system abruptly grade into low porosity (less than 20 percent), dense, micro-crystalline dolostones that make up the middle confining unit (Plate 3).

The top of the middle confining unit in the study area is between -600 to -1,100 feet NGVD and depth generally increases to the southeast (Figure 20 and Plate 3). The thickness of the middle confining unit ranges from 110 to 250 feet and decreases toward the south (Figure

21). Based on lithologic criteria, it appears that the middle confining unit is absent at the South Beaches injection well, demonstrating the significance of local geologic variation (Plate 4).

Quantitative field data and aquifer tests that describe the water transmitting characteristics of the middle confining unit were analyzed for the Merritt Island injection well (Appendix A1). Horizontal hydraulic conductivity is estimated at 2.7×10^{-4} cm/s, vertical hydraulic conductivity is 1.8×10^{-8} cm/s and transmissivity is 609 gpd/ft (Geraghty and Miller, 1984). Geophysical evidence coupled with borehole video observations indicate that the middle confining unit contains fractures at several of the well sites (Plate 3). Locally, vertical fractures may hydraulically connect the upper and lower Floridan aquifer system; however, the available data is insufficient to accurately make this determination.

Hydrogeology of the Lower Floridan Aquifer System

The lower Floridan aquifer system consists of all beds that lie below the middle confining unit (Plate 3) and above the sub-Floridan confining unit (Miller, 1986). If the middle confining unit is absent (i.e., South Beaches injection well), the upper boundary of the lower Floridan can be defined geochemically. The geochemical boundary (Meyer, 1989) is where the total dissolved solids in the ground water is equal to or greater than 10,000 mg/L (Plate 3).

The rocks of the lower Floridan aquifer system are comprised of a thick, complex sequence of limestones and dolostones with highly variable carbonate matrices. The higher porosity, less dense limestones of the lower Floridan aquifer system are geophysically identified where a slight decrease in gamma-ray activity and an increase in sonic interval transit time occurs (Plate 3).

Geophysical and lithologic evaluations of the injection wells indicates that the top of the lower

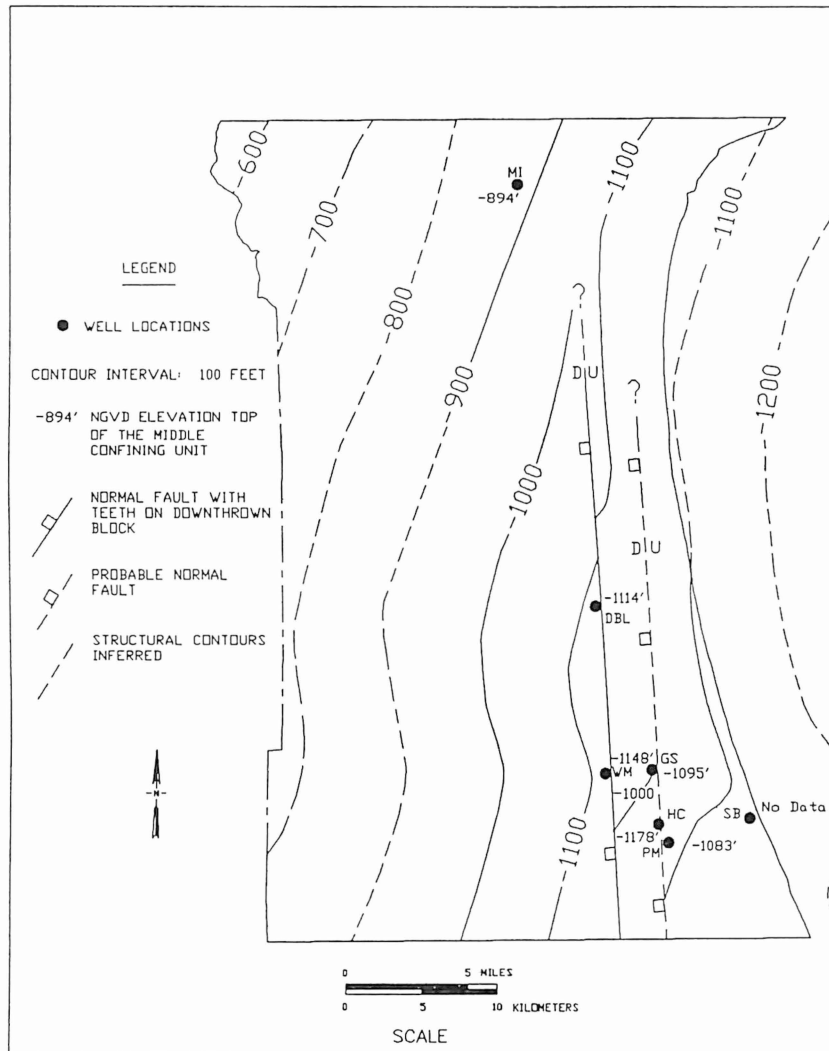


Figure 20. Top of the middle confining unit, in central Brevard County.

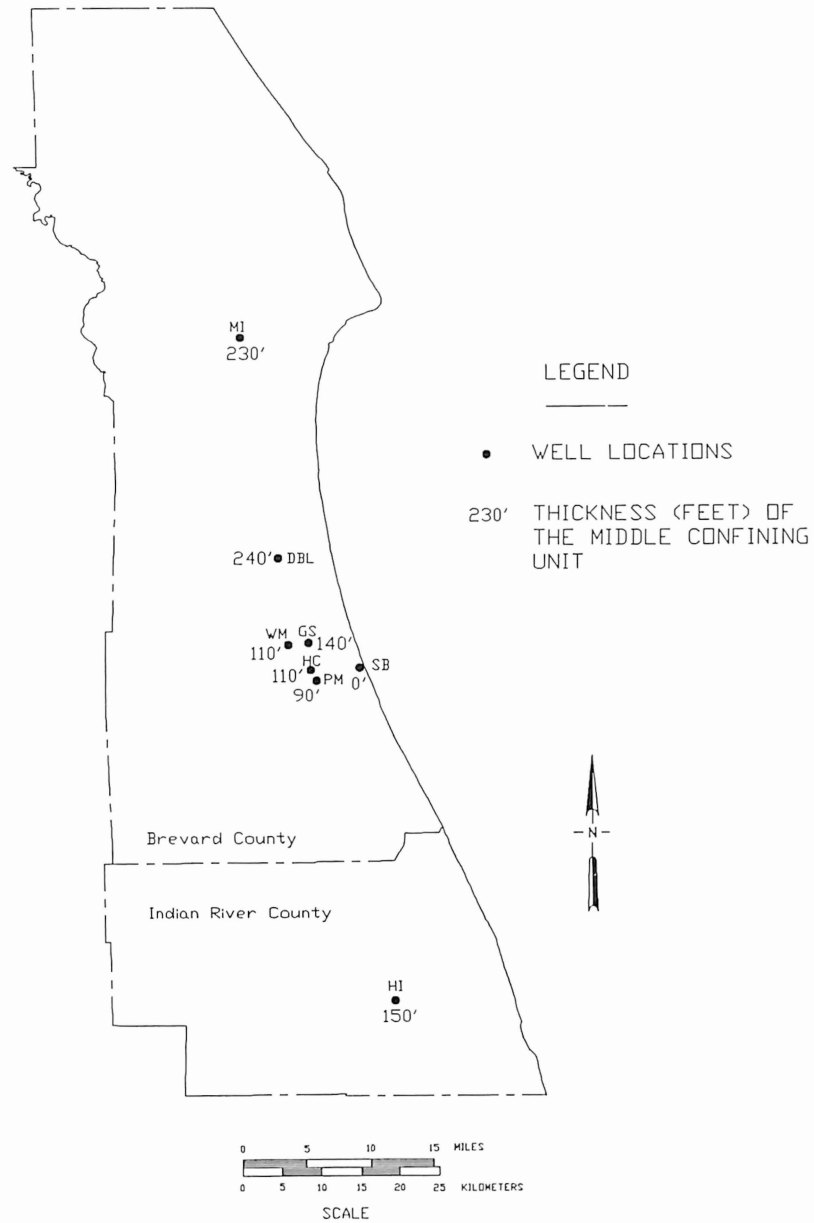


Figure 21. Thickness of the middle confining unit of the Floridan aquifer system for the injection wells in Brevard and Indian River counties.

Floridan aquifer system is located at approximately -1,000 feet NGVD in northwestern Brevard County and increases to -1,500 feet NGVD in southeastern Indian River County (Figure 22). The injection wells are not deep enough to fully penetrate the lower Floridan aquifer system. Miller's regional maps indicate that the thickness of the lower Floridan aquifer system increases in a southeast direction with estimated thicknesses in the study area ranging between 1,500 to 2,000 feet (Figure 23).

Ground-water movement in the lower Floridan aquifer system and middle confining unit has not been adequately determined due to lack of reliable head data and to the transitory effects of ocean, Earth and atmospheric tides (Meyer, 1989). However, direction of water movement can be inferred indirectly from temperature, chemical and isotopic data (Kohout, 1965). Kohout (1965) proposed that ground water is moving upward from the lower Floridan aquifer system through the circulation of cold seawater inland through the lower part of the Floridan aquifer system. Higher flow values result where the upper and lower Floridan aquifer systems are continuous or where zones of secondary porosity such as fractures and dissolutional karstic features occur. Geophysical logs and borehole videos indicate that possibility for numerous fracture zones in the lower Floridan aquifer system (Plate 3).

The quantitative methods used to describe aquifer parameters are usually based on homogeneous, isotropic conditions in a granular medium that assumes laminar flow. On a regional scale these methods may be satisfactory (Bush and Johnson, 1988); however, locally, the lower Floridan aquifer system is extremely heterogeneous, and fractured carbonates are strongly anisotropic with respect to orientation and number of fractures (Freeze and Cherry, 1979). Turbulent flow is common in karstic environments such as the Boulder Zone (Domenico and Schwartz, 1990). Therefore, local hydrologic analysis for transmissivity, hydraulic conduc-

tivity and confinement within a fractured medium should be viewed with skepticism.

The carbonates of the lower Floridan aquifer system are predominantly low-permeability, interbedded dolostones and limestones with zones of moderate to high permeability (Miller, 1986) (Plates 1, 2 and 3) (Appendix A). Hydraulic conductivity analyses by various consulting firms (Appendix A) indicate that vertical groundwater movement in the lower Floridan aquifer system is generally low with values less than 10^{-4} cm/s in the vertical direction (Appendix A). Horizontal hydraulic conductivity (when analyzed) was higher with values no greater than 10^{-3} cm/s (Appendix A). Transmissivity values for the lower Floridan aquifer system above the Boulder Zone were reported only in the Merritt Island, Port Malabar and Hercules injection wells. Transmissivity estimates were variable and ranged between 2.2 to 609 gpd/ft (Appendix A1, A6 and A8).

Boulder Zone

The Boulder Zone (Kohout, 1965) is a sub-zone of the lower Floridan aquifer system consisting of dolostones that display vertical and horizontal fractures and cavities. The Boulder Zone is a zone of high transmissivity which records a period when paleowater tables were at a level that resulted in karstification of the upper part of the carbonate sequence (Vernon, 1970). Where the overlying dolostone is effectively confining, the Boulder Zone is used extensively for receiving liquid wastes because of high transmissivities (Appendix A). The Boulder Zone has no stratigraphic significance and can exist at any level or locale where paleoconditions allowed karstic processes to occur.

The Boulder Zone in the study area is generally located in the Middle Eocene Oldsmar Formation at a depth of approximately -2,000 feet NGVD between the glauconite marker bed and the "C" marker bed (Figure 24 and Plate 3). Thickness of the Boulder Zone is locally variable

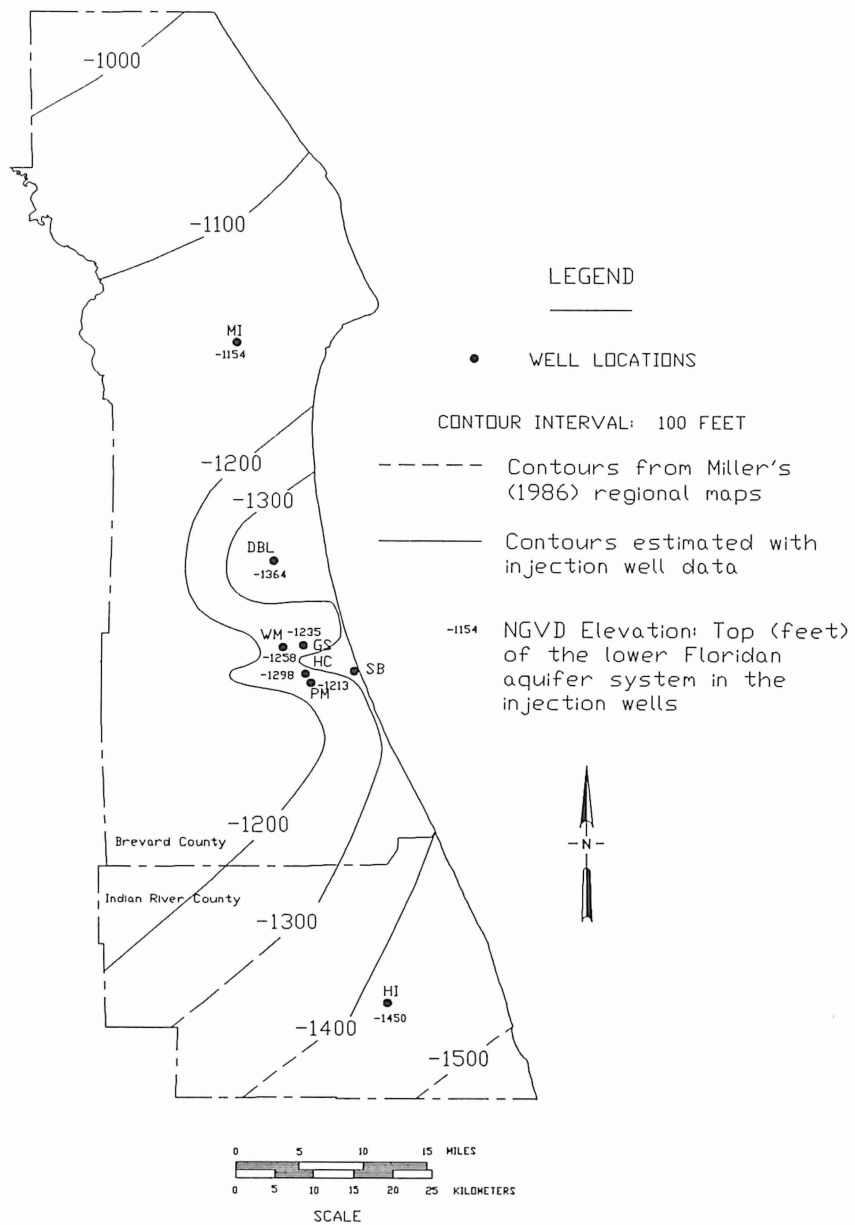


Figure 22. Top of the lower Floridan aquifer system, Brevard and Indian River counties (modified from Miller, 1986).

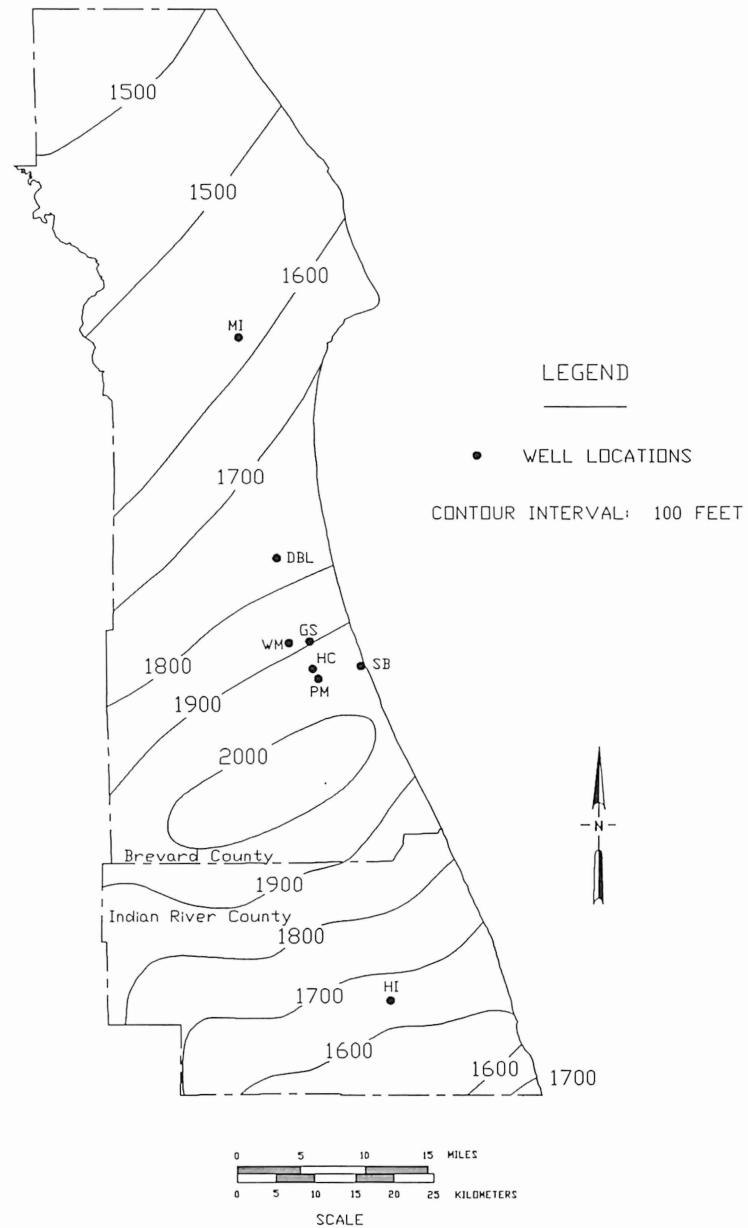


Figure 23. Thickness of the lower Floridan aquifer system, Brevard and Indian River counties (after Miller, 1986).

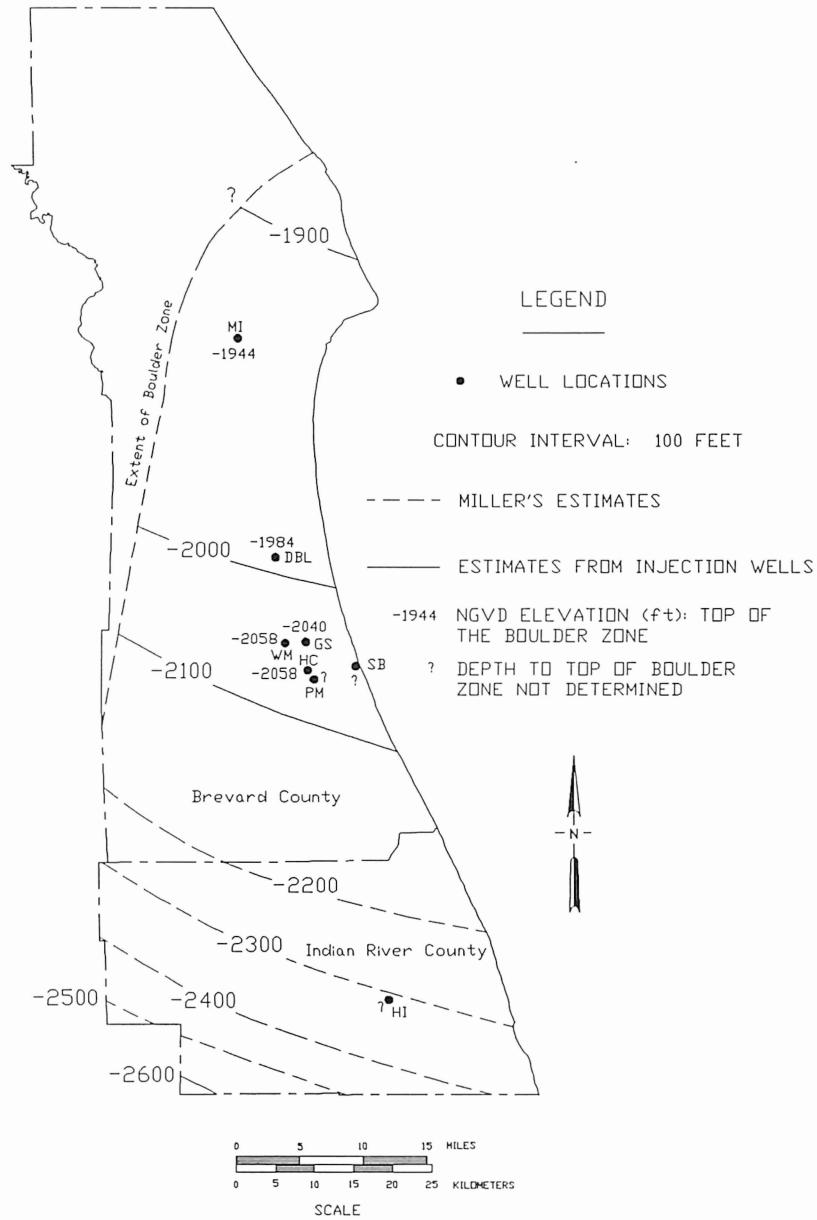


Figure 24. Top of the Boulder Zone, Brevard and Indian River counties (modified from Miller, 1986).

and ranged between 85 to 190 feet (Plate 3). The cavernous nature of the Boulder Zone in peninsular Florida diminishes northward (Miller, 1986) (Figure 24).

The carbonates immediately overlying the Boulder Zone consist of interbedded wackestones, packstones and dolostones of the upper Oldsmar Formation (Plates 1 and 3). Porosities, estimated from the sonic logs, are generally greater than 20 percent. Geophysical logs, samples and borehole videos suggest that this zone is fractured in some injection well boreholes (Plate 3).

Where the Boulder Zone is utilized for waste disposal, there is a traditional view that the dense dolostone immediately above and below the Boulder Zone contains no secondary porosity and operates as a confining layer. However, a study of four injection sites along the east coast of Florida by Safko and Hickey (1992) concluded that fracture porosity is the principal type of secondary porosity both within the Boulder Zone and the dolomitic rocks that lie above it. The present study utilizing core samples, borehole videos and geophysical logs, supports this hypothesis.

Confining Layers

Possible confining layers above the Boulder Zone, within the lower Floridan aquifer system, were defined conservatively in this study and are not always in agreement with confining layers delineated by the various consulting firms (Plate 3 and Appendix A). Criteria used for defining layers of confinement are based on geophysical logs and lithologic samples. In general, non-vuggy, fractureless micritic limestone and or microcrystalline dolostone with sonic log porosities less than 20 percent, that are traceable and correlative in the subsurface between the injection wells, are defined as confining layers.

There is a well defined, highly correlative and widespread glauconitic, micritic wackestone located in the uppermost Oldsmar Formation (Plates 1 and 3). The glauconite marker bed is located approximately 60 to 235 feet above the Boulder Zone (Plate 3). Porosities estimated from sonic logs range between 10 to 37 percent and fracturing and/or vuggy lithology is absent. This layer is between 35 to 45 feet thick and appears to be a well defined zone of confinement (Plates 1 and 3). Hydraulic conductivity analyses conducted by the various consulting firms (Appendix A) for the Merritt Island, West Melbourne and Port Malabar injection wells report values ranging between 10^{-5} to 10^{-6} cm/s supporting the assumption that this layer is confining.

Locally, above the glauconite marker bed, there is a zone of rocks with confining qualities (Plate 3). This zone is located in the lower Avon Park Formation and has been delineated as the lower Avon Park confining zone by the Florida Geological Survey (Plate 3).

Geophysical logs, borehole videos and lithologic samples suggest that the lower Avon Park confining zone contains fractures and/or vuggy lithology. The data are insufficient to determine the degree of fracture connectivity within these layers and it is not known whether these layers can transmit water via the fracture network. Thus, it is not known if the lower Avon Park confining zone is a good confining layer.

The rocks underlying the Boulder Zone are dense micro-crystalline dolostones with porosities less than 15 percent. These dolostones are fractured in places and extend below the total depth of the injection wells. These carbonates appear to be a layer of confinement (Plate 3).

Fractures and Vertical Flow

As stated previously, analysis of geophysical logs, lithologic samples and borehole videos indicate that numerous fractures exist through-

out the lower Floridan aquifer system (Plate 3). When determining confining properties, the presence or absence of fracture systems is extremely important. Fracture systems, with the proper orientation and connectivity, can transport water through rocks that appear to be confining.

Given the right geologic setting, brittle rocks of low porosity are most susceptible to fracturing (Domenico and Schwartz, 1990). Dolostone is considered one of the most fracture-prone sedimentary rocks, second only to quartzite (Stearns, 1967) (Figure 25). Van Golf-Racht (1982) cites three cases where stress related fractures may occur:

1. In response to folding and/or faulting;
2. Deep erosion or removal of the overburden, which will produce differential stresses that can cause fractures;
3. Rock volume shrinkage (shrinkage cracks) where water is lost, for example, in shales or shaley sands;

Cases 1 and 2 are believed to have occurred in the study area (see Lithostratigraphy and Structural sections for further discussion) and further support Safko and Hickey's (1992) hypothesis of vertical fracturing of dolostones overlying the Boulder Zone.

Increases in hydraulic conductivity due to secondary porosity can occur as a result of dissolution of limestone by circulating ground water moving along fractures and bedding planes. Analyses of the sediment cores, geophysical logs and borehole videos indicate fractured dolostones in and above the injection zone (boulder zone) in the D. B. Lee and other injection wells (Plate 3). Normal faulting in the area where the West Melbourne and D. B. Lee wells are located could result in increased secondary porosity along the fault plane and enhanced fracturing locally (see Structural Geology section for further discussion).

Hydrogeologically, the most important fracture properties are orientation, density, aperture opening, smoothness of fracture walls, and most importantly, the degree of connectivity (Domenico and Schwartz, 1990). If a given set of fractures does not extend through a confining layer or are not interconnected, then the rock cannot transmit water via the fracture network. As previously stated, there is strong evidence for fractures throughout the rocks within the lower Floridan aquifer system. The degree of connectivity between these fractures is not known and the water transmitting character is uncertain.

Dissolutional enlargement of fault planes and fractures within zones of relatively impermeable carbonates can dramatically increase vertical and lateral hydraulic conductivity and result in localized transport of different waters through potential confining layers. Fault planes can function as conduits causing water to breach confining layers and bypass monitor wells. Figure 26 is a schematic diagram demonstrating these phenomena.

Hydraulic Head in Wells

By definition, a true impervious layer will not transmit pressure, due to a hydraulic head increase, between confined aquifers. Hydrogeologic units that are separated from each other by a confining layer(s) should demonstrate contrasting hydrologic behavior. Distinct hydrologic systems which respond similarly suggest a hydraulic connection. Differences in head values and fluctuation between the monitor and injection wells indicate hydraulic separation. When the hydraulic heads fluctuate in a similar pattern a hydraulic connection could be present and vertical flow may be occurring.

However, confined aquifers are compressible and elastic over certain stress ranges and thus respond to changes in forces acting upon them. These stresses include periodic loading by ocean and earth tides, earthquakes; fluctuations

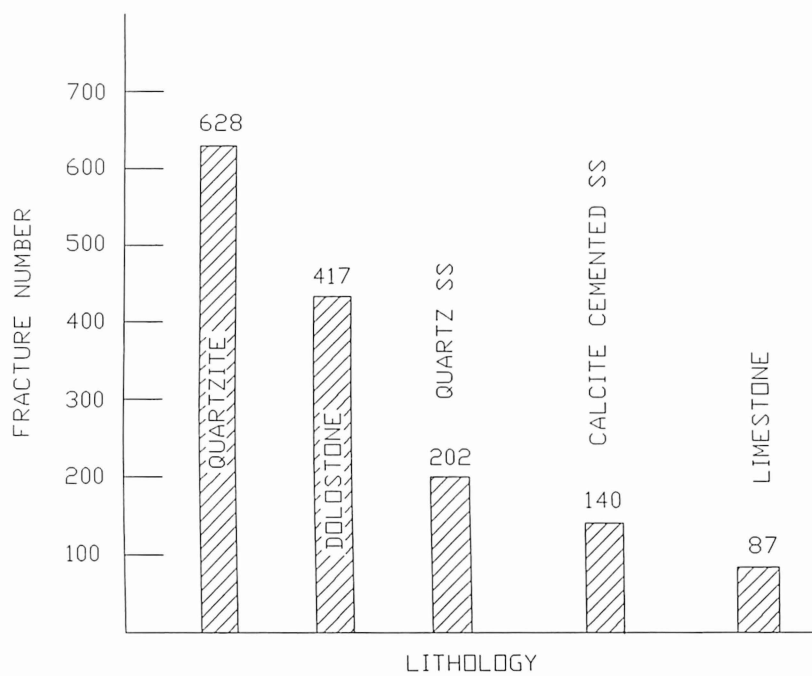


Figure 25. Average fracture density for several common rock types naturally deformed in the same physical environment (after Stearns, 1967).

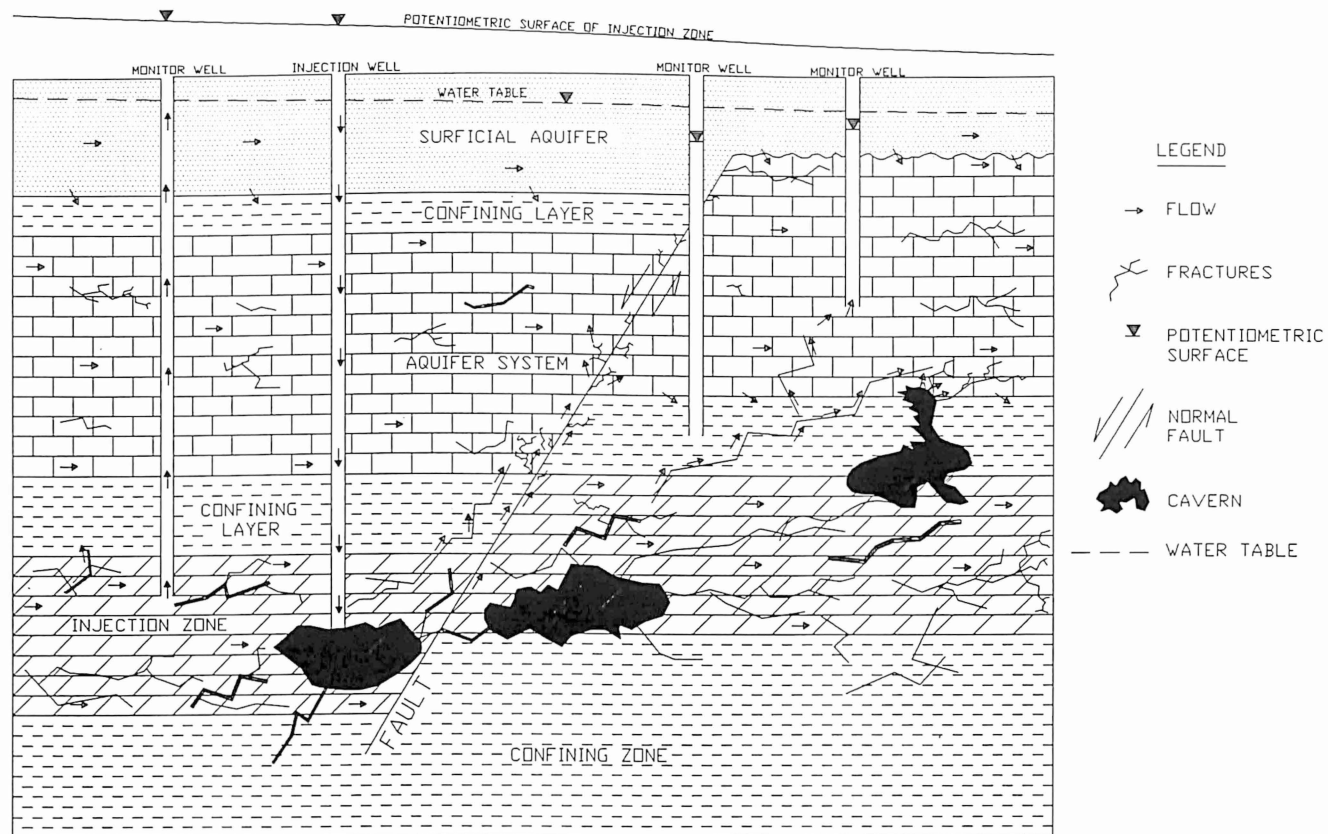


Figure 26. Hypothetical hydrogeologic conditions which could result in vertical flow of different waters.

of atmospheric pressure, rainfall, river and lake stages; and man-induced causes (Domenico and Schwartz, 1990). External loading stresses can cause similar hydraulic behavior (i.e., water level fluctuations in wells) in separate hydrogeologic systems.

Because Brevard County is located adjacent to the Atlantic Ocean, oceanic tidal loading has a noticeable impact on hydraulic head fluctuations in wells that penetrate confined aquifer systems. The response of water levels in wells due to oceanic tidal loading occurs as a result of three processes:

1. Mechanical loading of the aquifer at its oceanic extension;
2. Propagation and attenuation of the pressure wave inland through the aquifer;
3. Flow of ground water between the aquifer and the borehole.

Aquifer Loading

Mechanical loading of the aquifer at its oceanic extension causes the water level in a well to increase at high tide and decrease at low tide. As wells are located away from the ocean the inland transfer of the pressure wave through the aquifer occurs with a diminishing amplitude and increasing time lag (Enright, 1990) (Figure 27).

Responses to earth tides in wells occur, by definition, at the same frequencies as ocean tides, but are orders of magnitude smaller (the largest are 0.5-1 inches). Because of a difference in phase and amplitude, any earth tidal fluctuations near the coast typically is masked by the oceanic tidal fluctuations. The net effect of earth tides is to decrease by a small amount the amplitude of oceanic tidal fluctuations (Parker and Springfield, 1950; Gregg, 1966; Bredehoeft, 1967; Enright, 1990).

An inverse relationship exists between barometric pressure and water levels in wells. An increase in barometric pressure is transmitted to the confined aquifer system through the overly-

ing confining layer and the aquifer responds with an increase in pressure head. This causes water to flow into the well resulting in an increase in water level. However, the well has a direct connection with the atmosphere, and because the atmospheric load is partially supported by the aquifer "skeleton," the net effect of atmospheric loading is a decrease in water level during increased barometric pressures and an increase in water level during decreased barometric pressure (Domenico and Schwartz, 1990; Enright, 1990). This relationship is demonstrated in Figure 28 where the D. B. Lee monitor wells are inversely responding to the increases and decreases of barometric pressure.

If a well system is monitored continuously (such as the D. B. Lee injection and monitor wells, Figure 28), the response to these external loading stresses can be observed as corresponding fluctuations of water levels. These stresses may conceal the true behavior of the aquifer system(s) in response to injection tests.

For example, the simultaneous increase in well pressure within the monitor wells during the injection test could be a result of a hydraulic connection between the injection well and the monitor wells, oceanic tidal loading, a decrease in barometric pressure, or a combination of these phenomena.

When analyzing the aquifer(s) reactions to injection well tests, the monitor well hydraulic head responses to atmospheric and ocean tidal loading may mask the effect of the injection test on the monitor wells. Therefore, in order to isolate the hydraulic head response of the monitor wells to the injection test, the ocean tidal and atmospheric loading influences need to be removed by determining the tidal efficiency and barometric efficiency of the aquifer(s) in which the well(s) are located. Methods for determining tidal and barometric efficiency are described by Jacobs (1940) and Domenico and Schwartz (1990).

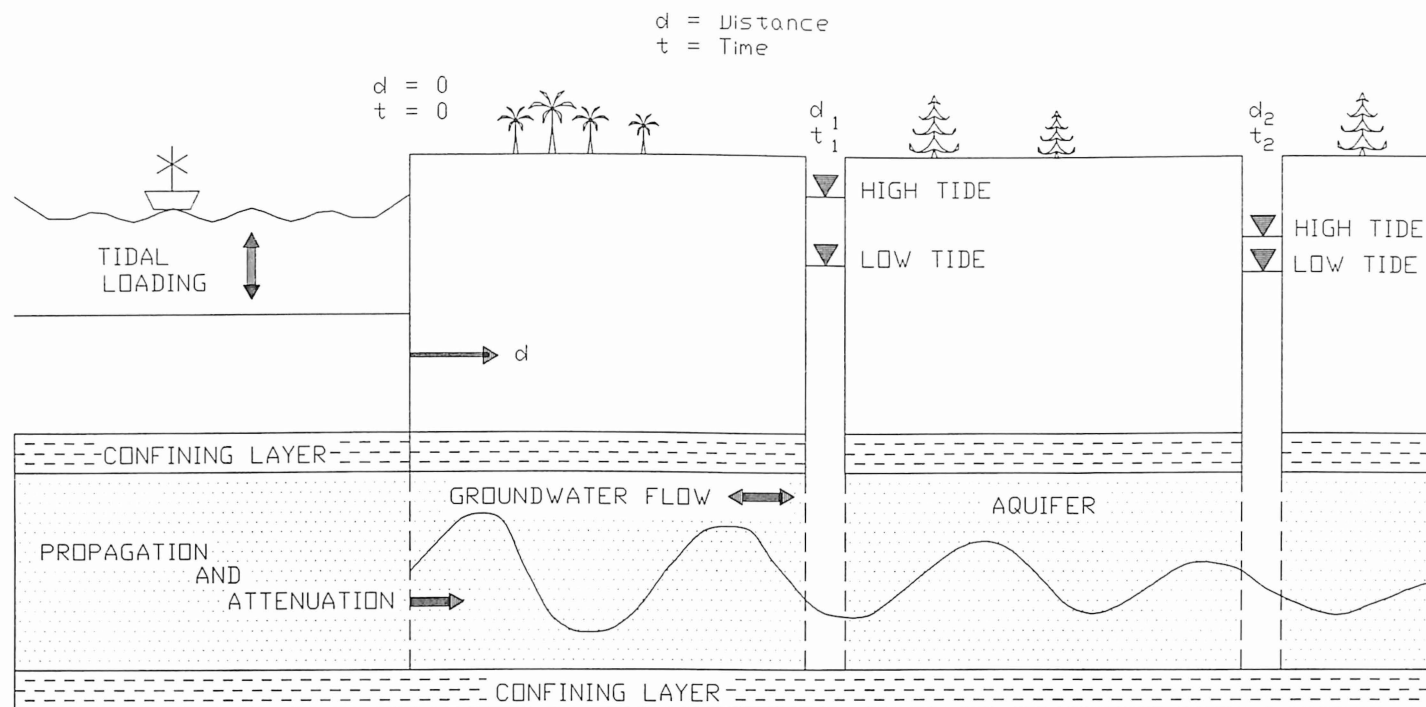


Figure 27. Response of water in a well penetrating a confined aquifer to oceanic tidal loading (modified from Enright, 1990).

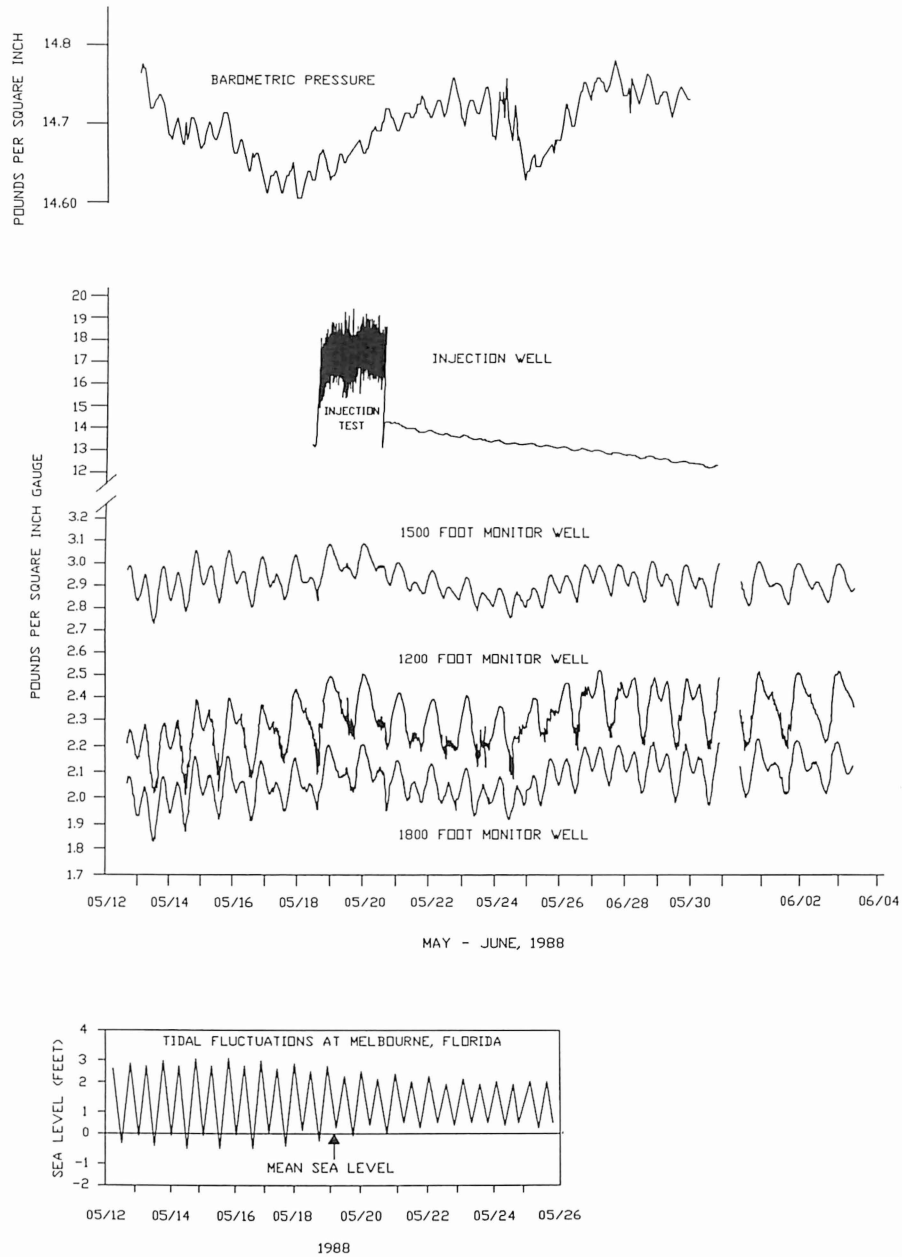


Figure 28. The effect of oceanic tidal loading and barometric loading on water levels in the D. B. Lee injection and monitor wells (Data from Geraghty and Miller, 1988).

Hydraulic head results are summarized in Figures 29, 30 and 31 for the Harris, Port Malabar and D. B. Lee wells. The water level readings observed during daily low tides were analyzed for the D. B. Lee wells (Figure 31) in an attempt to partially filter the effects of diurnal tidal loading (Figure 28) on the confined aquifer systems. Similar patterns of hydraulic head fluctuation within both the Port Malabar and D. B. Lee monitor wells may be indicative of a hydraulic connection between the injection and monitor zones (Figures 30 and 31) at these two sites.

The D. B. Lee 1,500 and 1,800-foot monitor wells (Figure 31) demonstrate patterns of hydraulic head fluctuations that are suspiciously similar. Both wells are located in a highly fractured or vuggy dolostone (Plate 3) and there may be a hydraulic connection between the two. Although not as apparent, the shallow monitor well, located in the middle confining unit, is also exhibiting a pattern of water level fluctuation similar to the two deeper monitor wells. These similar responses could be due to a hydraulic connection between the wells, or they may be reacting to external loading stresses such as barometric pressure (Figure 28). Hydro Designs (1989) conducted four injection/recovery tests on the D. B. Lee injection and monitor well system. The results (Figures 32 - 34) of the first test are presented in this report.

The wells were allowed to stabilize (Figure 32) prior to the first test in order to quantify and remove oceanic tidal loading effects on pressure fluctuations in the monitor wells. The injection/recovery tests were designed so they would not interfere with the normal operation of the plant. Theoretically, the recovery phase should be the mirror image of the injection phase. This, however, was not the case (Figure 34) because the injection flow was automatically reduced in steps by the injection pumps in operation (Hydro Design, 1989).

A nearly simultaneous increase of hydraulic head in the injection and monitor wells during the injection tests (Figure 33) strongly indicates a hydraulic connection between the injection and monitor zones. A definite trend in the change of water chemistry in each of the monitor wells (see Ground-Water Chemistry Analysis this report) supports this conclusion. The exact cause of the upward leakage cannot be determined. Lack of structural integrity of the well bores is one possibility. The D. B. Lee injection and monitor well system is located in a highly fractured or vuggy dolostone (Plate 3). A lack of confinement between injection and monitor zones would occur if the fracture network is connected. It is also feasible that both lack of confinement and improper well construction could be contributing to upward leakage from the injection zone.

Geothermal Gradients

Deep well temperature surveys in southern Florida have shown that geothermal gradients underlying the Florida Platform are affected by the presence of cold sea water. At depths of 1,500 to 3,000 feet the water in the Floridan aquifer system becomes anomalously cooler with depth (Meyer, 1989). The average temperature near the cold sea water bodies averages about 60 degrees F and increases to 108 degrees F along the central axis of the Florida Plateau (Kohout et al., 1977). Horizontal and vertical temperature distributions suggest that cold, dense sea water flows inland through cavernous dolostones of the Boulder Zone where it becomes progressively warmed by geothermal heat flow. The reduction of density produces upward circulation. After mixing with less saline water in the upper part of the aquifer, the diluted saltwater flows seaward to discharge by upward leakage through confining beds or through submarine springs on the continental shelf (Kohout et al., 1977) (Figure 35).

Borehole temperature logs, provided by the various consulting firms were closely inspected

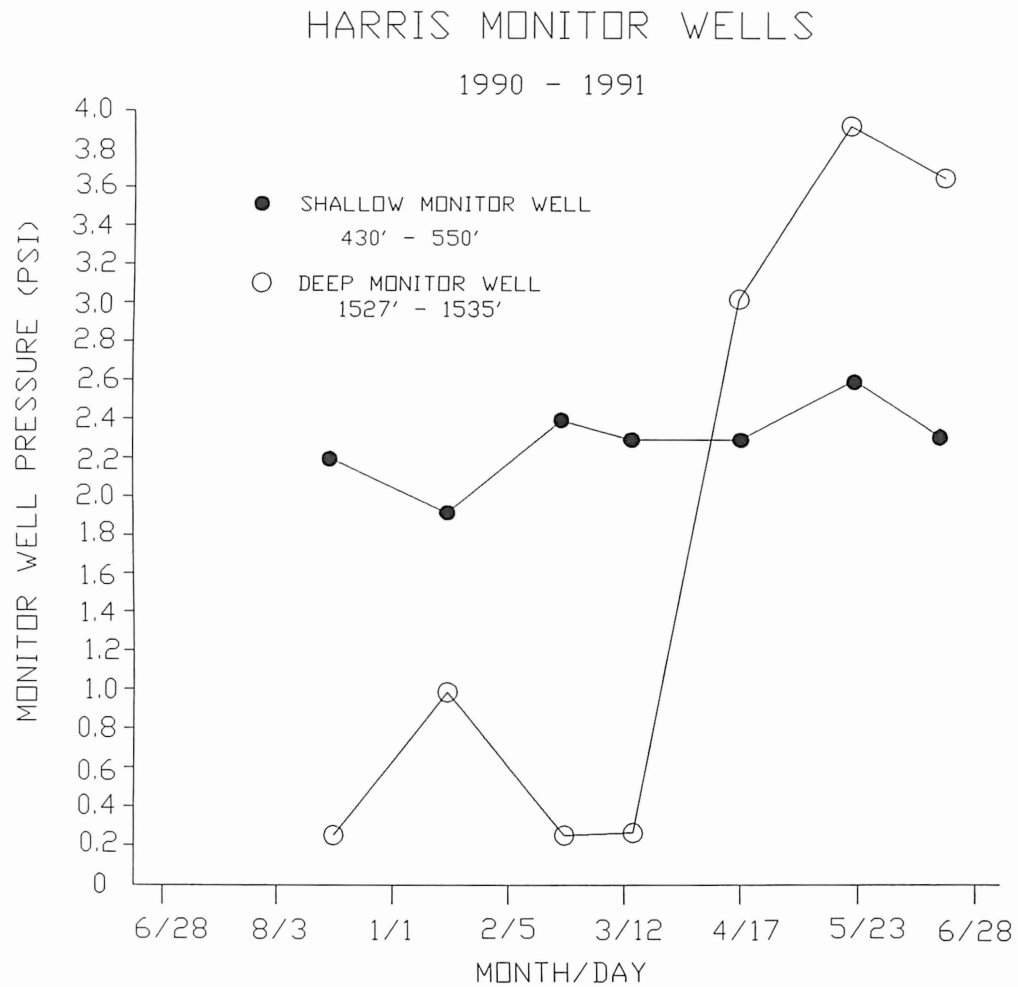


Figure 29. Comparison of hydraulic head values between the two Harris Corporation monitor wells (data from DER, 1991).

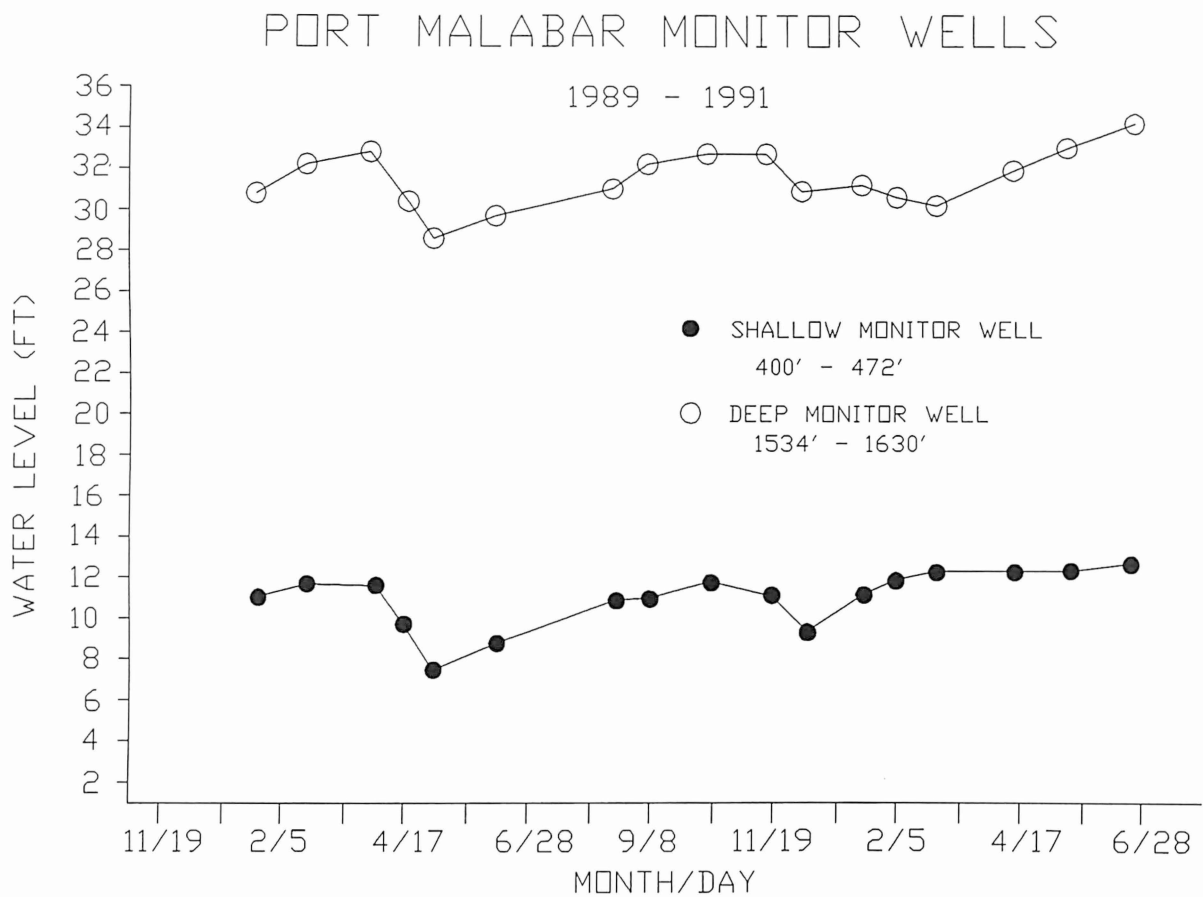


Figure 30. Comparison of hydraulic head values between two Port Malabar monitor wells (data from DER, 1991a).

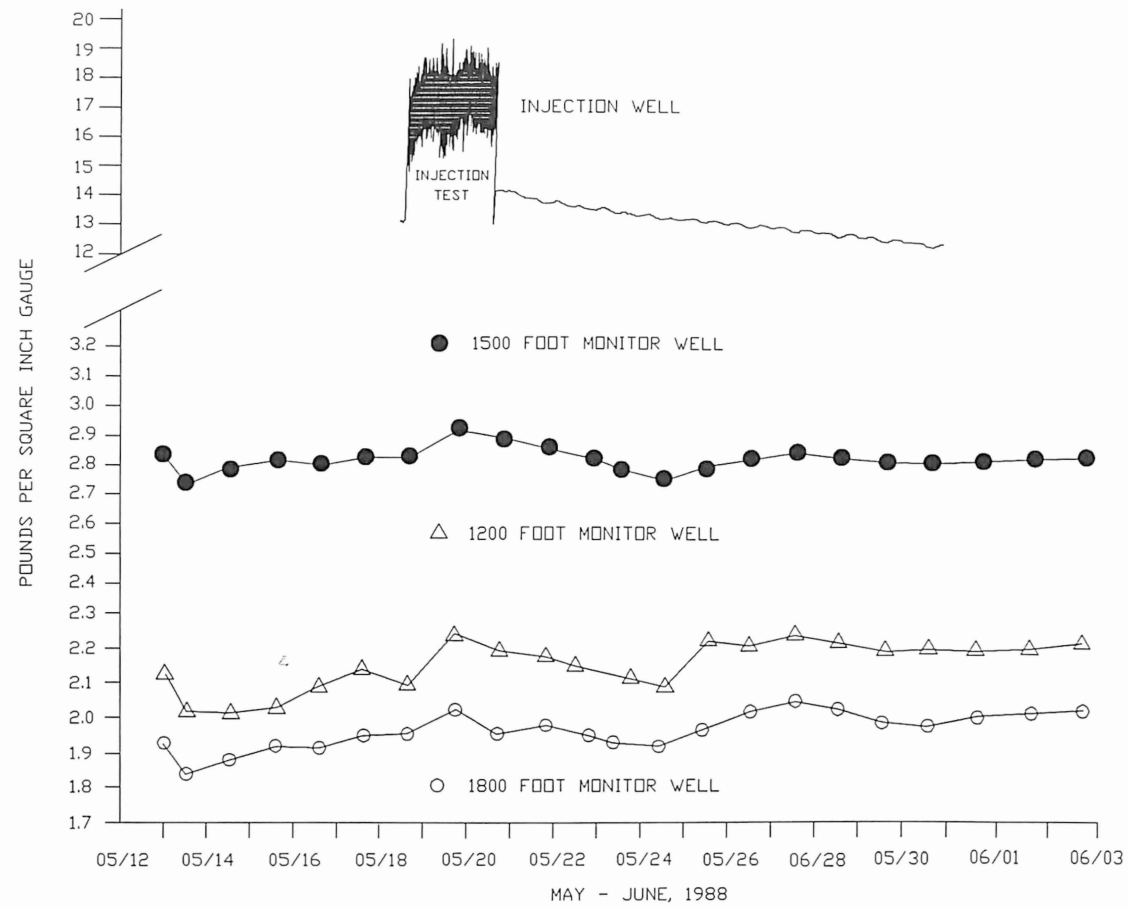


Figure 31. Comparison of hydraulic head values over time between the D. B. Lee injection and monitor wells (data modified from Geraghty and Miller, 1988).

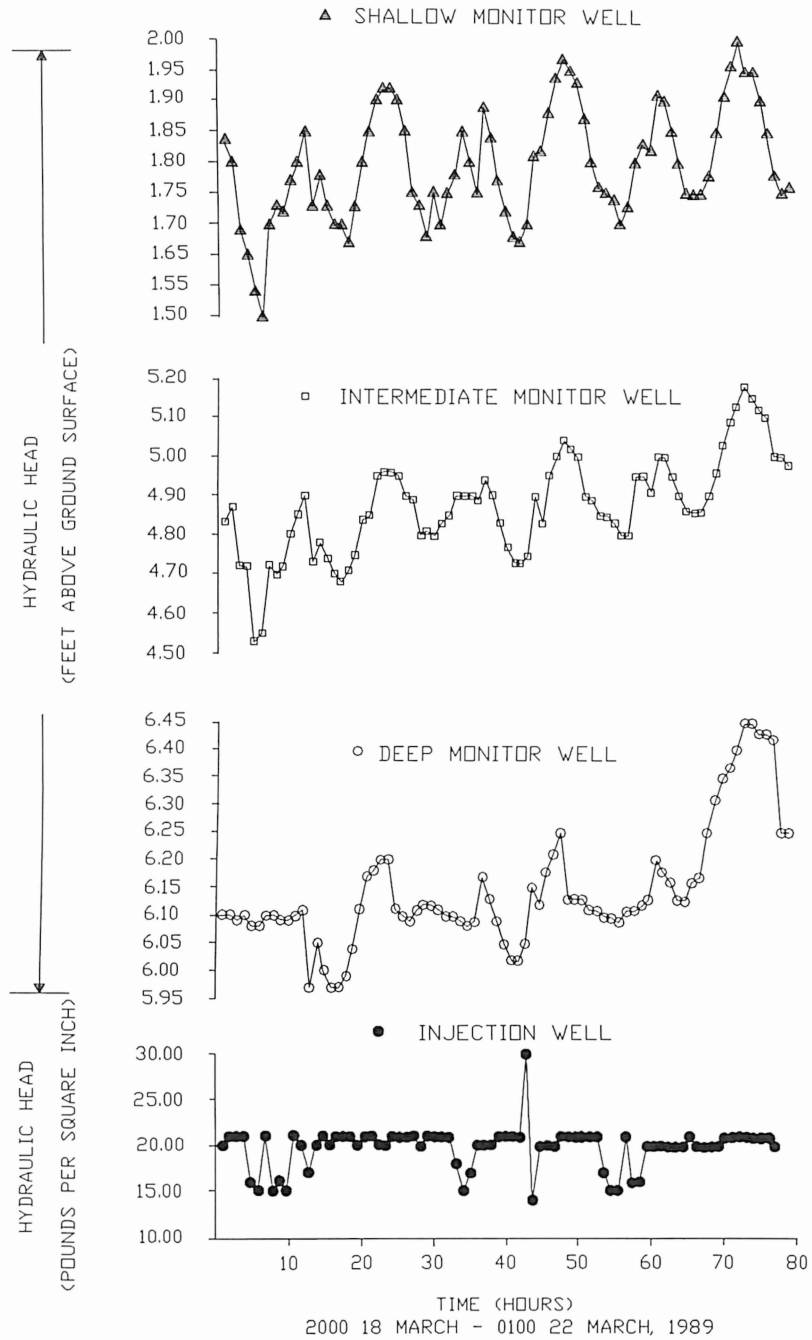


Figure 32. Background readings for the D. B. Lee injection and monitor wells prior to the injection tests (data from Hydro Designs, 1989).

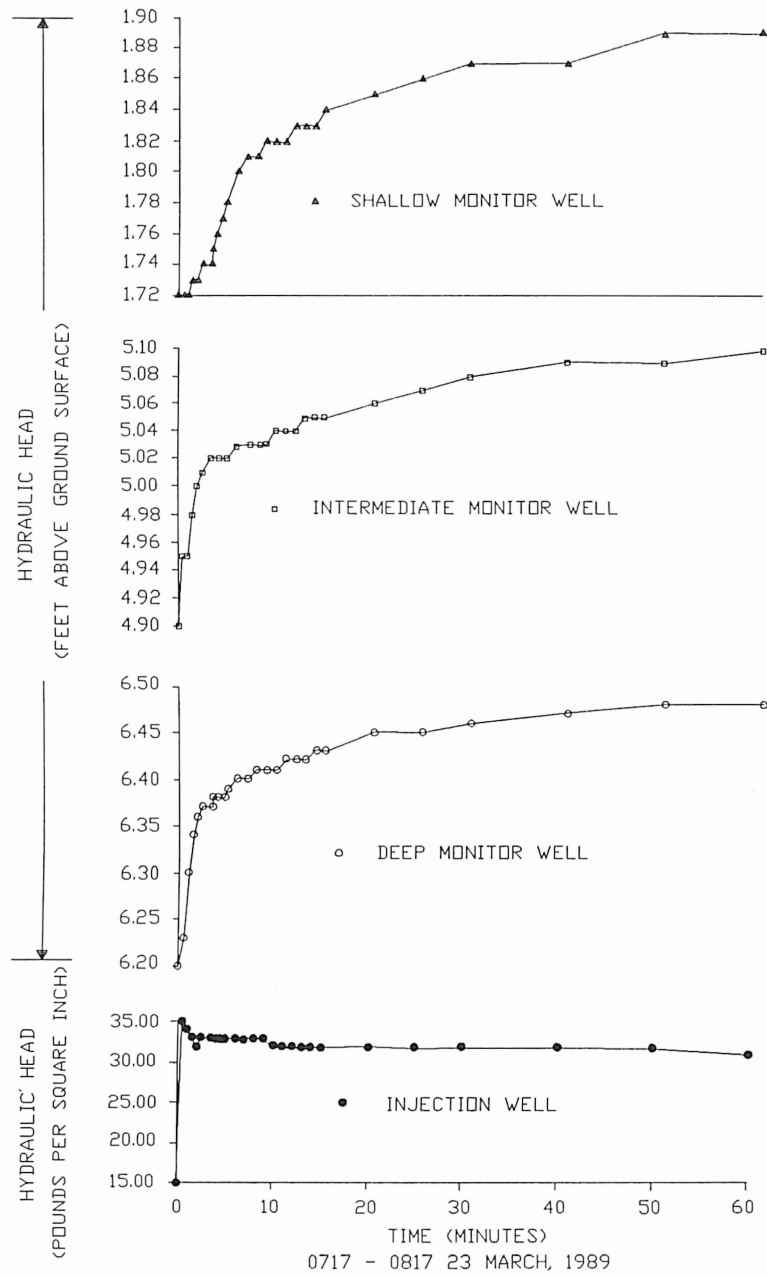


Figure 33. Results of first D. B. Lee injection test (data from Hydro Designs, 1989).

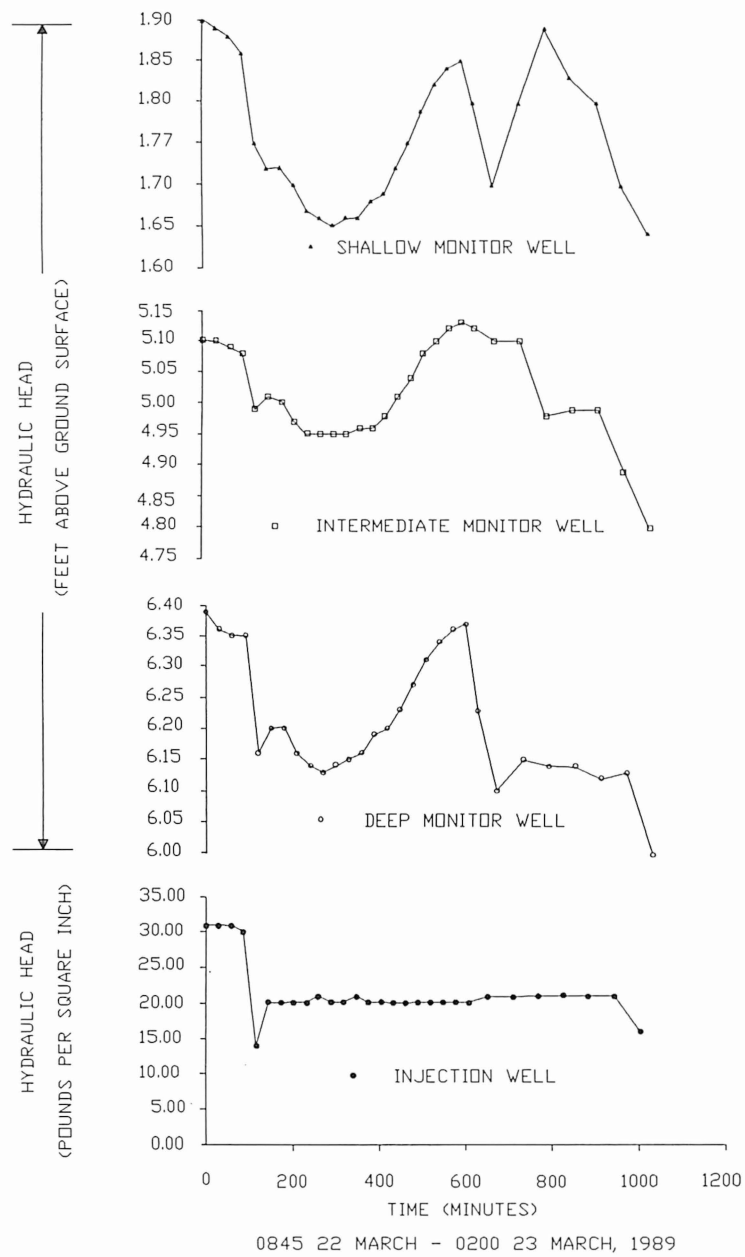


Figure 34. Recovery of D. B. Lee injection and monitor wells after first injection test (data from Hydro Designs, 1989).

DEPTH (FT), BELOW MEAN SEA LEVEL

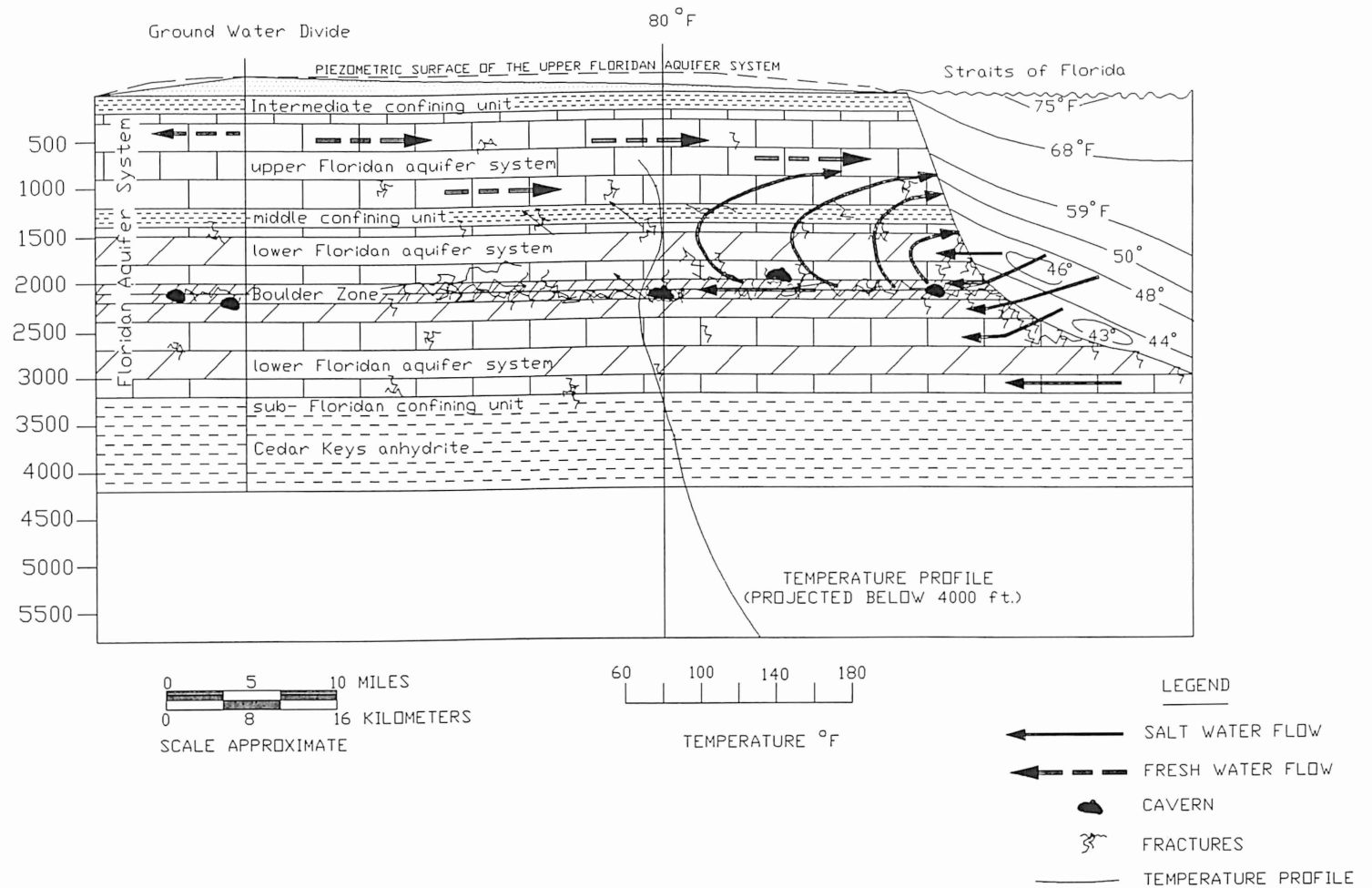


Figure 35. Hypothetical hydrogeologic cross section through peninsular Florida demonstrating the concept of cyclic flow of seawater induced by geothermal heating (modified from Kohout et al., 1977).

for any anomalous temperature decreases. Temperatures generally ranged between 80 and 112 degrees F at depths greater than 1,000 feet and generally increased with depth; therefore, no cyclic or convective circulation is suspected in the study area. Temperature decreases have been documented in south Florida where the Straits of Florida are adjacent to the Florida Platform. The occurrence of convective circulation should be investigated when injection wells are proposed for these areas.

GROUND-WATER CHEMISTRY ANALYSIS

Introduction

Water-quality data, confining zone, and injection zone information for seven wells in Brevard County and one well in Indian River County (Hercules Corporation) were analyzed for this investigation. Three wells, the Merritt Island, South Beaches, and D. B. Lee injection wells, were chosen for detailed study because of obvious trends observed in water-quality data. For these wells, confining, injection, and monitor zone lithologies were examined to determine any physical properties that might help explain observed monitor zone contamination. Determining the mechanical integrity of the injection wells was beyond the scope of this study.

The injection intervals of all eight wells occur in the Boulder Zone of the lower Floridan aquifer system (Figure 36), in the Oldsmar Formation (with the possible exception of the Port Malabar injection interval where the Boulder Zone is not well developed; see Plate 3). This zone is generally highly fractured and cavernous, with transmissivity values ranging up to 21 million gpd/ft (Haberfeld, 1991). The high transmissivities in the injection zone, and pumping rates which can be tens-of-millions of gallons per day, result in only minimal increases in wellhead pressure in most wells (Haberfeld, 1991). This implies the possibility that the injected waters are circulating freely. Fractures, discontinuities, and cavities in

the designated confining zones of the wells could provide conduits for the circulating water.

The injected fluids are generally low-salinity, treated municipal waste water. Industrial waste waters are injected at the Harris Corp. and Hercules, Inc. sites. Injected waters are less dense than formation water, and since fluids in the injection and lower monitor zones are highly saline, "contamination" from injected fluids will be seen as freshening trends in monitor well data. For example, such trends show up as a decrease in total dissolved solids (TDS) and/or chloride concentration. Occasionally, marked increases in these parameters are observed, and this is attributed to deeper saline waters being displaced upward by injected fluids (J. Haberfeld, DER, personal communication, 1991).

Nitrogen content is monitored because treated waste water will generally have higher nitrogen concentrations than ambient formation water. It is measured as total kjeldahl nitrogen (TKN), which is organic nitrogen plus ammonia. Another important measurement is the depth at which the TDS value exceeds 10,000 mg/L. United States Environmental Protection Agency guidelines state that the TDS value of formation waters in an injection zone must exceed 10,000 mg/L, so consultants note the depth at which the transition occurs. For the transition depths, only pre-injection values are available.

The TDS, chloride, and TKN are among the parameters tracked in the various monitor zones, and these three were chosen for close investigation because time series data on them are available for the monitor zones of the injection wells.

The three primary wells are the Merritt Island, the South Beaches, and the D. B. Lee injection wells. These are discussed first, and are followed by summaries of data for the Harris Corp., Grant Street, Port Malabar, West Melbourne, and Hercules, Inc. injection wells.

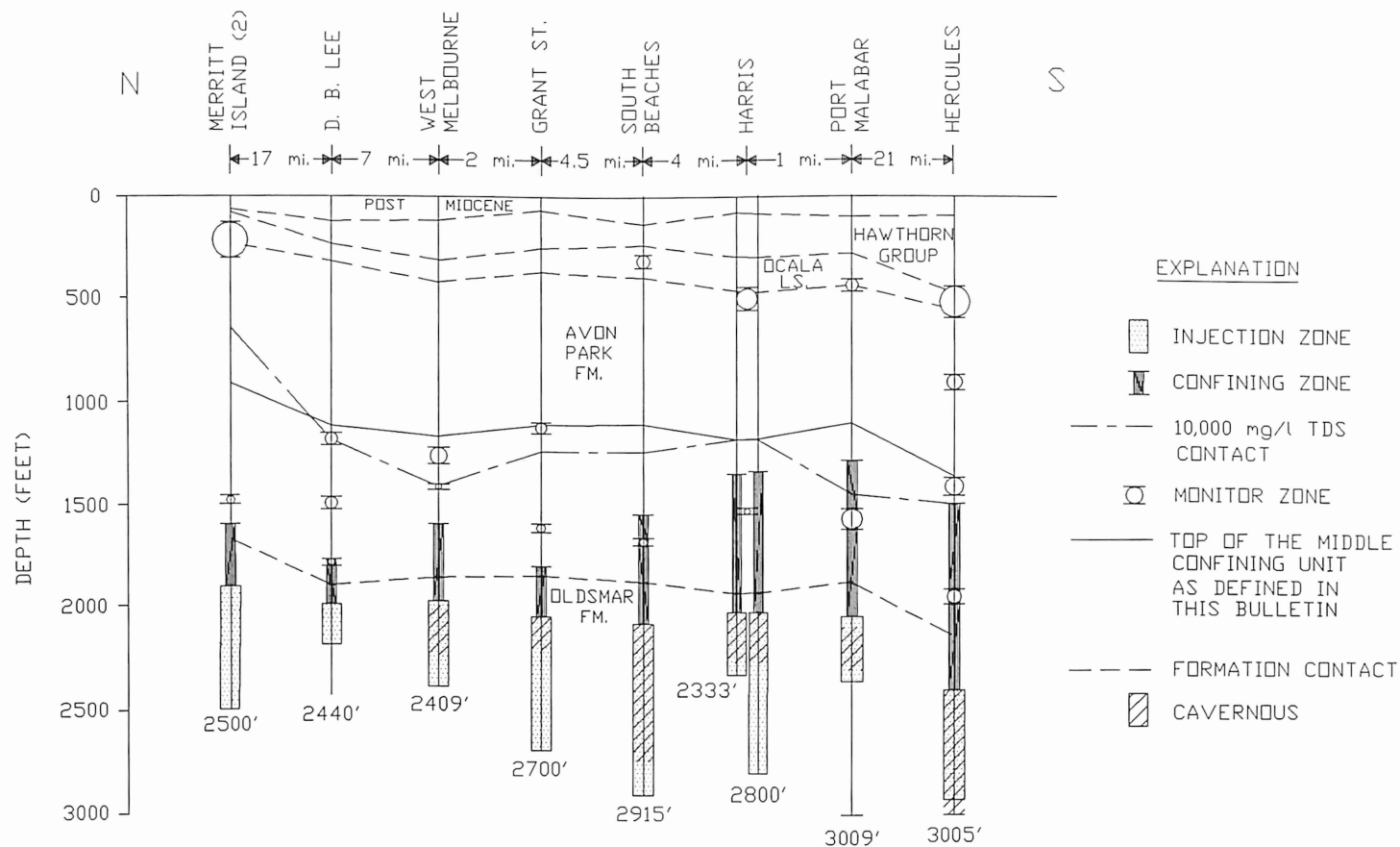


Figure 36. Relationships of monitor, confining, and injection zones of the study wells (data from consultant reports).

In this section, the definitions of the extent of confining, injection and monitor zones are those made by the consultant companies during drilling. The consultants chose the placement of monitor zones based on their definitions, so the water-quality data from the monitor zones are analyzed and discussed in terms of those definitions.

However, the consultants' hydrogeological interpretations often differ from those of the Florida Geological Survey (FGS). Characteristically, their definitions of confinement cover a broad interval. Available data allowed FGS geologists to better delineate confining zones within the lower Floridan aquifer system. These data allowed the definition of three confining zones: the middle confining unit, the lower Avon Park confining zone, and the glauconite marker bed. These units are discussed in the **Hydrogeology of the Middle Confining Unit of the Floridan Aquifer System** and the **Hydrogeology of the Lower Floridan Aquifer System**. Plate 3 shows the confining zones delineated by the FGS geologists.

In addition to the definitions of confining, injection and monitoring zones, the consultants' reports provided background water-quality data. The Bureau of Drinking and Ground Water Resources of the DER provided the time series water-quality data taken from the monitor wells at each site. Lithologic descriptions were done by FGS geologists. Porosity, induration, and permeability descriptions were based on visual inspection of cuttings and cores, and were supplemented by geophysical log data, whenever possible.

The description of samples involved determining lithologies and physical properties. Physical properties determined for each sample include color, porosity, permeability, grain size, induration, cement type, sedimentary structures, accessory minerals, and presence or absence

of fossils. These descriptions are a part of the FGS well-file database. General lithologies are illustrated on Plates 1, 2, and 3.

The lithologic descriptions were also correlated with geophysical logs (for example, see Plate 1). When possible, porosity values calculated from sonic logs were used to supplement the descriptions.

Monitor zone water-quality data were examined to ascertain if there has been any migration of injection or formation waters due to pumping. Vertical migration of injection waters would be indicated by falling TDS and chloride concentrations, and by rising TKN concentrations. If vertical migration or contamination occurred, these trends would be most prominent in data from the lower monitor zones.

Primary Wells

Merritt Island

At the Merritt Island site, there are two closely spaced injection wells completed in the Oldsmar Formation at a total depth of 2,500 feet BLS. The monitor well has an upper monitor zone from 128 to 340 feet BLS in the Ocala Limestone, and a lower monitor zone extending from 1,470 to 1,500 feet BLS in the Avon Park Formation (Appendix A1). The confining zone, as defined by Geraghty & Miller, Inc. (1986), extends from 1,600 to 1,850 feet BLS, in the lower Avon Park and upper Oldsmar Formations. The uncased injection zone interval is 1,850 to 2,500 feet BLS in the Oldsmar Formation.

The lower monitor zone is in dolostone of the lower Avon Park Formation. The interval from 1,470 to 1,498 feet BLS is dolostone of 10 percent to 20 percent porosity, good induration, and low to medium permeability. From 1,498 to 1,518 feet BLS the dolostone has 25 percent porosity and possibly high permeability. This more permeable zone extends into the interval between the monitor zone and the confining zone.

Between the lower monitor zone and the confining zone dolostone is the dominant rock type. Below the permeable zone noted above, from 1,518 to 1,530 feet BLS the rock averages 10 percent porosity, is well indurated, and has apparently low permeability. The section from 1,530 to 1,599 feet BLS has 30 percent to 35 percent porosity and possibly high permeability.

The confining zone in this area as defined by the consultants occurs in the lower Avon Park and upper Oldsmar Formations, extending from 1,600 to 1,900 feet BLS. The interval consists of alternating layers of dolostone, mudstone, wackestone, and packstone from 1,600 to 1,830 feet BLS, and dolostone from 1,830 to 1,900 feet BLS. Porosity and permeability are highly

variable throughout this zone. Fractures were noted in two cored intervals, from 1,720 to 1,723 feet BLS and from 1,820 to 1,830 feet BLS.

The background water-quality report on the lower monitor zone shows that the ambient water quality before injection was as follows: TDS = 34,630 mg/L; chloride = 19,200 mg/L; and TKN = 0.69 mg/L (Geraghty & Miller, Inc., 1986). For comparison, water containing more than 2,000 to 3,000 mg/L TDS is too salty to drink, and seawater has approximately 35,000 mg/L TDS (Freeze and Cherry, 1979). In this area TDS values exceed 10,000 mg/L at approximately 1,200 feet BLS.

Data on lower monitor zone water quality shows changes in all these values since injection started in January 1987. TDS show a steady decrease beginning in February 1987, from over 34,000 mg/L to below 22,000 mg/L in July of 1991 (Figure 37). Chloride concentrations decreased from over 16,000 mg/L to below 12,000 mg/L (Figure 38). TKN increased from 1987 when injection began to a high of over 2.6 mg/L in early 1988. Concentrations since then have decreased in an erratic manner (Figure 39). The increase can be attributed to rising injection waters. The decrease after the peak is probably due to the increasing efficiency of the treatment plant that treats the effluent before it is injected (J. Haberkamp, DER, personal communication, 1991).

Data from the upper monitor zone show a slight decrease in TDS values, and chloride and TKN values vary widely. The change in TDS values is too small to infer that injected waste water has traveled that high in the section.

Regression analyses were performed on the deep monitor well data to determine the significance of the observed trends. A high R-squared value, or coefficient of determination (R is the correlation coefficient), indicates low scatter of the data, or a definite relationship between time and concentration values. The R-squared value

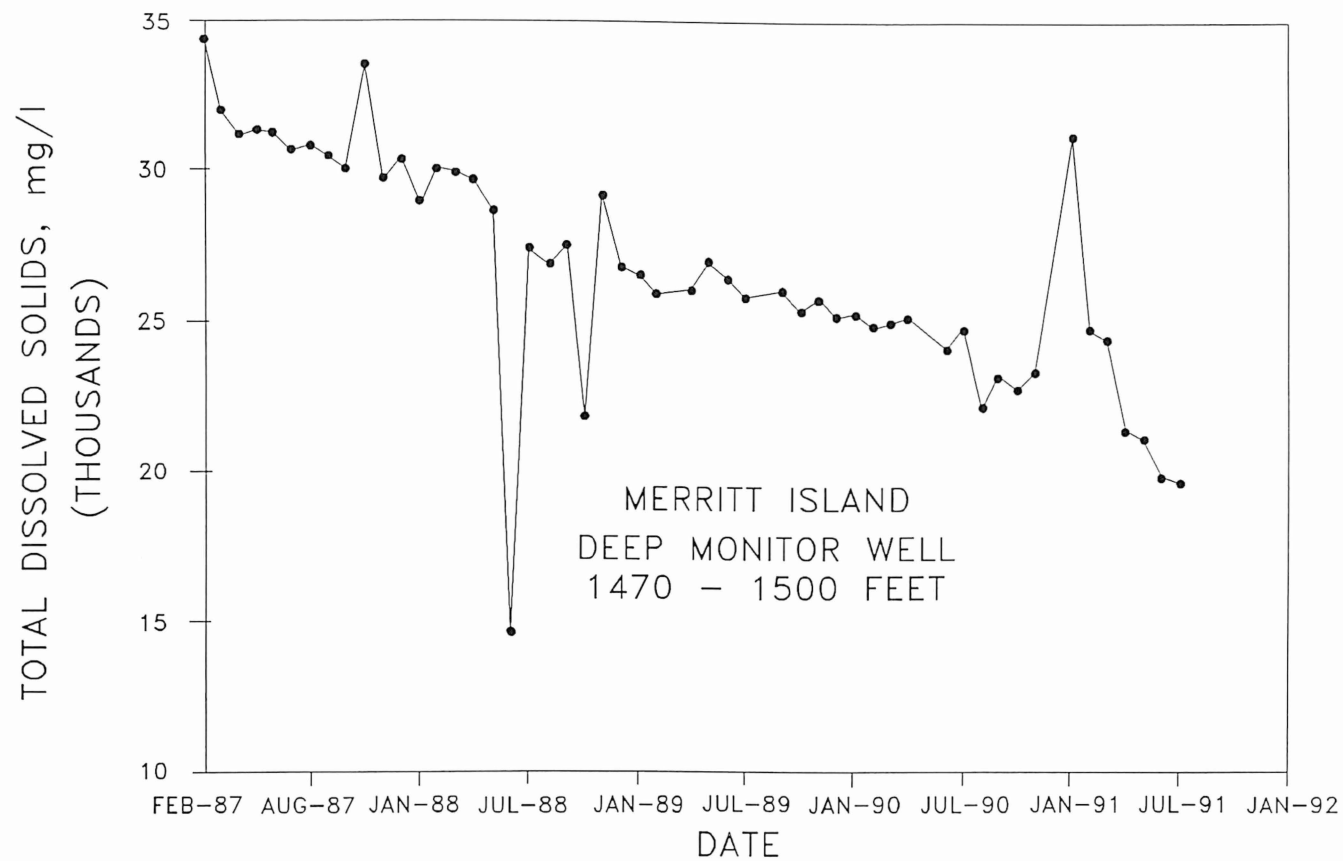


Figure 37. TDS values of the Merritt Island well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

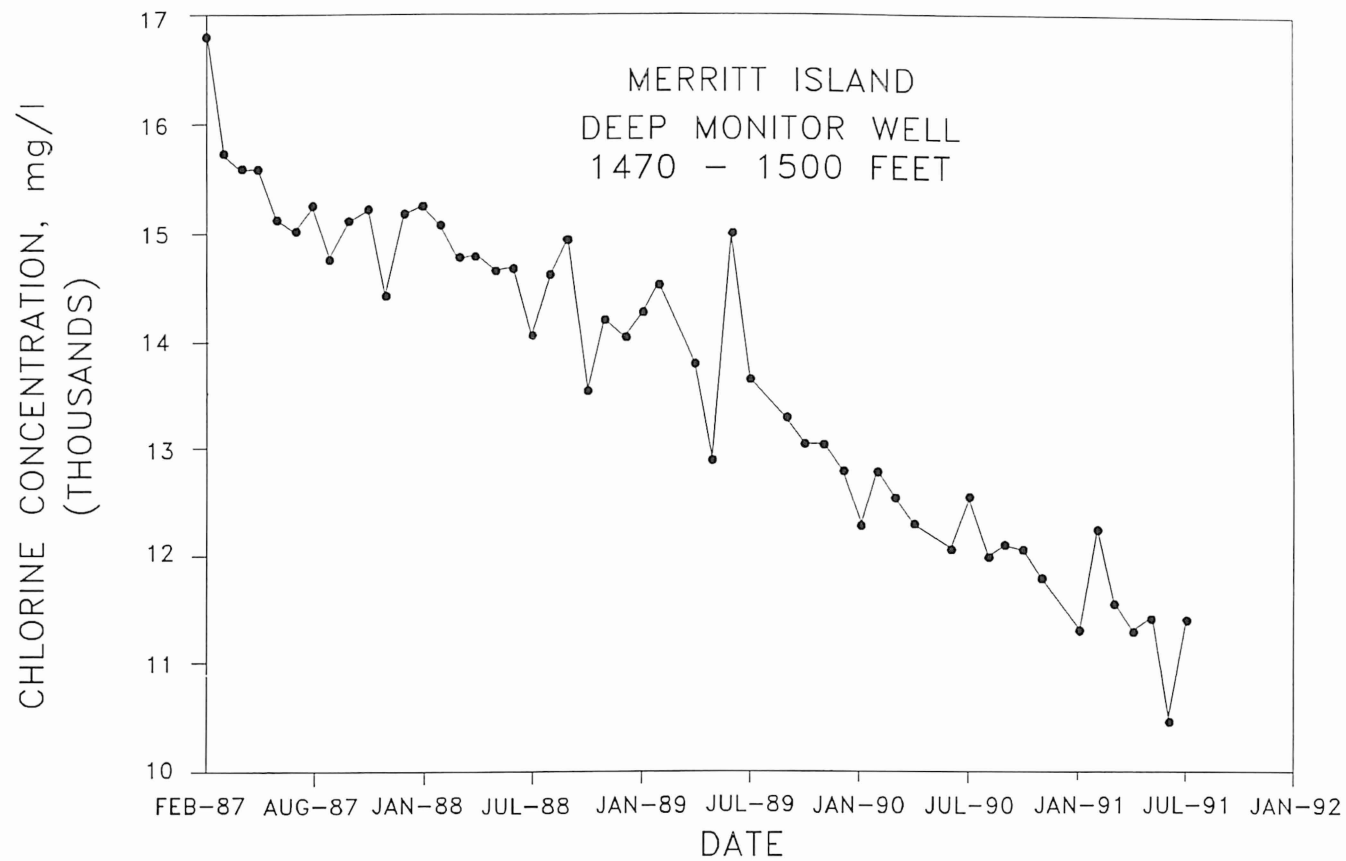


Figure 38. Chloride concentrations of the Merritt Island well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

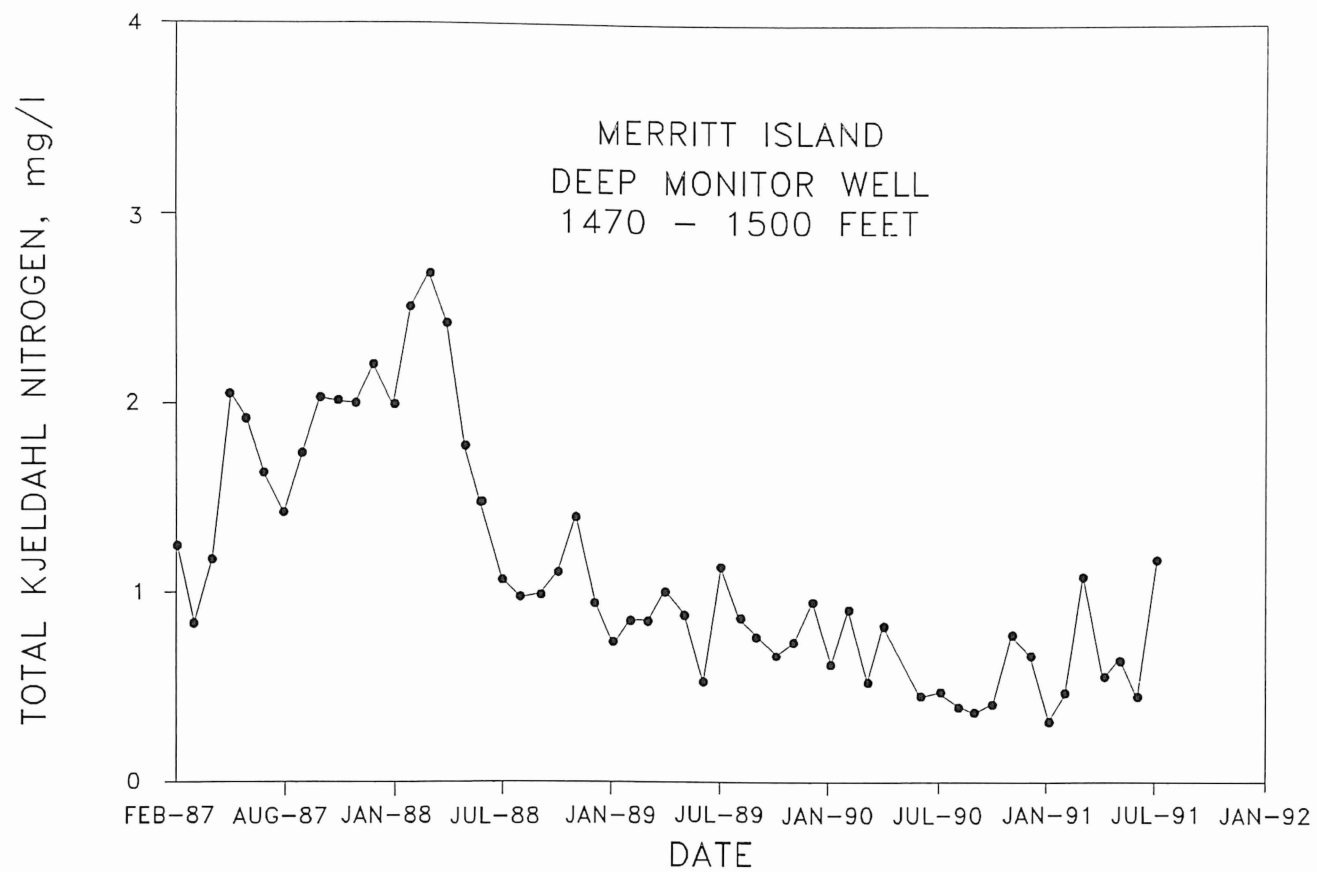


Figure 39. TKN values of the Merritt Island well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

for the chloride plot is 0.92. The TDS value is 0.54, but jumps to 0.74 when the obvious outlying values are removed. For the TKN regression, values from February 1987 to April 1988 were used, to determine the significance of the increase in concentration. The R-squared value for that period is 0.71. These high R-squared values tend to support the interpretation that possibly fractures and the general discontinuous nature of the confining interval have allowed injected fluids to migrate vertically through the confining layer.

South Beaches

The South Beaches injection well has a total depth of 2,916 feet BLS in the Oldsmar Formation. There are two separate monitor wells at the site. The upper Floridan aquifer system well monitors the zone from 300 to 350 feet BLS in the Ocala Limestone, and the lower Floridan aquifer system well monitors from 1,550 to 1,700 feet BLS in the Avon Park Formation (Appendix A2). The confining zone, as defined by Dames and Moore (1985), extends from 1,665 to 2,081 feet BLS in the Avon Park and Oldsmar Formations. The injection zone extends from 2,081 to total depth, but the interval with the most fractures and cavities is from 2,081 to 2,760 feet BLS (Dames and Moore, 1985).

The lower monitor zone, in the lower Avon Park Formation, has interbedded dolostone, mudstone, and wackestone, with porosities ranging from 10 percent to 15 percent, moderate to good induration, and apparently low permeability.

The confining zone, in the lower Avon Park and upper Oldsmar, has interbedded mudstone, wackestone, packstone, and dolostone layers. Porosities range from five percent in a few interbedded cherty layers, to 20 percent in the wackestones and packstones. Both induration and permeability have wide ranges, from low to high in alternating layers. Slickensides related to

fracturing and/or faulting were observed in cores within and above the confining zone.

The background water-quality report (Dames and Moore, 1985) on the lower monitor zone shows that before injection the average TDS value was 23,975 mg/L, and the average chloride value was 14,410 mg/L. In this area TDS values exceed 10,000 mg/L at approximately 1,250 feet BLS. No TKN measurements were taken, but nitrogen, measured as nitrate, was 0.03 mg/L.

Dramatic changes in these values have been observed since injection began in May 1987. TDS fell from over 21,000 mg/L to less than 10,000 mg/L (Figure 40). Chloride values fell from over 16,000 mg/L to less than 5,000 mg/L, starting in July 1987 (Figure 41). These changes are attributed to injection waters rising through the confining units. Values of TKN show a pattern similar to that of the Merritt Island well lower monitor zone. There was a rise from approximately 0.5 mg/L to a peak at about 3.0 mg/L, and then a decline (Figure 42). This is again attributed to the increasing efficiency of the treatment plant at the South Beaches site. It is not known why the values increased rapidly in mid-1991. No trends were observed in the upper monitor zone.

Regression results show an R-squared value of 0.78 for the observed chloride trend, with the value increasing to 0.87 when outliers are removed from the calculations. The R-squared value for the TDS plot is 0.9. Regression of TKN values was done for the period from July 1987 to March 1988, to determine if the increasing concentration trend was significant. The R-squared value for that period is 0.88. These values tend to support the conclusion that the fractures, cavities, and the discontinuous nature of the confining zone have allowed migration of injected fluids into the monitor zone.

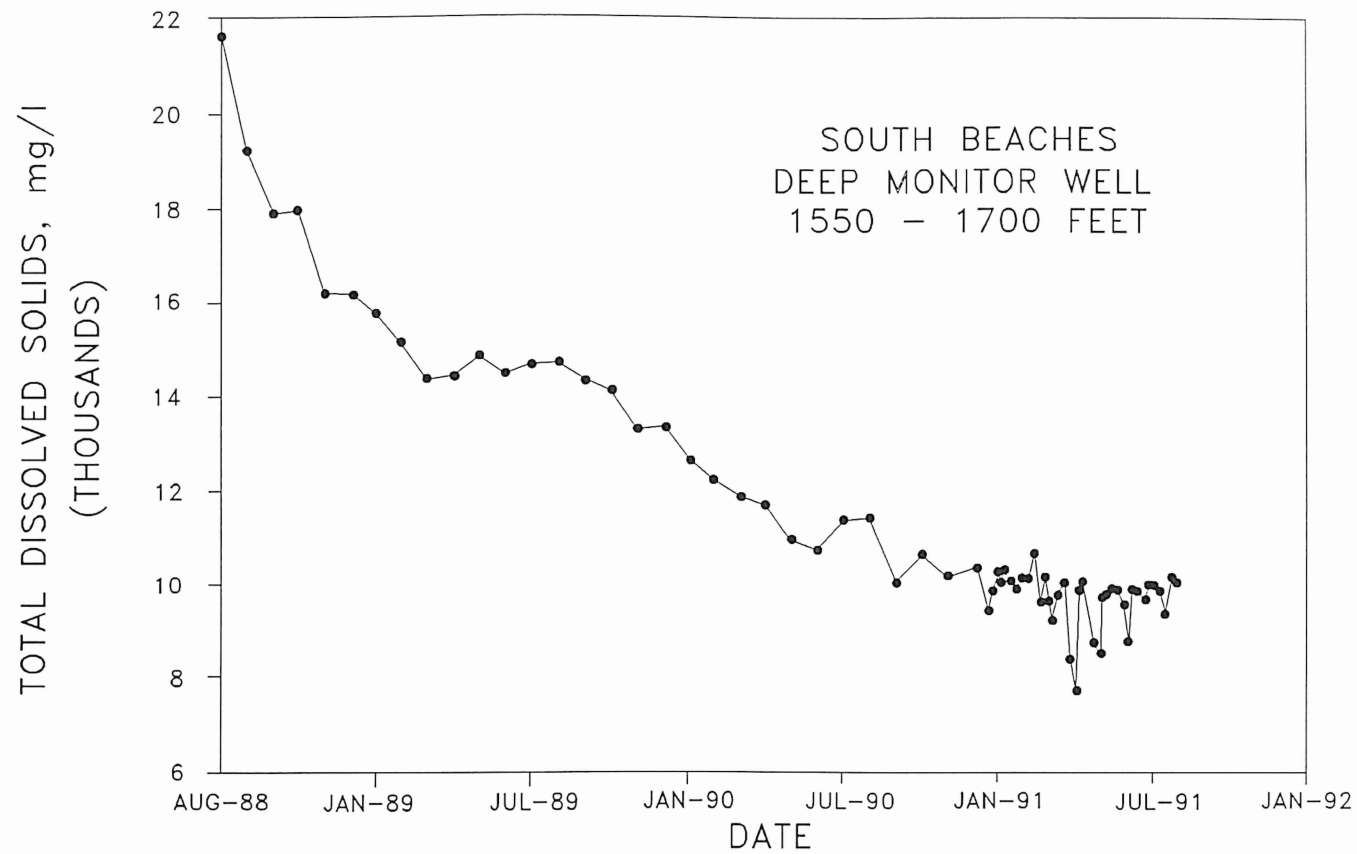


Figure 40. TDS values of the South Beaches well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

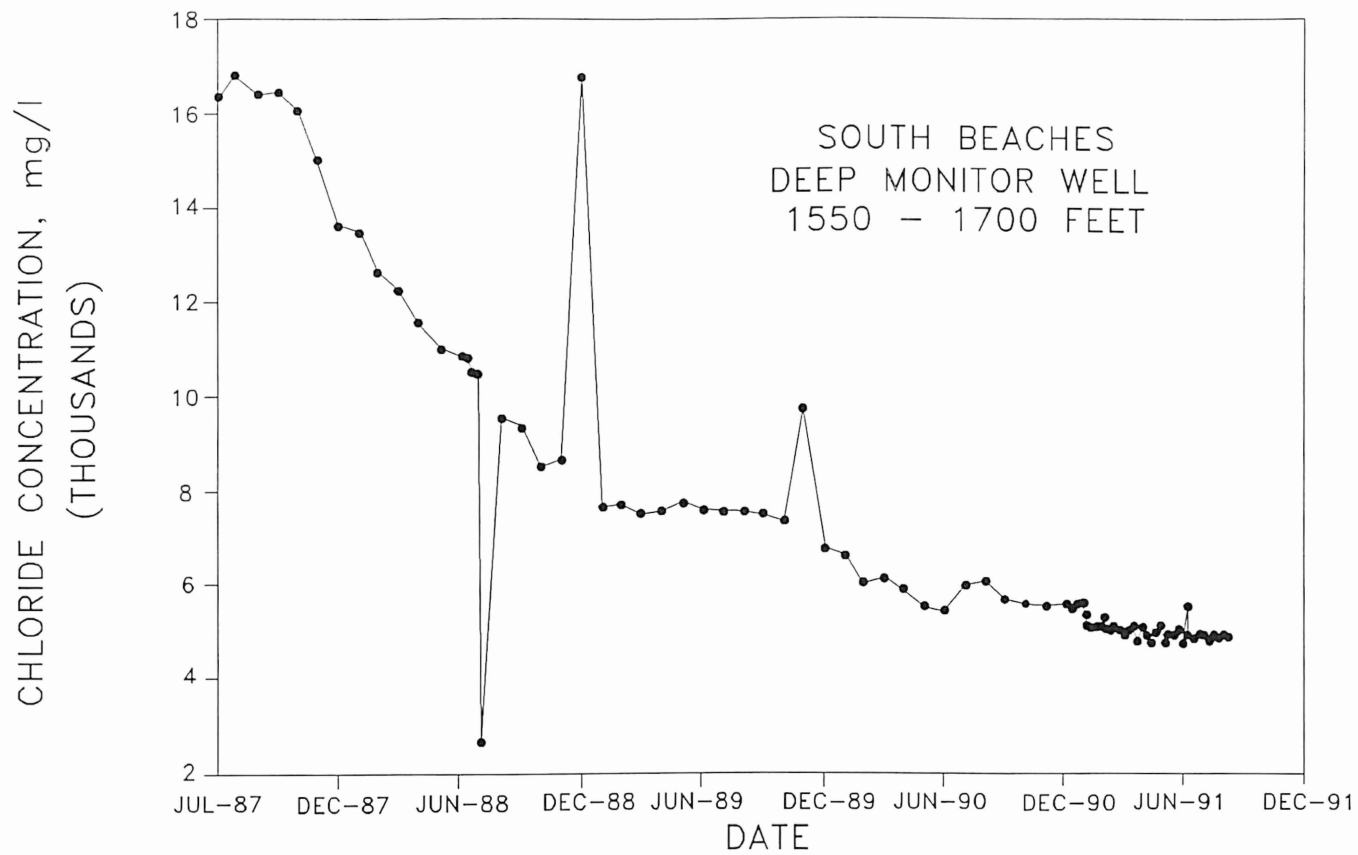


Figure 41. Chloride concentrations of the South Beaches well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

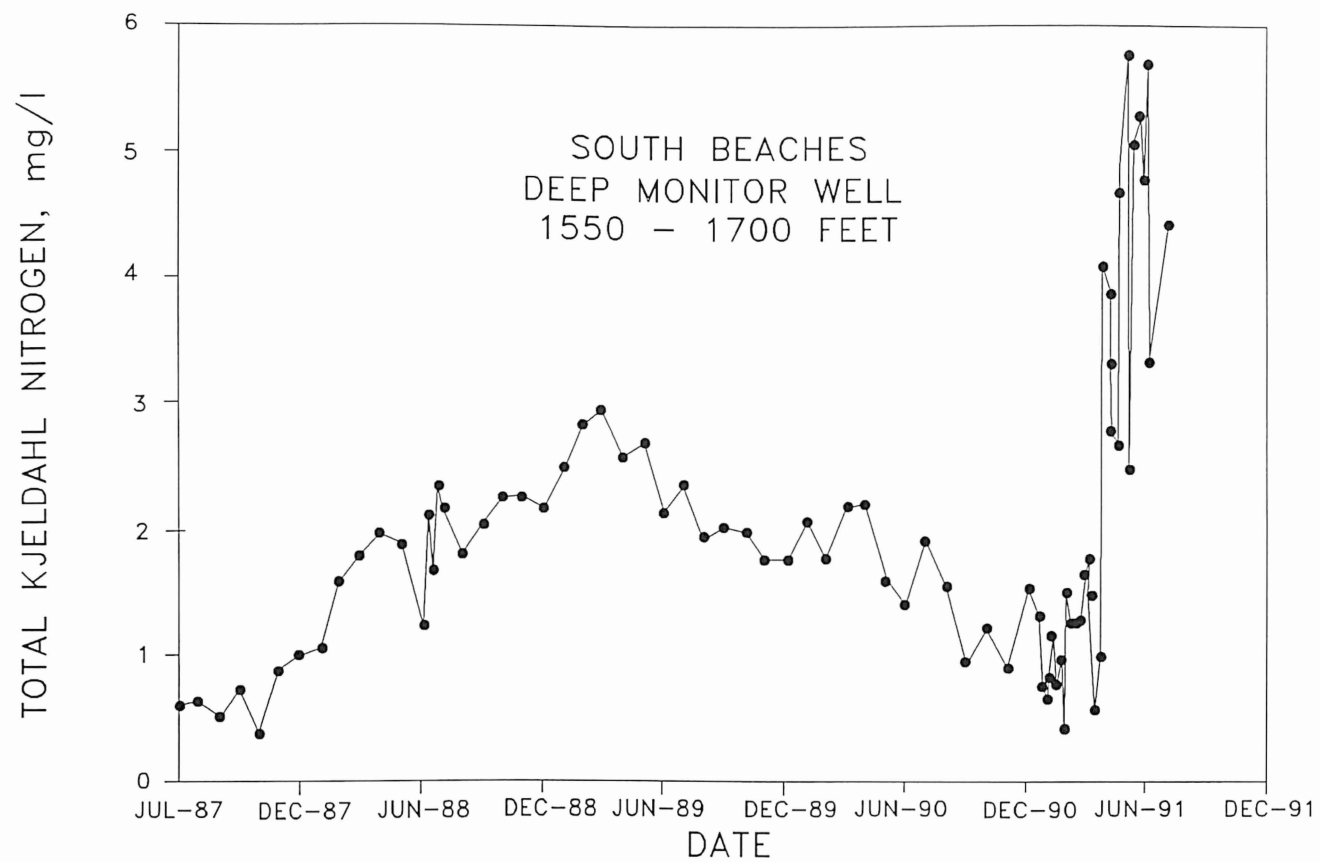


Figure 42. TKN values of the South Beaches well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

D. B. Lee

The D. B. Lee injection well has a total depth of 2,440 feet BLS, in the Oldsmar Formation. There are three separate monitor wells at the site (Appendix A3). The upper well monitors the zone from 1,159 to 1,208 feet BLS in the middle Avon Park Formation. The intermediate well, called the deep well in the Geraghty & Miller, Inc. report (1988), monitors the interval from 1,469 to 1,517 feet BLS in the lower Avon Park Formation. The lower well, called the lower Floridan monitor well, monitors from 1,794 to 1,844 feet BLS in the lower Avon Park Formation. The confining zone, as defined by Geraghty & Miller, Inc. (1988), extends from 1,360 to 2,000 feet BLS, with the principal confining part extending from 1,770 to 2,000 feet BLS. The injection zone extends from 2,000 feet BLS to 2,200 BLS.

The confining zone from 1,770 to 1,934 feet BLS is in dolostone of the lower Avon Park Formation. The interval has 10 percent to 15 percent porosity, good induration, and low permeability. There is a cherty zone from 1,800 to 1,810 feet BLS, and a possible clayey layer from 1,914 to 1,922 feet BLS. The rest of the confining zone, which is in the upper Oldsmar Formation, has more variable lithologies. From 1,934 to 1,944 feet BLS the rock is wackestone with 10 percent to 20 percent porosity, poor to moderate induration, and medium permeability. The interval from 1,944 feet BLS to 1,964 feet BLS is dolostone of 5 percent to 15 percent porosity, moderate to good induration, and low to medium permeability. From 1,964 to 2,001 feet BLS the interval consists of wackestones and packstones of 5 percent to 25 percent porosity, poor to good induration, and low to high permeability.

In addition to the widely varying porosity values and permeabilities of the confining zone, many cavities and fractures were observed on borehole video surveys. For example, on one video covering the interval from 1,638 to 1,805

feet BLS six cavities were observed, including one that extended from 1,793 feet BLS to 1,800 feet BLS. Drilling records indicate a cavern from 1,180-1,225 feet BLS. The cavities may have been enlarged by wash-out during drilling. On the same video, fractures were observed at 1,725 feet BLS, 1,740 feet BLS, 1,770 feet BLS, 1,798 feet BLS, and 1,801 feet BLS. Also, in a report on well tests conducted at the D. B. Lee site, Knapp (1989) notes that the "...sequence from 900 feet to 2,000 feet below land surface is dominated by dolomites (dolostones) with lost circulation and caving zones being prevalent throughout the interval..." and "...excessive drilling problems (lost bits, cement overruns, dredging times, hole stabilization techniques, etc.) were caused by the dense dolomites (dolostones) and cavities encountered in this area...." The interpreted normal fault at approximately 2,100 feet BLS occurs within the injection zone and could explain some of the drilling difficulties encountered here.

The background water-quality report of the lowest monitor zone shows a TDS value of 33,700 mg/L, and a chloride concentration of 17,500 mg/L. No TKN values were reported. TDS values exceed 10,000 mg/L at approximately 1,200 feet BLS.

The D. B. Lee well operated from July 1988 to April 1989, and trends in water-quality data show dramatic changes related to the beginning and ending of injection. Beginning in August 1988, TDS values in the deep monitor well declined from over 27,000 mg/L to under 13,000 mg/L in April 1989 (Figure 43). Values immediately began to increase once injection was stopped. The same kind of pattern was seen in chloride values, where there was a decline from over 11,000 mg/L to under 6,000 mg/L. Values again began to increase when injection stopped (Figure 44). Although there are visible trends on the plots, the data are somewhat scattered, probably due to the irregular injection pattern at the site. There was no background TKN information, but it can be assumed that background values were low, in the 1 mg/L range (J.

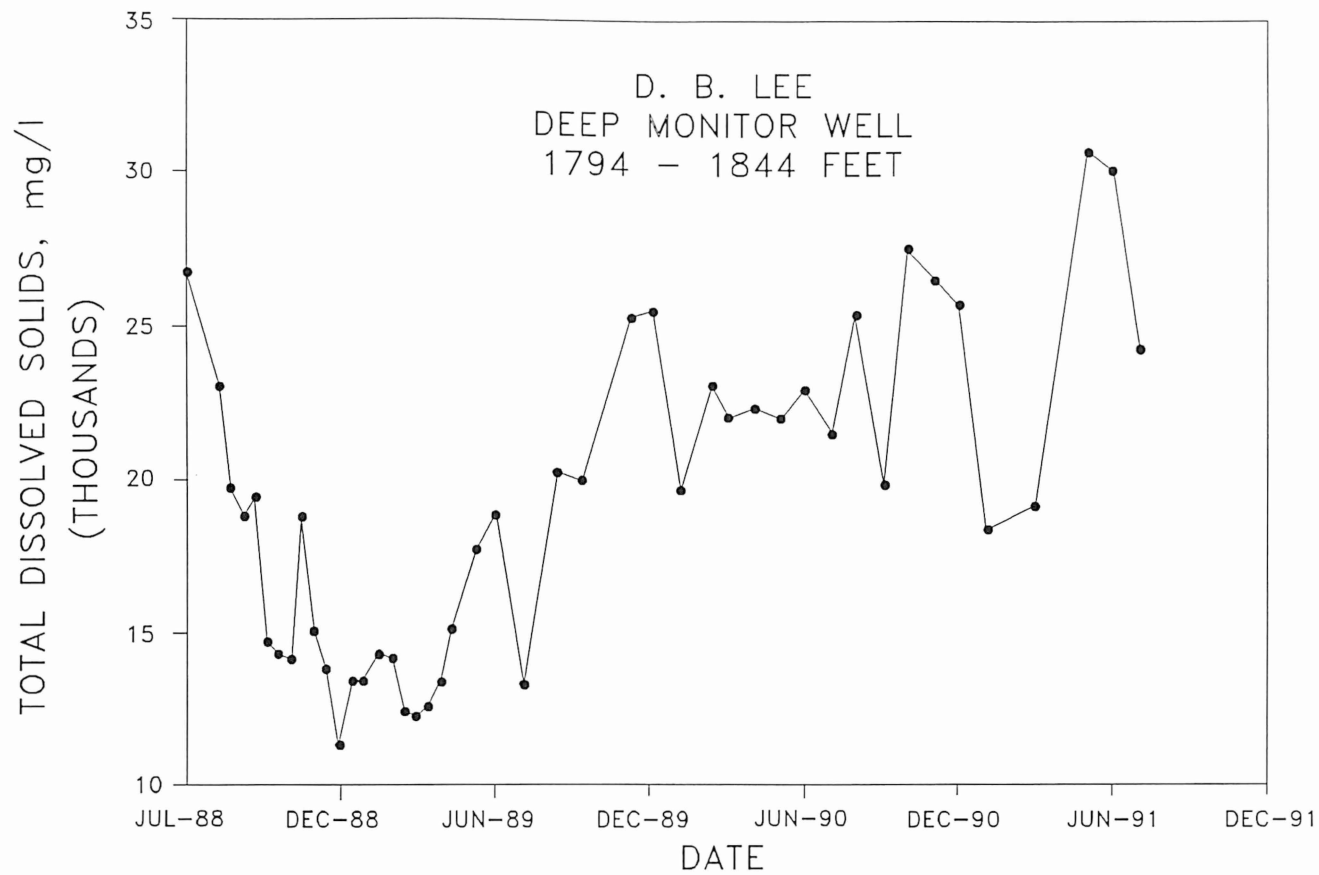


Figure 43. TDS values of the D. B. Lee well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

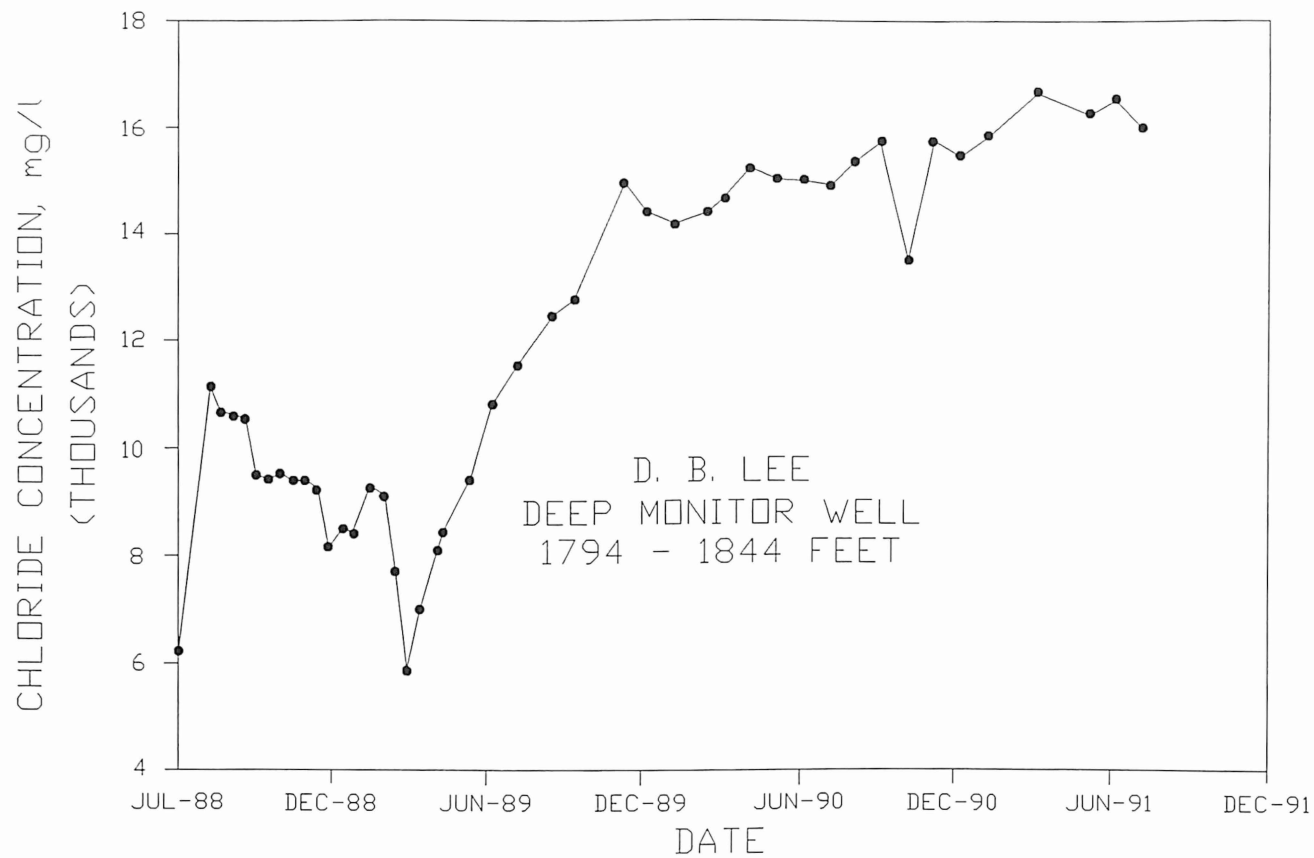


Figure 44. Chloride concentrations of the D. B. Lee well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

Haberfeld, DER, personal communication, 1991). This assumption is consistent with available TKN background values for other injection wells (see, for example, the Merritt Island background water quality section). When injection began, TKN values began to rise from around 4.0 mg/L to about 12.0 mg/L when injection stopped (Figure 45). The anomalous 34 mg/L value is probably due to sampling or analytical error. Values continued to rise for a short time after injection stopped (approximately 2 months), and then began to decline again. These patterns are best explained by rising injection waters and communication between the injection and monitor zones. One reason that the trends in the lower monitor zone are so prominent is that it is within 220 feet of the top of the injection zone.

For the regression analyses, the chloride and TDS divided into two parts. Data collected during injection, from July 1988 to March 1989, comprise the first part, and data collected after injection stopped are in the second part. The R-squared value for TDS values during injection is 0.69, and is 0.51 for the period after injection stopped. The values for chloride are 0.74 for both periods. These values seem slightly low because the patterns of declining and increasing concentrations are readily apparent on the graphs. This is probably due to the scatter of the data, most likely caused by fluctuating injection rates. Regression of TKN data was conducted for the time period from July 1988 to July 1989, to assess the significance of the increasing concentrations values. The R-squared value for this period is 0.93.

The intermediate well water-quality data show trends which indicate rising injection water, though the patterns are somewhat erratic and attenuated. In particular, chloride values decreased from a high of approximately 16,000 mg/L to a low of approximately 10,000 mg/L during injection, and increased after injection stopped.

The upper monitor well water-quality data show patterns that indicate increasing salinity. These patterns are most likely related to rising formation water, displaced upwards by injection water. TDS values increased from about 8,000 mg/L to over 17,000 mg/L and chloride concentrations increased from about 4,000 mg/L to a high of almost 14,000 mg/L just before injection stopped. Concentrations then dropped and fluctuated around 9,000 mg/L. TKN values increased from about 1 mg/L to over 12 mg/L.

The changing ground-water chemistry observed in all three monitor zones indicates that the existence of a coherent confining zone in this area is highly questionable. Knapp (1989) concluded that there is "...inadequate information to determine if a confining sequence exists between 1,900 and 2,000 feet below land surface..." and the report confirms the freshening trends seen in the deep and intermediate monitor zones and the increasing salinity of the upper monitor zone during injection (Knapp, 1989). He also concluded, "The rate of change in the water quality indicates that there is a direct conduit from the injection zones into the monitor zones."

Secondary Wells

Harris Corporation

There are two injection wells at the Harris Corp. site, one with a total depth of 2,800 feet BLS and the other completed at 2,333 feet BLS, both in the Oldsmar Formation. The confining zone, as defined by Geraghty & Miller, Inc. (1984), extends from 1,362 to 2,030 feet BLS, in the lower Avon Park and upper Oldsmar Formations. The major injection interval in both wells is from 2,030 to 2,245 feet BLS (Appendix A4). There is a dual zone monitor well at the site, with the upper zone monitoring the interval from 430 to 550 feet BLS in the lower Ocala Limestone and upper Avon Park Formation, and the lower monitor zone extending from 1,527 to 1,535 feet BLS in the lower Avon Park Formation.

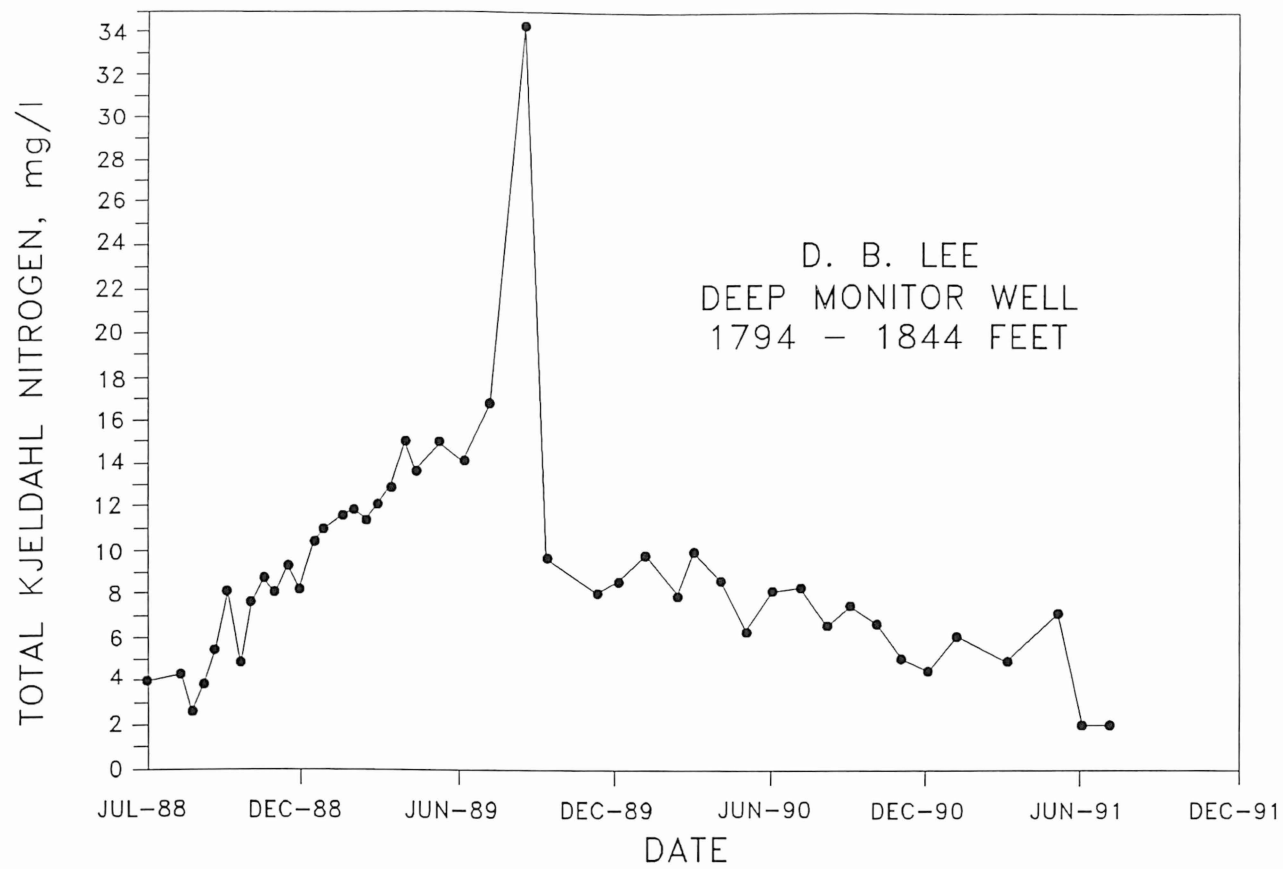


Figure 45. TKN values of the D. B. Lee well deep monitor zone (data from the DER Bureau of Drinking and Groundwater Resources).

As in the three primary wells, the confining zone in this area contains alternating layers of mudstone, wackestone, packstone and dolostone, with widely varying porosity values and permeabilities, and moderate to good induration (Appendix A4 and Plates 1, 2, & 3). Fractures were observed in core from 1,904 to 1,912 feet BLS.

The background water-quality report (Geraghty & Miller, Inc., 1984) shows that the ambient conditions at the level of the deep monitor zone, before injection began in August 1986, were as follows: TDS = 31,000 mg/L, chloride = 17,000 mg/L, and TKN = <0.04 mg/L. The 10,000 mg/L boundary occurs at approximately 1,200 feet BLS.

Deep monitor zone water-quality data show trends similar to those seen in the three primary wells, though the patterns are more erratic. TDS values declined from over 31,000 mg/L in 1986 to under 25,000 mg/L in 1991, and chloride concentrations declined from over 18,000 mg/L to under 13,000 mg/L in the same period. The more erratic patterns of decline may be due to the variable rates of injection at the site. Injection volumes commonly vary by tens-of-millions of gallons from month-to-month. TKN values did increase to over 2 mg/L by mid-1991, but the trend is not very dramatic. No trends were discernible in the upper monitor zone data.

Grant Street

The Grant Street well has a total depth of 2,700 feet BLS in the Oldsmar Formation. The main confining zone, as defined by Hydro Designs (1989), is from 1,815 to 2,050 feet BLS in the lower Avon Park and upper Oldsmar Formations. The major injection interval extends from 2,035 to 2,700 feet BLS in the Oldsmar Formation (Appendix A5). There are two separate monitor wells at the site. The upper well monitors from 1,100 to 1,150 feet BLS in the upper Avon Park Formation, and the lower well monitors from 1,594 to 1,644 feet BLS in the lower Avon Park Formation.

The confining zone can be divided into two broad categories. The upper section, from 1,815 to 1,880 feet BLS, is predominantly dolostone, with interbedded wackestones and packstones (Appendix A5). Permeabilities are generally low, and porosity ranges from five to ten percent. Induration is generally good. The lower section, from 1,880 to 2,050 feet BLS, is composed mainly of packstone, with a few interbedded wackestone and thin dolostone beds. Permeabilities are generally high, porosity ranges from 15 to 35 percent, and induration is poor to moderate.

The background water-quality report for the lower monitor zone shows a TDS value of 23,600 mg/L, a chloride concentration of 850 mg/L, and a TKN value of 0.5 mg/L (Hydro Designs, 1989). These values appear to be slightly low, because Florida DER monitoring data (unpublished data, 1991) show initial values that start higher than those quoted in the Hydro Designs report. Further examination of the water-quality report indicated that the samples for the background readings were taken soon after the well was developed, and ambient conditions were probably not reestablished at that time. TDS values exceed 10,000 mg/L at approximately 1,250 feet BLS.

Injection began in April 1989. The water-quality data show trends at this site, but the magnitudes of changes are not as great as at other wells. TDS values decline in a somewhat irregular manner from just over 27,000 mg/L in mid-1989 to around 17,000 mg/L in 1991. Chloride concentrations show a small but fairly steady decline from over 16,000 mg/L in 1989 to below 13,000 mg/L in 1991. TKN values increased from 2.0 mg/L in 1989 to a high of about 10.0 mg/L in 1990, and then declined to about 5.0 mg/L by mid-1991.

Data from the upper monitor well show increases consistent with rising formation waters. Background analyses showed a chloride concentration of 215 mg/L, a TDS value of 2.5

mg/L, and a TKN value of 2.3 mg/L (again, probably low because the analysis was conducted soon after well development). After injection started in April 1989, chloride values rose from about 900 mg/L to over 1,800 mg/L in 1991. TDS values increased from 1,600 mg/L to about 3,200 mg/L. TKN values were very erratic.

Port Malabar

The Port Malabar injection well has a total depth of 3,009 feet BLS in the Oldsmar Formation. The confining zone, defined by CH2M Hill (1987) as an "intra-aquifer low permeability zone," extends from 1,300 to 2,050 feet BLS. The injection zone extends from 2,050 feet to 2,300 BLS (Appendix A6). The dual zone monitor well at the site has an upper monitor zone from 400 to 472 feet BLS in the lower Ocala Limestone and upper Avon Park Formation, and a lower monitor zone from 1,534 to 1,630 feet BLS in the lower Avon Park Formation.

The confining zone from 1,300 to 1,470 feet BLS is predominantly wackestone, with a few interbedded packstone layers (Appendix A6). Porosity ranges from 10 percent to 25 percent and permeability generally appears to be high. In this interval, the rocks are moderately indurated. From 1,470 to 1,640 feet BLS the rocks are interbedded dolostones, mudstones and wackestones. Porosity in the mudstones and dolostones ranges from 5 to 15 percent. The dolostones are well indurated and have low permeability, and the mudstones are poorly to moderately indurated and have low permeability. The wackestones are moderately indurated, generally have high permeability, and porosity ranges from 15 to 20 percent. From 1,640 to 1,880 feet BLS dolostone is the dominant rock, and there are several zones where chert is thinly interbedded. Porosity in this interval is five percent to 15 percent, permeability is low, and induration is good. From 1,880 to 2,050 feet BLS the rocks are interbedded dolostones, wackestones, and packstones. In the dolostones porosity ranges

from five percent to 15 percent, permeability is low, and induration is good. The wackestones and packstones have porosities ranging from 15 percent to 20 percent, generally high permeability, and are moderately indurated.

The only background water-quality information available for the lower monitor zone is a chloride concentration of approximately 10,890 mg/L (CH2M Hill, 1987). The 10,000 mg/L TDS boundary occurs at approximately 1,450 feet BLS.

Injection at this site started in August 1987. In general, the plots for TDS, chloride, and TKN are irregular, and it is difficult to see any trends. Chloride values drop from a high of over 13,000 mg/L in late 1987, stabilizing around 10,000 mg/L from late 1988 to early 1990. The values increase after early 1990. TDS data are available only from 1989 to the present. The values peak in late 1989 around 25,000 mg/L, and drop off to about 19,000 mg/L in mid-1991. The shallow monitor zone water-quality data do not show any significant trends. In this area available data cannot be used to determine conclusively if vertical migration of injection water has occurred.

West Melbourne

The West Melbourne injection well has a total depth of 2,409 feet BLS in the Oldsmar Formation. The confining interval, as defined by CH2M Hill (1986), extends from 1,600 to 1,980 feet BLS in the lower Avon Park Formation. The injection zone extends from 1,980 to 2,409 feet BLS with the main injection interval extending from 2,000 to 2,200 feet BLS in the Oldsmar Formation (Appendix A7). The monitor zones are a part of the injection well annulus, with an upper zone from 1,234 to 1,306 feet BLS, and a lower zone from 1,410 to 1,450 feet BLS, both in the middle Avon Park Formation.

From 1,600 to 1,840 feet BLS the confining zone as defined by CH2M Hill is dolostone with porosity ranging from five percent to 30 percent,

depending on the degree of dolomitization. The interval is generally well indurated (Appendix A7). From 1,840 to 1,980 feet BLS the dominant lithologies are interbedded wackestones and packstones with 10 percent to 25 percent porosity and moderate induration. No permeability estimates are available for this interval.

Background water-quality data (CH2M Hill, 1986), taken while the well was being drilled, show a chloride value of approximately 3,500 mg/L at the level of the lower monitor zone. A packer test at the interval from 1,426 to 1,436 feet BLS in the lower monitor zone, shows an average TDS value of 10,150 mg/L. The 10,000 mg/L TDS boundary in this area occurs at approximately 1,450 feet BLS.

Injection at this site started in November 1986. Lower monitor zone water-quality data show a slight increase in TDS from 2,000 mg/L in mid-1989, when TDS data were first collected, to 5,000 mg/L in early 1991. There is then a jump to over 11,000 mg/L by mid-1991. Note that the initial TDS values taken in 1989 are markedly lower than the background value of 10,150 mg/L taken in 1986. Water in the monitor zone could have experienced freshening between 1986 and 1989, before the increase in salinity in 1989 to 1991. More likely, the background value is erroneous because it was taken during drilling when ambient conditions would have been disrupted.

Chloride values hold steady around 1,000 mg/L from late-1986 to mid-1989, and then increase to 5,000 mg/L by mid-1991. The initial Florida DER values are again lower than the background readings. However, the increase in chloride concentrations from mid-1989 to 1991 does correspond to the increase in TDS values, indicating that saline formation water is being displaced upwards by injected water.

Hercules, Inc.

The Hercules injection well has a total depth of 3,005 feet BLS in the Oldsmar Formation.

The confining interval, defined by CH2M Hill (1979), is from 1,500 to 2,400 feet BLS in the lower Avon Park and upper Oldsmar Formations. The main injection zone extends from 2,378 to 2,930 feet BLS in the Oldsmar Formation (Appendix A8). There is a separate multizone monitor well with four zones: 1) the upper Floridan, from 466 to 591 feet BLS in the Ocala Limestone, 2) the middle Floridan, from 880 to 931 feet BLS in the upper Avon Park Formation, 3) the lower Floridan, from 1,387 to 1,451 feet BLS in the middle Avon Park Formation, and 4) the primary, extending from 1,905 to 1,963 feet BLS in the lower Avon Park Formation.

The confining zone, as defined by CH2M Hill, from 1,500 to 1,900 feet BLS is primarily packstone, with a few interbedded dolostone layers. The porosity of this section ranges from 20 to 35 percent. The section is generally moderately indurated, and permeability is estimated to be high. From 1,900 to 2,300 feet BLS dolostone dominates, with scattered wackestone and packstone interbeds. Porosity ranges between two percent and 10 percent in the dolostone, and between 15 percent and 25 percent in the interbeds. The section is well indurated and appears to have low permeability. From 2,300 to 2,400 feet BLS wackestones and packstones of 20 percent to 25 percent porosity, moderate induration and medium permeability dominate.

Background water-quality data show that in the primary monitor zone the chloride concentration was 17,350 mg/L, and in the lower Floridan monitor zone it was 4,490 mg/L. A packer test in the interval from 1,949 to 1,959 feet BLS in the primary monitor zone showed values of 17,600 mg/L for chloride, and 28,200 mg/L for TDS.

Injection at the site started in November 1979. However, collection of data on TDS and TKN for the primary monitor zone didn't begin until 1990, and no patterns are discernible. Chloride concentration data fluctuates between 17,000 and

21,000 mg/L for the period from 1979 to 1991. Interestingly, chloride data for the lower Floridan monitor zone do show a pattern. From 1979 to 1987 values fluctuate between 2,000 and 4,000 mg/L, but then concentrations increase steadily to over 12,000 mg/L by mid-1991, indicating displaced formation water. Again, TDS and TKN data were not collected until 1990, and no patterns are observed. Data for the middle and upper Floridan monitor zones also show no patterns.

DISCUSSION AND CONCLUSIONS

The geologic framework of the lower Floridan aquifer system in Brevard County embodies a shallow water carbonate platform sequence, the character of which has been determined by a diversity of factors including depositional environment, diagenesis, and geologic structure. Variations in these components can result in considerable differences in local lithofacies, porosity, permeability, and hydrogeologic character of the aquifer.

Ground-water chemistry trends for several injection wells indicate that injected waste liquids are migrating upward through the "confining" rocks immediately above the injection zones. Since apparently low permeability dolostones are common in the "confining" sequence,

injected waste waters are probably moving vertically along fractures and possibly along fault planes where present. Fractures commonly observed in borehole cores and videos justify this supposition. Faults, however subtle and small scale, can enhance fracture-related permeability locally and serve as conduits for vertical fluid migration. If injected waste fluids migrate preferentially upward along dissolutionally enlarged fault planes, conceptually, the fault could effectively mask contamination detection in monitor wells depending on the location of the monitor zone relative to the fault.

A more satisfactory understanding of the lower Floridan aquifer system in Brevard County can only be achieved by further study accompanied by the acquisition of additional data. Thorough coring of strata overlying injection zones is highly desirable so that lithofacies and hydrologic characteristics can be adequately detailed. A seismic survey program should be considered in order to identify and map the extent of possible faulting in proximity to current and proposed injection well sites. Because of their value to subsurface geological evaluations, borehole videos and complete geophysical log suites (including gamma-ray, sonic, and neutron-density) should be run over the entire borehole of future injection and monitor wells.

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APPENDICES

APPENDIX A: HYDROGEOLOGIC SUMMARIES OF INJECTION WELL SITES

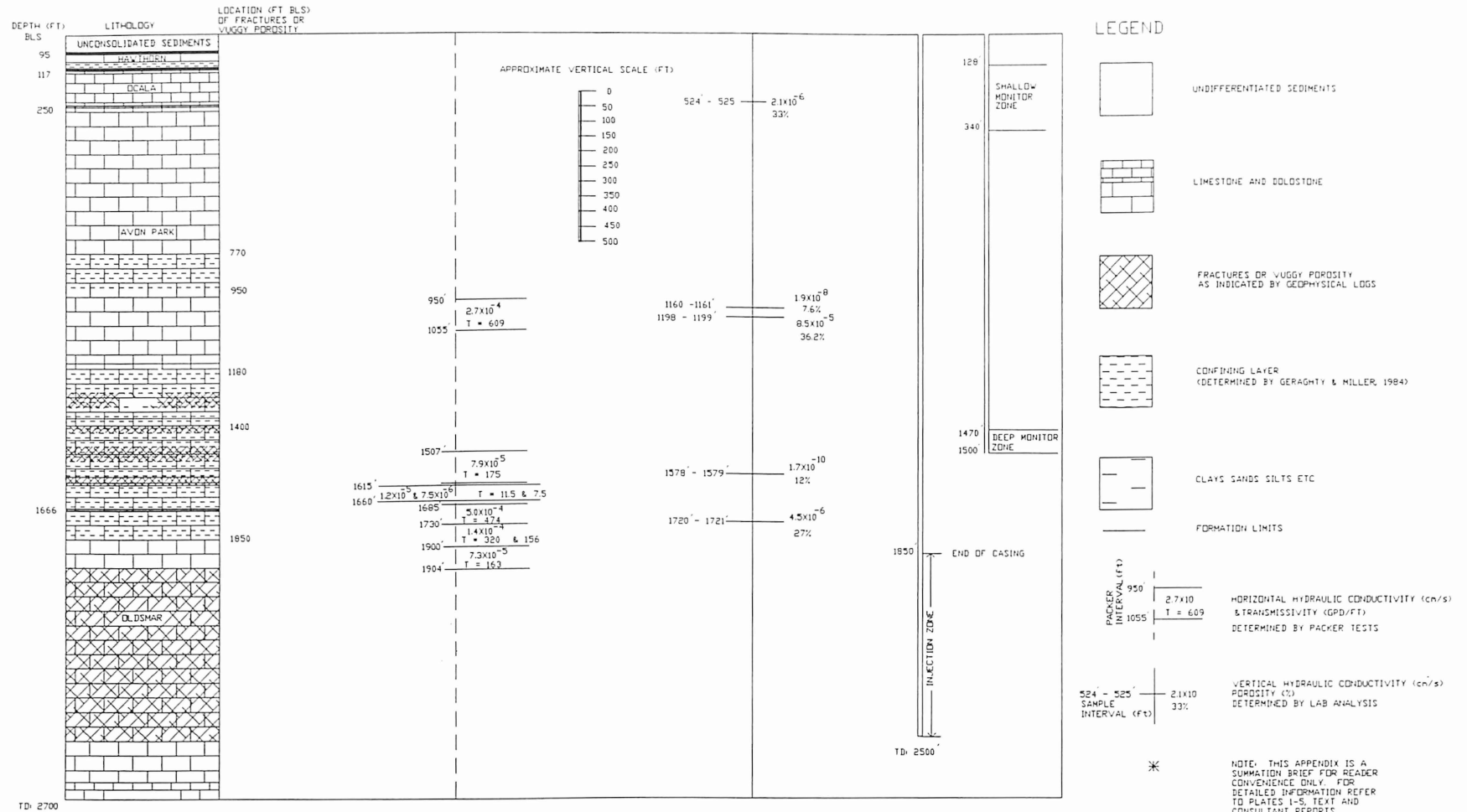
- A1. Merritt Island Injection Well, W-16226*
- A2. South Beaches Injection Well, W-15890
- A3. D. B. Lee Injection Well, W-30016
- A4. Harris Corporation Injection Well #2, w-15944
- A5. Grant Street Injection Well, W-16297
- A6. Port Malabar Injection Well, W-16133
- A7. West Melbourne Injection Well, W-15961
- A8. Hercules, Inc. Injection Well, W-14167

*FGS Well file numbers; detailed lithographic descriptions are on file and available from the FGS.

APPENDIX A1

* HYDROGEOLOGIC SUMMARY OF MERRITT ISLAND INJECTION WELL

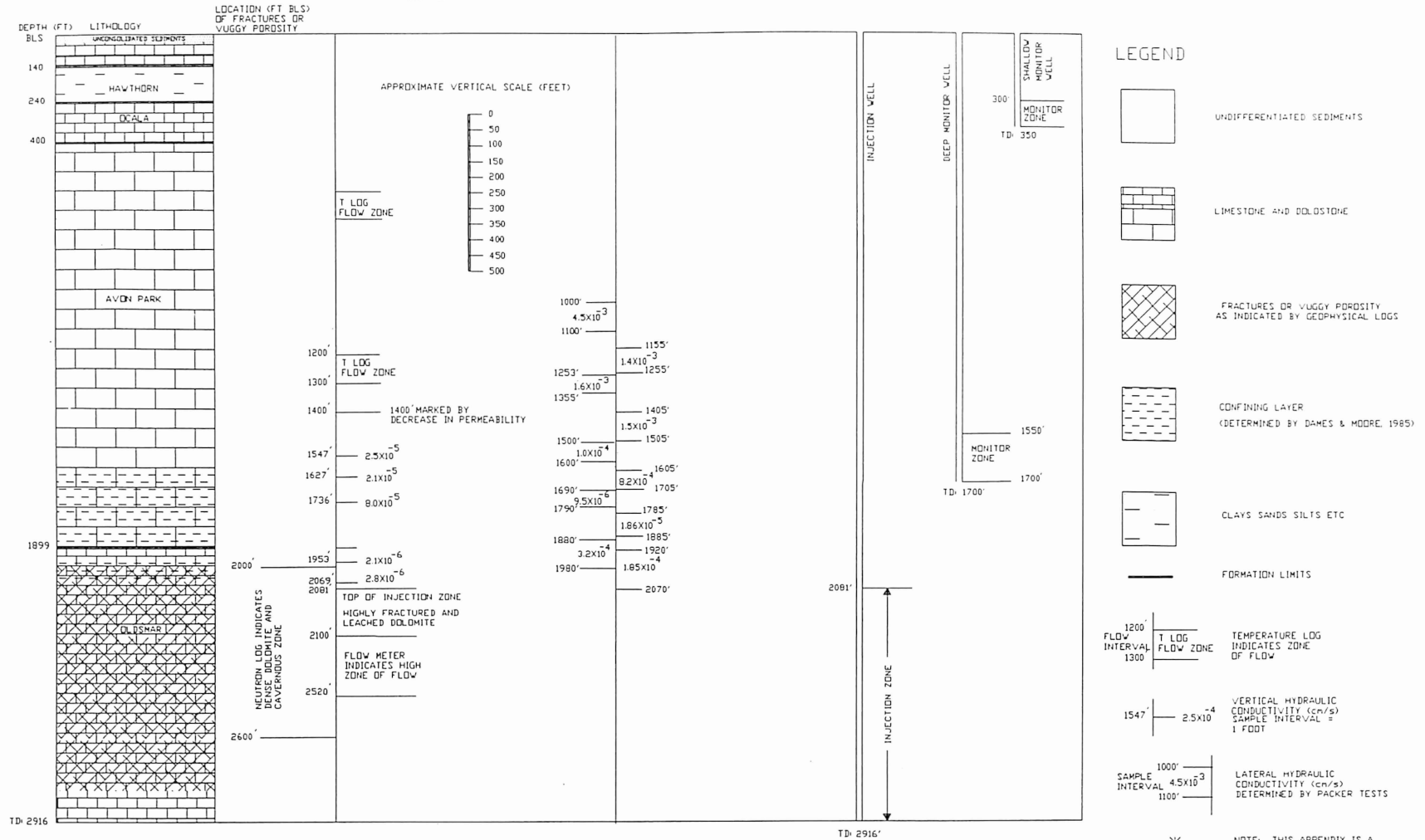
HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM GERAGHTY & MILLER, INC. (1984)
LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)



APPENDIX A2

*HYDROGEOLOGIC SUMMARY OF SOUTH BEACHES INJECTION WELL

HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM DAMES & MOORE (1985)
LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)

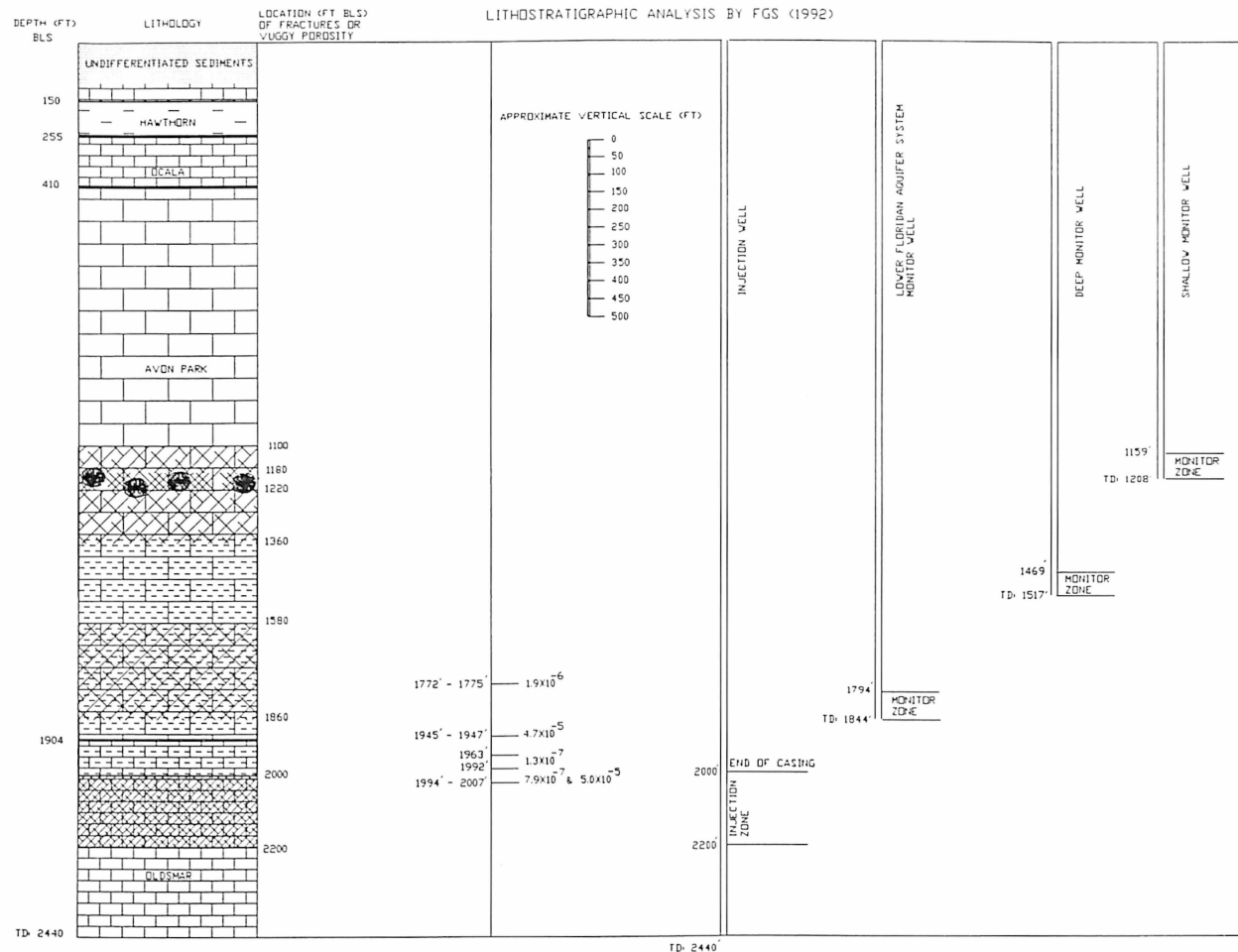


APPENDIX A3

*HYDROGEOLOGIC SUMMARY OF D. B. LEE INJECTION WELL

HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM GERAGHTY & MILLER, INC. (1988)

LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)



LEGEND



UNDIFFERENTIATED SEDIMENTS



LIMESTONE AND DOLOSTONE



FRACTURES OR VUGGY POROSITY
AS INDICATED BY GEOPHYSICAL LOGS



CAVERNOUS ZONE



CONFINING LAYER
(DETERMINED BY GERAGHTY & MILLER, 1988)



CLAYS SANDS SILTS ETC



FORMATION LIMITS

1772' - 1775'
SAMPLE
INTERVAL
(FEET)

1.9×10^{-6}

VERTICAL HYDRAULIC CONDUCTIVITY (cm/s)
DETERMINED FROM LABORATORY
ANALYSIS

*

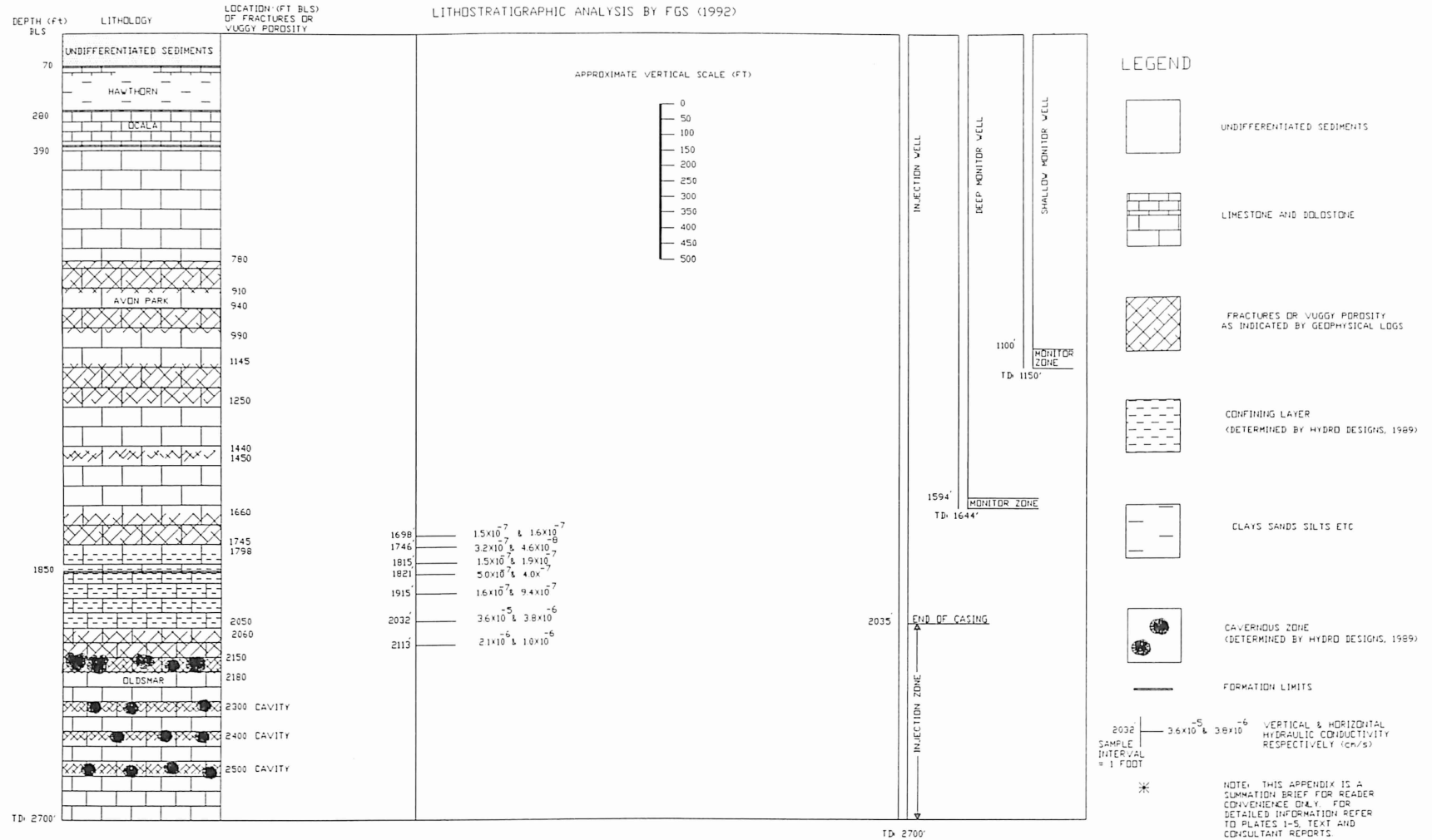
NOTE: THIS APPENDIX IS A
SUMMARY BRIEF FOR READER
CONVENIENCE ONLY. FOR
DETAILED INFORMATION REFER
TO PLATES 1-5, TEXT AND
CONSULTANT REPORTS.

APPENDIX A5

* HYDROGEOLOGIC SUMMARY OF GRANT STREET INJECTION WELL

HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM HYDRO DESIGNS (1989)

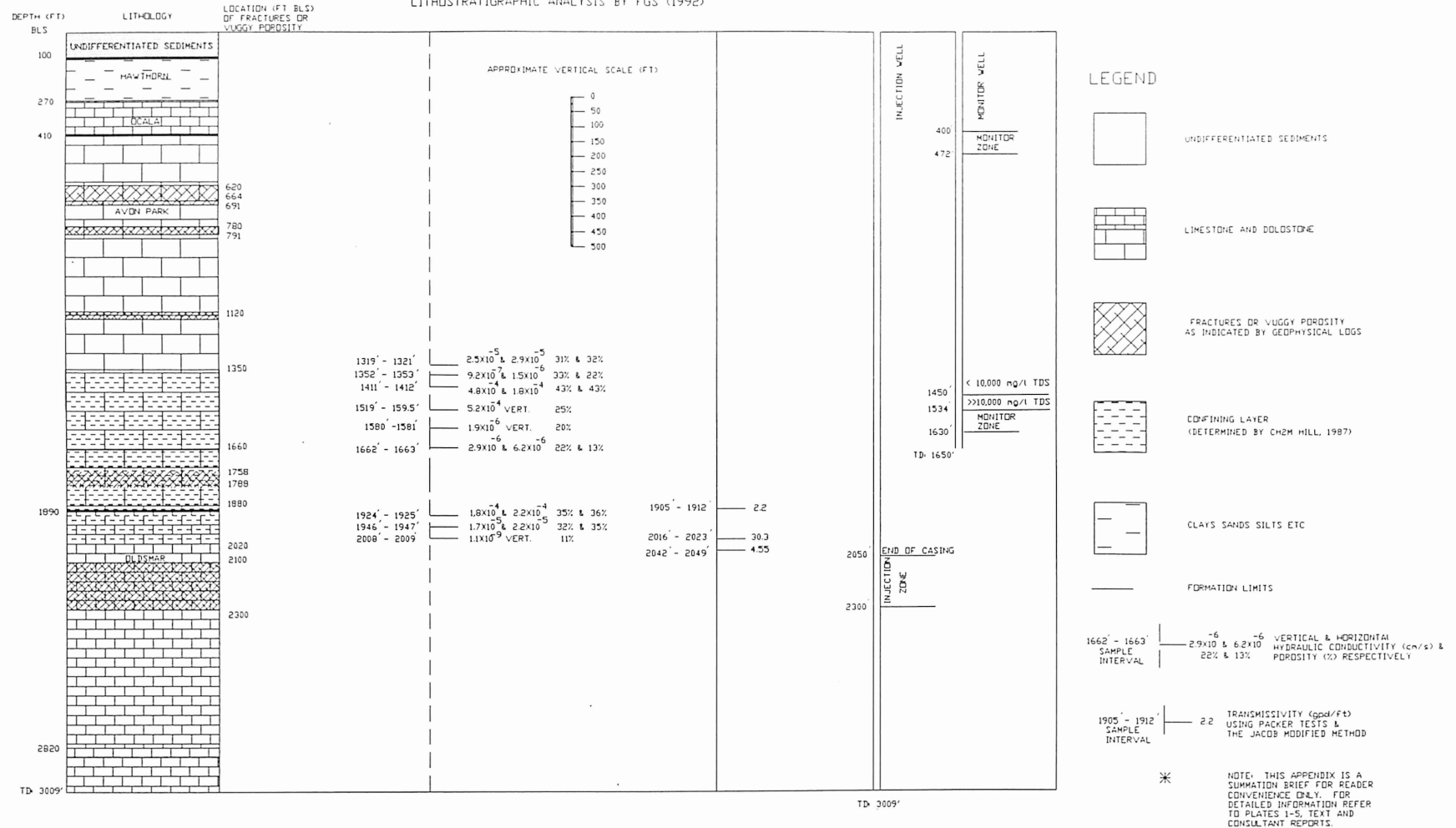
LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)



APPENDIX A6

* HYDROGEOLOGIC SUMMARY OF PORT MALABAR INJECTION WELL

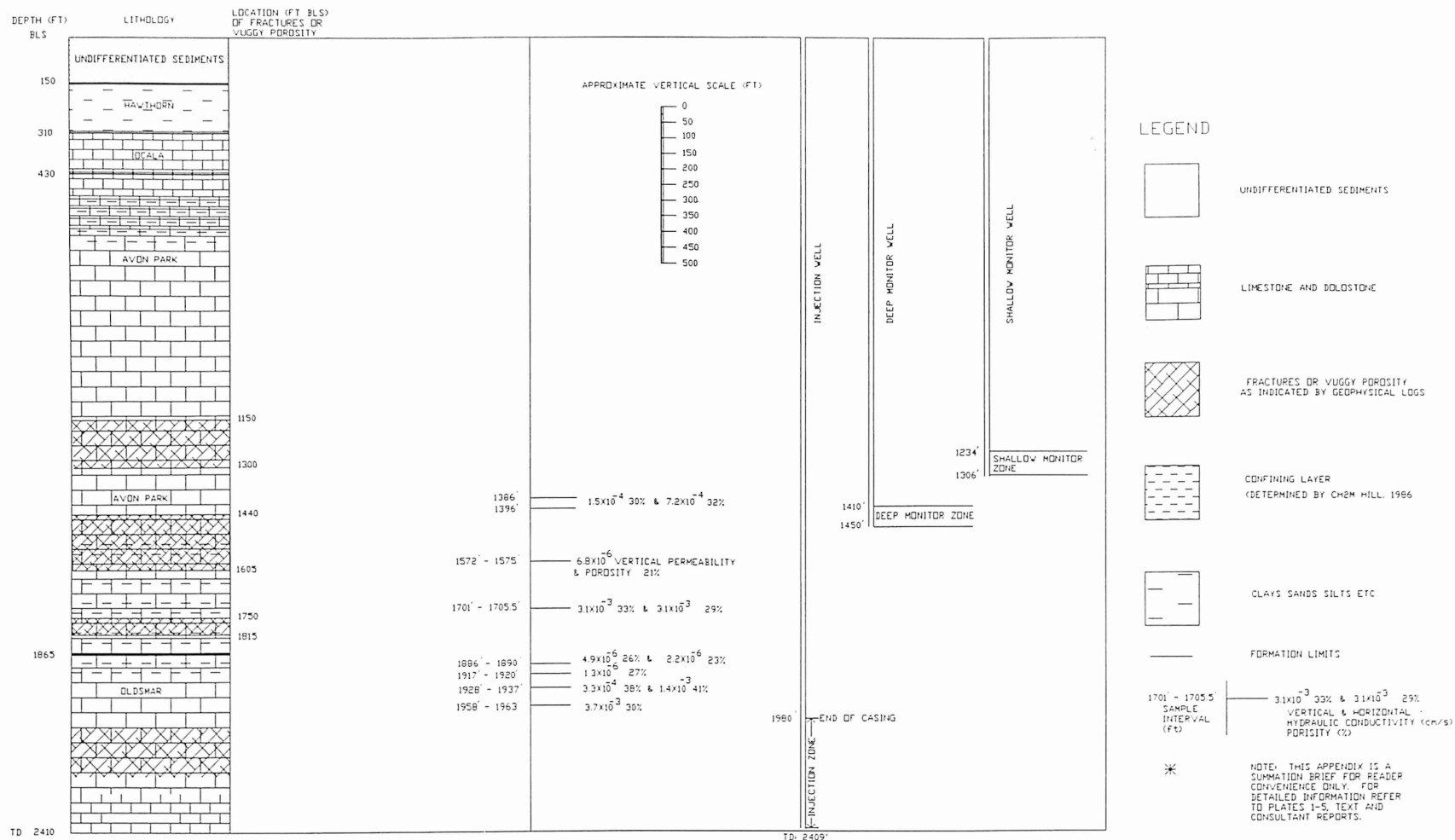
HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM CH2M HILL (1987)
LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)



APPENDIX A7

* HYDROGEOLOGIC SUMMARY OF WEST MELBOURNE INJECTION WELL

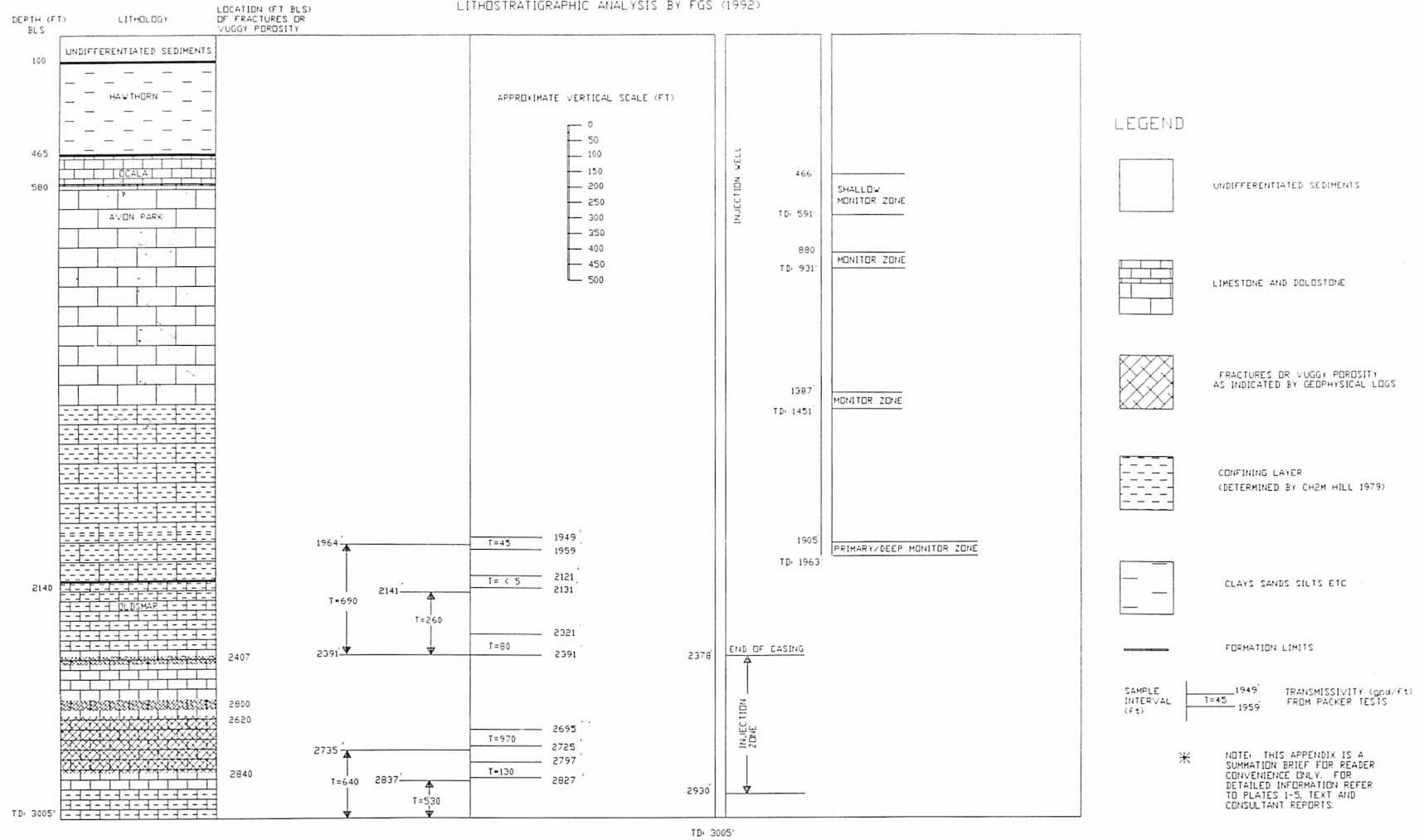
HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM CH2M HILL (1986)
LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)



APPENDIX A8

* HYDROGEOLOGIC SUMMARY OF HERCULES INC INJECTION WELL

HYDROLOGICAL AND GEOPHYSICAL ANALYSIS FROM CH2M HILL (1979)
LITHOSTRATIGRAPHIC ANALYSIS BY FGS (1992)



PLATES TO ACCOMPANY
FLORIDA GEOLOGICAL SURVEY BULLETIN NO. 64
GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM,
BREVARD COUNTY, FLORIDA

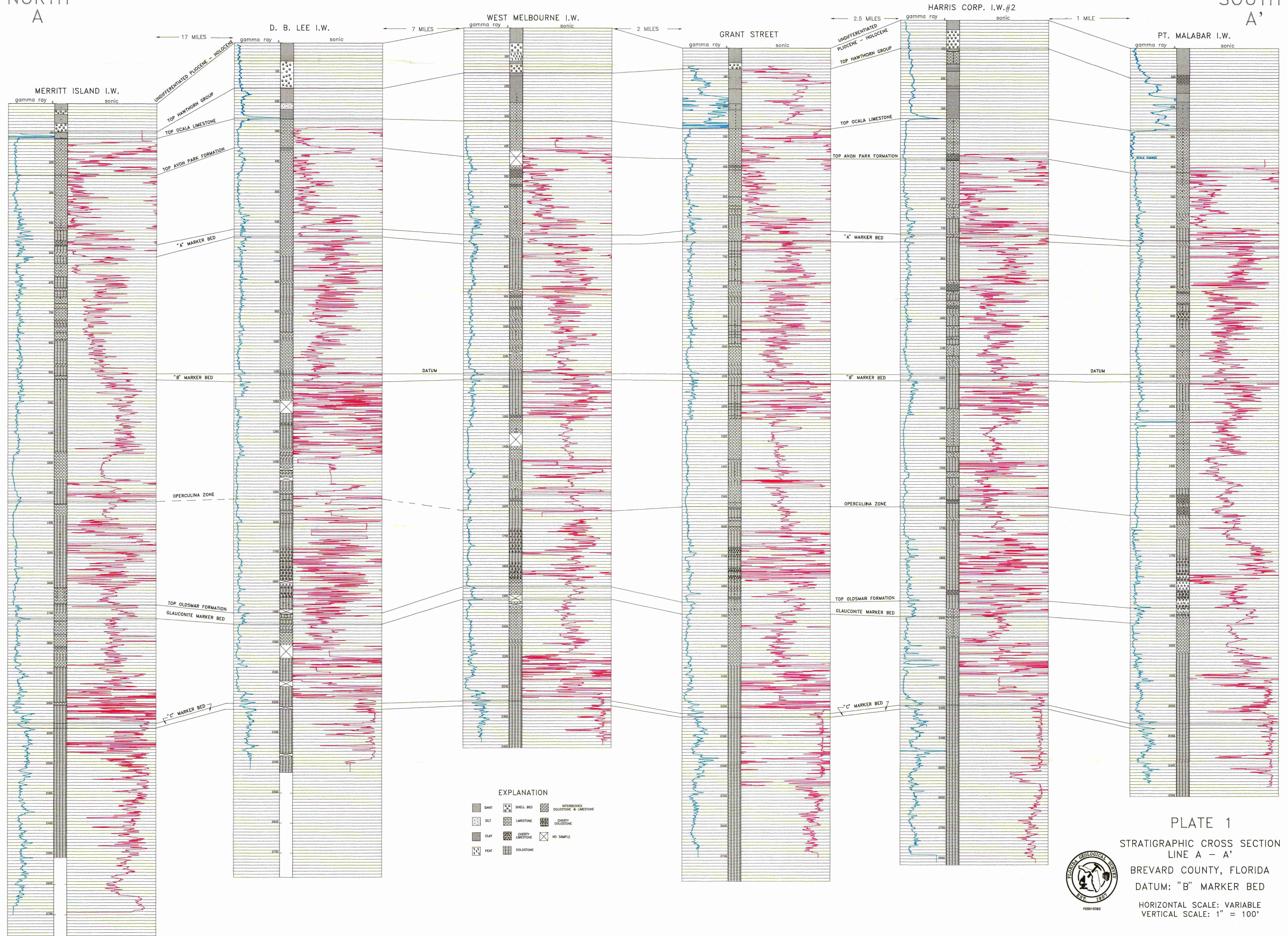
by

Joel G. Duncan, William L. Evans, III and Koren L. Taylor

GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM, BREVARD COUNTY, FLORIDA

By

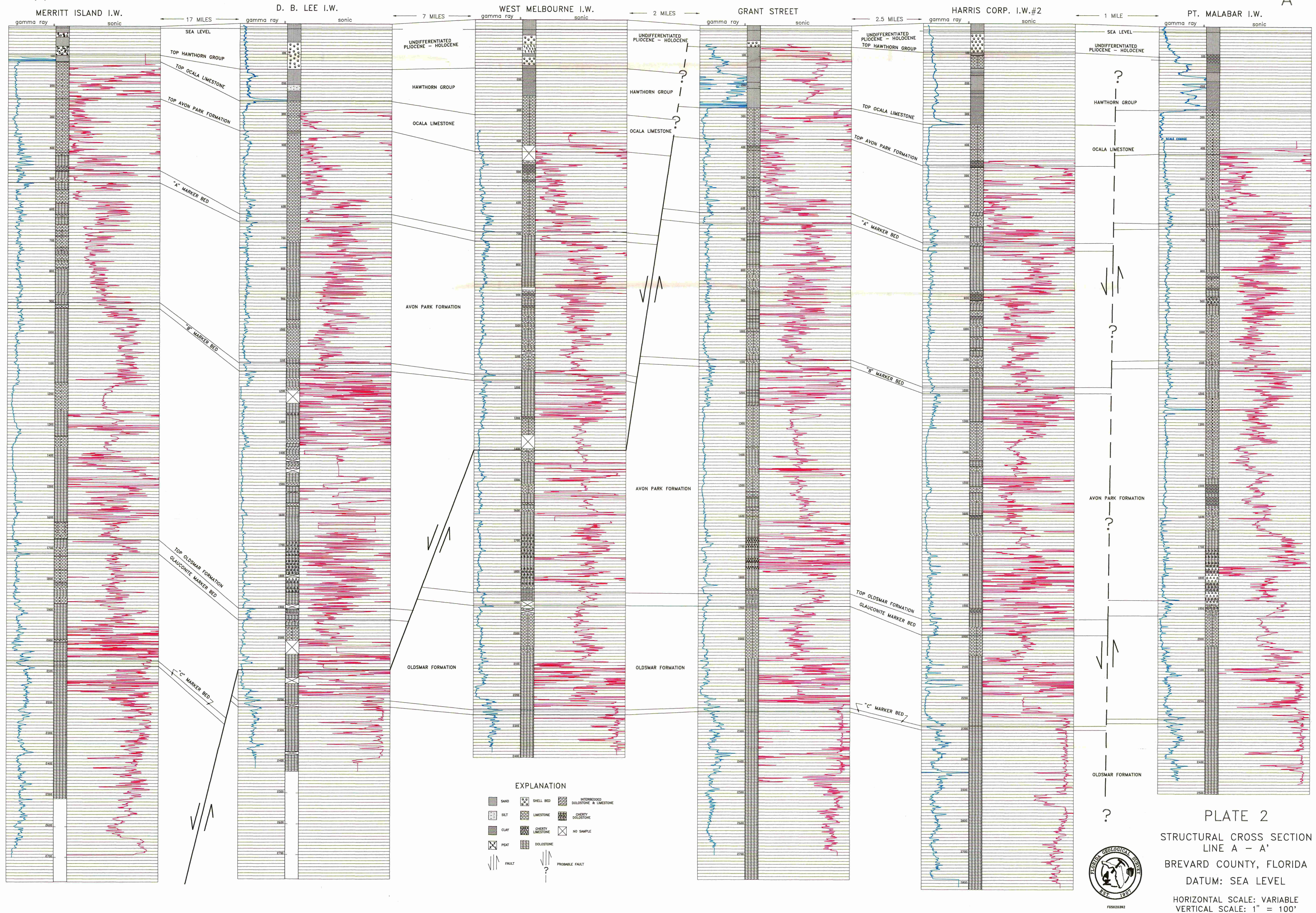
Joel G. Duncan, William L. Evans III and Koren L. Taylor

NORTH
ASOUTH
A'

GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM, BREVARD COUNTY, FLORIDA

By

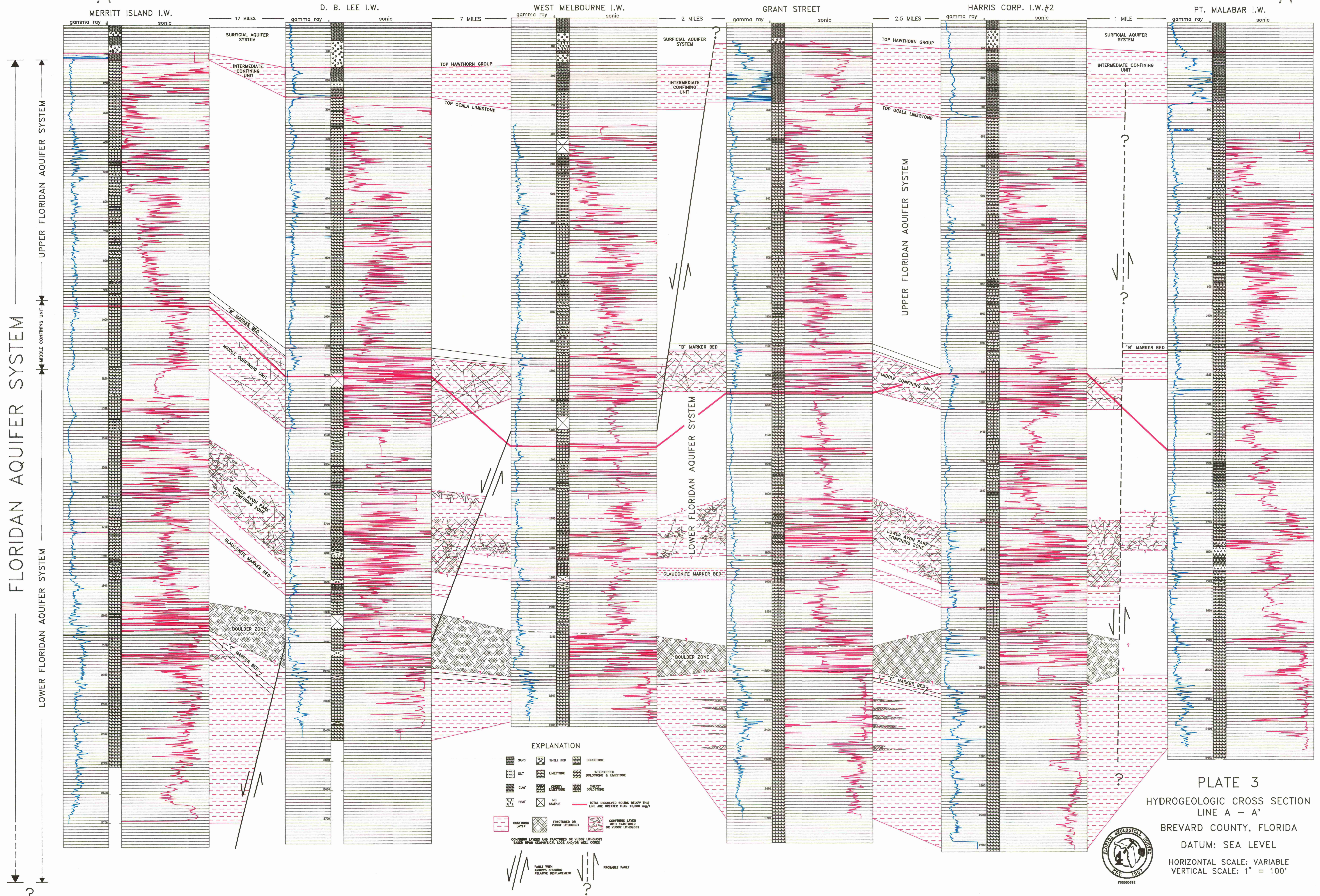
Joel G. Duncan, William L. Evans III and Koren L. Taylor

NORTH
ASOUTH
A'

GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM, BREVARD COUNTY, FLORIDA

By

Joel G. Duncan, William L. Evans III and Koren L. Taylor

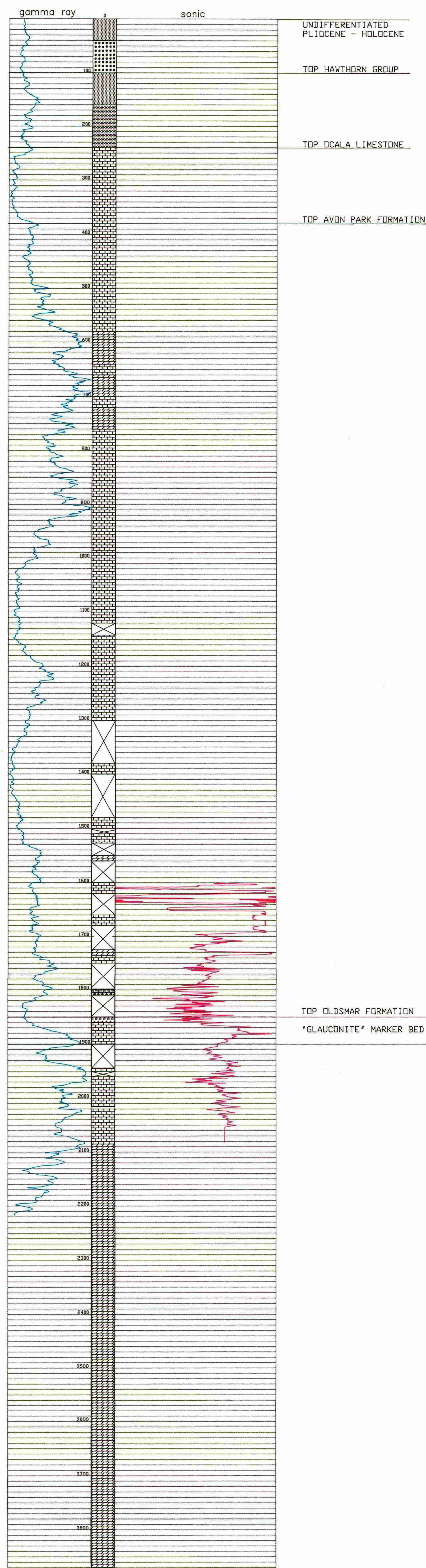
NORTH
ASOUTH
A'

GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM, BREVARD COUNTY, FLORIDA

By

Joel G. Duncan, William L. Evans III and Koren L. Taylor

SOUTH BEACHES I.W.



EXPLANATION

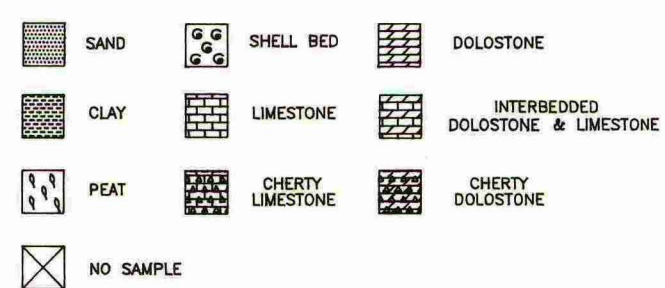
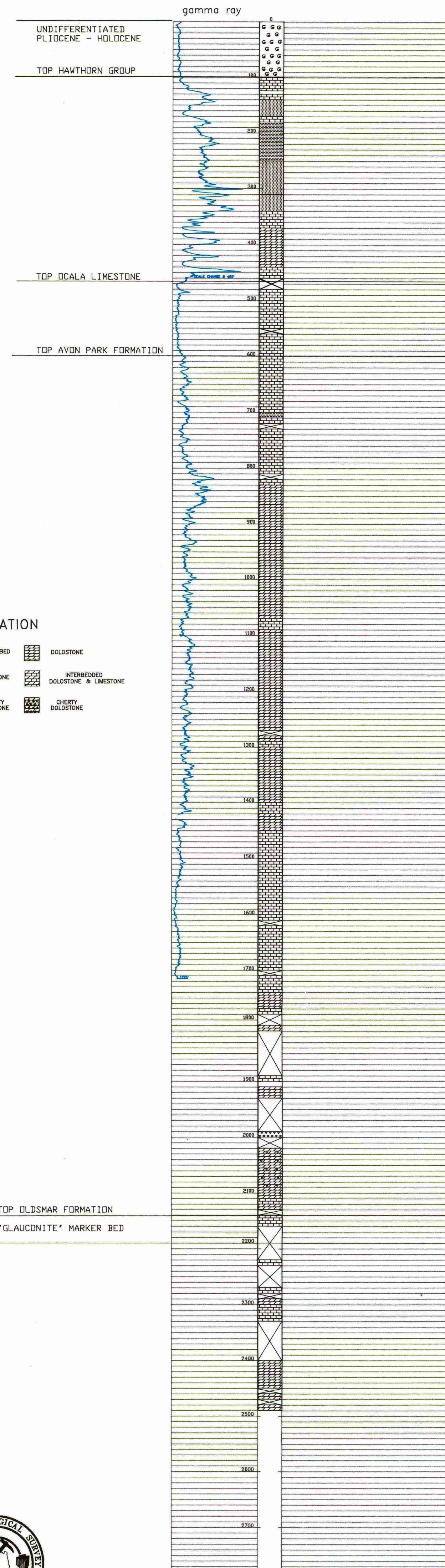


PLATE 4

LITHOSTRATIGRAPHIC COLUMN,
GAMMA RAY AND SONIC LOGS FOR
SOUTH BEACHES INJECTION WELL

VERTICAL SCALE: 1" = 100'

HERCULES INC. I.W.



EXPLANATION

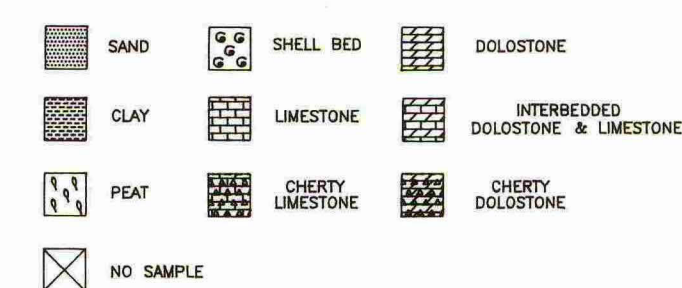
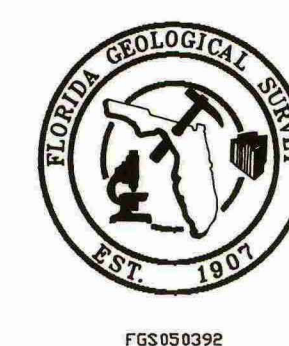


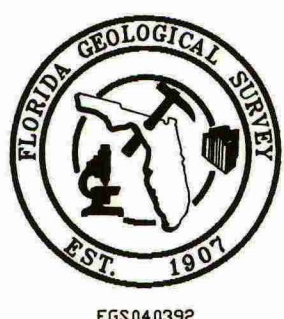
PLATE 5

LITHOSTRATIGRAPHIC COLUMN AND GAMA RAY LOG
FOR HERCULES, INC. INJECTION WELL

VERTICAL SCALE: 1" = 100'



FGS050392



FGS040392

**FLORIDA GEOLOGICAL SURVEY
903 WEST TENNESSEE ST.
TALLAHASSEE, FLORIDA 32304-7700**

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Sandie Ray, Administrative Assistant Alice Jordan, Librarian
Jessie Hawkins, Custodian Cindy Collier, Administrative Secretary
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Jon Arthur, Petrologist Ted Kiper, Cartographer
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Paulette Bond, Geochemist Li Li, Research Assistant
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Steve Campbell, Research Assistant Tippi Polo, Research Assistant
Joel Duncan, Sedimentary Petrologist Jennifer Rooks, Staff Assistant
Will Evans, Senior Research Associate Frank Rupert, Paleontologist
Catherine Florko, Biologist Frank Rush, Lab Technician
Rick Green, Senior Research Associate Jim Trindell, Assistant Driller
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