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Geologic Framework of the Lower Floridan Aquifer System, St. Lucie, Martin and Palm Beach Counties, Florida
Volume I: Text

By

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EXECUTIVE SUMMARY

The disposal of liquid waste products (treated municipal sewage and industrial waste) is a characteristic problem confronting coastal communities in St. Lucie, Martin, and Palm Beach Counties. A common solution utilizes underground injection-disposal wells whereby liquid waste is pumped into highly permeable rocks within the non-potable portion of the lower Floridan aquifer system. Ideally, lower permeability or "confining" strata above the high permeability injection zone prevent the liquid waste from migrating upward into potable portions of the aquifer system. Problems related to leaky confinement in areas like Brevard County to the north indicate that a better understanding of the lower Floridan aquifer system in southeastern Florida is needed to formulate protective criteria for present and future injection projects. Thus, the purpose of this study is to detail the geologic framework of the lower Floridan aquifer system between Brevard and Palm Beach Counties. Findings from this research provide further knowledge from which appropriate policies regarding injection well construction and location can be developed.

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

1. Structural geology
2. Lithostratigraphy
3. Depositional environments
4. Geophysical character

5. Dolomitization

6. Hydrogeology

7. Ground-water chemistry analysis

Strata of the lower Floridan aquifer system in the study area dip generally to the east-southeast at less than one-half degree. Steep, counter-regional dip (up to 17 degrees) at the the West Palm Beach and Palm Beach RRF sites indicates a zone of structural deformation related to normal faulting or monoclinal folding in eastern Palm Beach County. The abruptness of the dip-angle change at the West Palm Beach site suggests that a fault interpretation may be a more reasonable explanation for the apparent high dip-angles here. Two shortened stratigraphic sections in a West Palm Beach injection well (WPB-1R) could be related to normal faulting and suggest the presence of a broad zone of faulting rather than a single discrete fault.

Strata of the lower Floridan aquifer system in the study area consists of Paleocene to Middle Eocene (from 67 to 41 million years old), interbedded limestones and dolostones that comprise part of an extensive carbonate platform that existed from Late Cretaceous through the Late Oligocene (from 92 to 25 million years ago). The limestones are generally fossiliferous, moderately to poorly indurated, and have high porosity and permeability. Dolostones are typically well indurated and have fossil moldic, vugular, and intercrystalline porosity. In the lower Floridan aquifer system, dolostones are usually less porous and permeable than limestones.

In the study area, the Floridan aquifer system generally consists of two major permeable zones separated by a middle confining unit (Plates 4 and 5). The upper and lower Floridan aquifer systems and the middle confining unit consist of a vertically continuous sequence of Paleocene to Eocene carbonates. Locally variable, complex hydrogeologic conditions exist throughout the Floridan aquifer system, therefore, the carbonates may be hydraulically connected or separated.

The middle confining unit in the study area consists of dense dolostone with interbedded limestone and is generally located in close stratigraphic proximity to the middle Avon Park Formation geophysical marker (Plates 2-5). The middle confining unit, where present, acts as a single leaky confining unit within the main body of the permeable carbonates of the Floridan aquifer system.

The carbonates of the lower Floridan aquifer system are predominantly low permeability, interbedded dolostones and limestones with zones of moderate to high permeability. Ground-water movement is estimated to be chiefly upward from the lower Floridan aquifer through the middle confining unit, then laterally through the upper Floridan aquifer system toward the ocean.

The "Boulder Zone" of the lower Floridan aquifer system consists of highly fractured and sometimes cavernous dolostones that exhibit high transmissivities. Where the Boulder Zone is utilized for waste disposal, there is a traditional view that the dense dolostones immediately above and below the Boulder Zone contain no secondary porosity and function as a confining zone. However, a recent study of injection wells in southeast Florida by

Safko and Hickey (1992) concluded that fracture porosity is the principle type of secondary porosity both within the Boulder Zone and the dolomitic rocks that lie above it. Findings by Duncan et al. (1994) for Brevard County and this study support Safko and Hickey's hypothesis.

Above the Boulder Zone, there are layers of carbonates that demonstrate confining qualities (Plates 4 and 5). Analysis of geophysical logs, lithologic samples and borehole videos indicate that fractures are common in the lower Floridan aquifer system (Plate 4 and 5). Fracture systems, with the proper orientation and connectivity, may allow water movement through rocks that appear impermeable. The orientation and degree of connectivity between these fractures is not known and the water transmitting character is uncertain.

Ground-water chemistry data from monitor wells at the injection sites were reviewed to determine if any trends indicative of vertically migrating waste waters were evident. The Southern Region and Belle Glade injection wells show apparent trends in total dissolved solids (TDS), chloride, and total kjeldahl nitrogen (TKN) concentrations that are possibly related to injection fluids migrating upward through leaky confining beds. The upward movement of the less dense waste-water, barring any wellbore mechanical problems, may be due to vertical permeability related to fracturing, dissolutional cavities, and lithofacies variations.

The general lack of ground-water chemistry trends in the study area is problematic since no significant geologic differences between the study area and Brevard County are apparent. The lack of ground-water chemistry trends here may be related to the location (depth) of the deep monitor zone relative to the top of the Boulder Zone (injection zone). Deep monitor zones in Brevard County are typically located 500 feet or less above the Boulder Zone. In the study area, however, deep monitor zones are typically 1000 feet or more above the Boulder Zone. It is uncertain whether or not more wells would exhibit trends reflecting upward fluid migration if deep monitor zones were positioned closer to the injection zone as in Brevard County.

ACKNOWLEDGEMENTS

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GEOLOGIC FRAMEWORK OF THE LOWER FLORIDAN AQUIFER SYSTEM IN ST. LUCIE, MARTIN AND PALM BEACH COUNTIES, FLORIDA

By Joel Duncan, P.G. #396, William L. Evans III, Joseph G. Aylor, Jr., and Li Li

INTRODUCTION

St. Lucie, Martin, and Palm Beach Counties are located on the Atlantic coastline of peninsular Florida (Figure 1). According to White (1970), the geomorphology of the study area consists of, on the east, the Atlantic Coastal Ridge and on the west, the Eastern Valley (Figure 2). The Osceola Plain, is a broad, flat, elevated area located in western in St. Lucie and Martin Counties (Figure 2). The Everglades lie to the west and southwest of the Eastern Valley and Atlantic Coastal Ridge in Palm Beach County (White, 1970).

Coastal communities in southeastern peninsular Florida have experienced a substantial population increase over the past several decades. Rapid growth and development accompanying the population influx resulted in increased environmental demands. A common problem is the disposal of liquid waste, principally treated municipal sewage and, in some cases, industrial waste by-products. A common solution in south Florida utilizes injection-disposal wells whereby liquid waste is pumped underground into highly permeable rocks of lower Floridan aquifer system. In most of south Florida, ground-water within the lower Floridan aquifer system is highly mineralized and non-potable. Thus, injection of waste-water

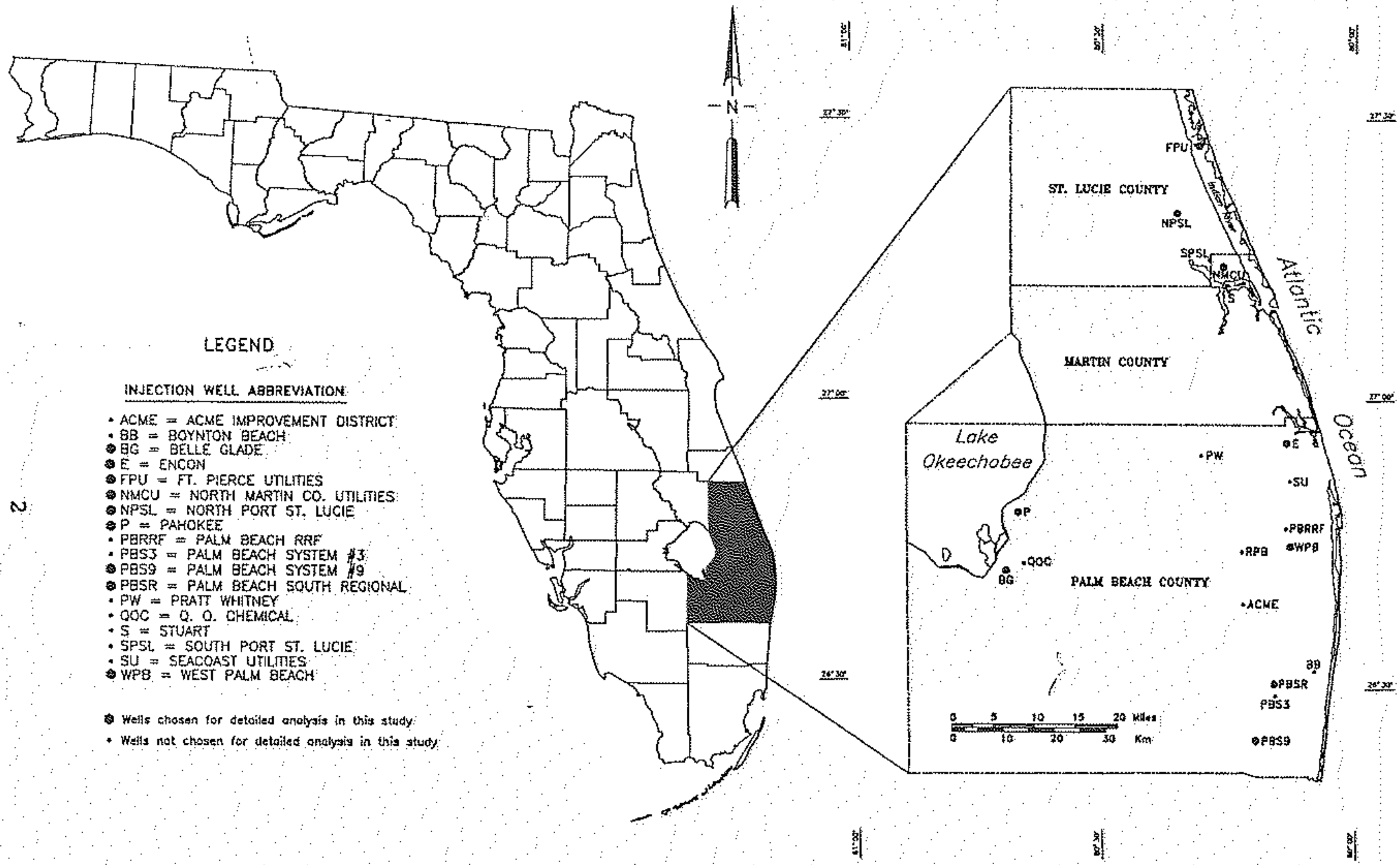


Figure 1. Map of peninsular Florida showing the location of the study area and the injection wells

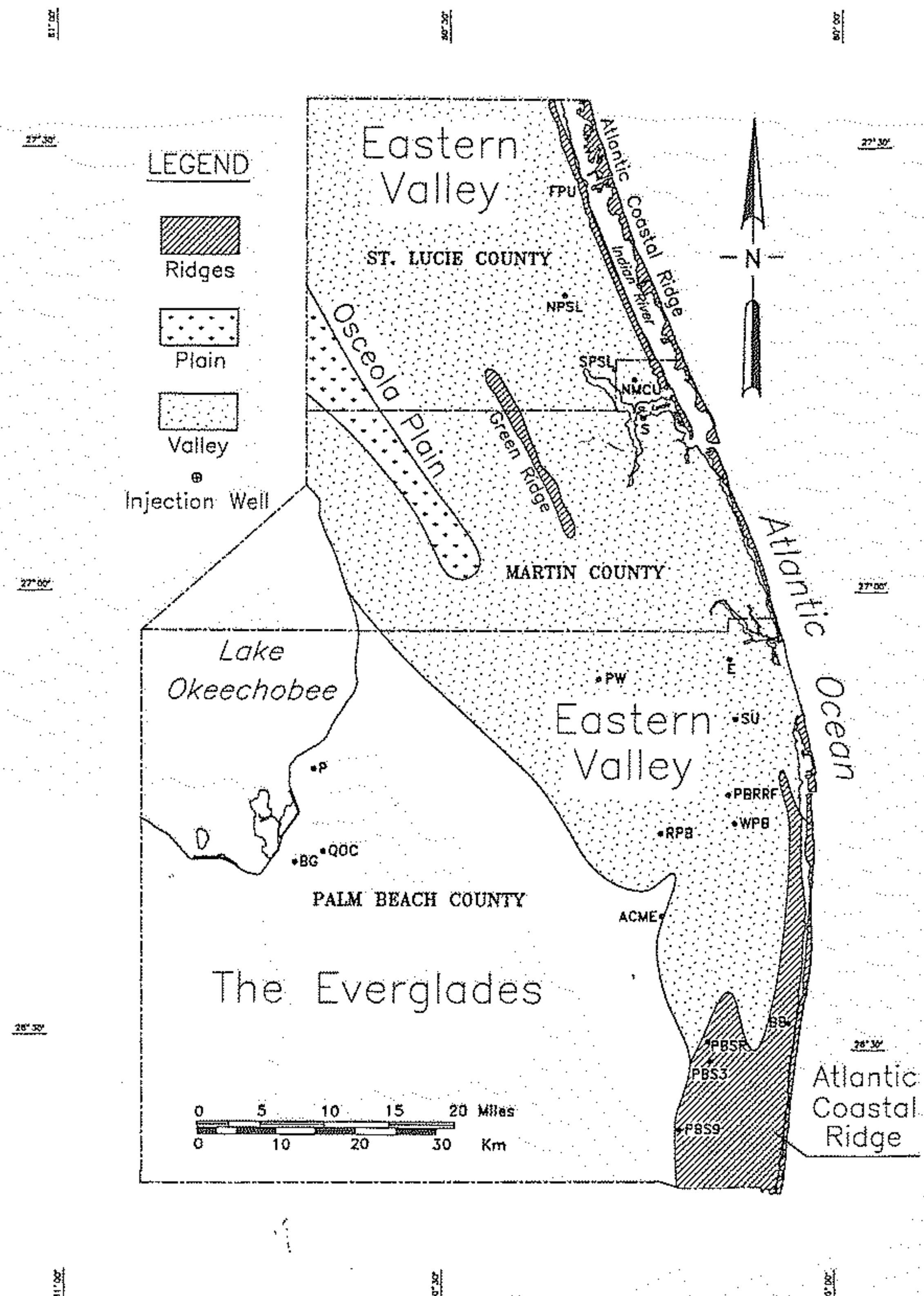


Figure 2. Geomorphologic features of St. Lucie, Martin and Palm Beach County (modified after White, 1970).

into this portion of the aquifer system is considered a solution to the problem of waste disposal. Ideally, a confining sequence of impermeable strata overlying the injection zone prevents upward migration of liquid waste into potable portions of the aquifer system. Problems related to leaky confinement in areas like Brevard County (Duncan et al., 1994) indicate that a better understanding of the lower Floridan aquifer system in southern Florida is necessary in formulating protective criteria for future injection projects.

Duncan et al. (1994) conducted a geologic framework study of the lower Floridan aquifer system in Brevard and Indian River Counties, Florida where ground-water chemistry trends compiled from monitor wells at several injection sites indicated that injected fluids were migrating upward through the "confining" sequence. Duncan et al. (1994) concluded that injected waste water was migrating upward along permeable conduits related to fractures, dissolution cavities, and lithofacies variations.

The purpose of this study is to detail the geologic framework of the lower Floridan aquifer system between Brevard and Broward Counties. The geologic framework of the study area can then be compared with Brevard and Indian River Counties (Duncan et al., 1994). Findings from this research provide a basic knowledge from which appropriate policies related to injection well construction can be formulated.

This investigation summarizes the geology and ground-water chemistry of the lower Floridan aquifer system based on data from two injection wells in St. Lucie County, one well in Martin County and six injection wells in Palm Beach County. Figure 3 shows the locations of the injection wells and geologic cross section lines A-A' (Plate 2 and 4) and B-B' (Plates 3 and 5). This study was conducted utilizing well cuttings, cores, injection well tests, borehole videos, geophysical logs, and monitor-well water chemistry information.

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

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

STRUCTURAL GEOLOGY

Depth to basement ranges from approximately -11,000 feet National Geodetic Vertical Datum (NGVD) in St. Lucie County to -17,000 feet NGVD in southern Palm Beach County (Barnett, 1975). Basement rock in the study area consists of early Mesozoic felsic volcanics except in eastern St. Lucie and Martin Counties where Cambrian high grade metamorphics (quartz diorite gneiss and amphibolite) are present (Chowns and Williams, 1983). A sequence of Jurassic to Cretaceous siliciclastics, evaporites and carbonates of the South Florida Basin (Figure 4) disconformably onlap the basement surface (Applin and Applin, 1965; Chowns and Williams

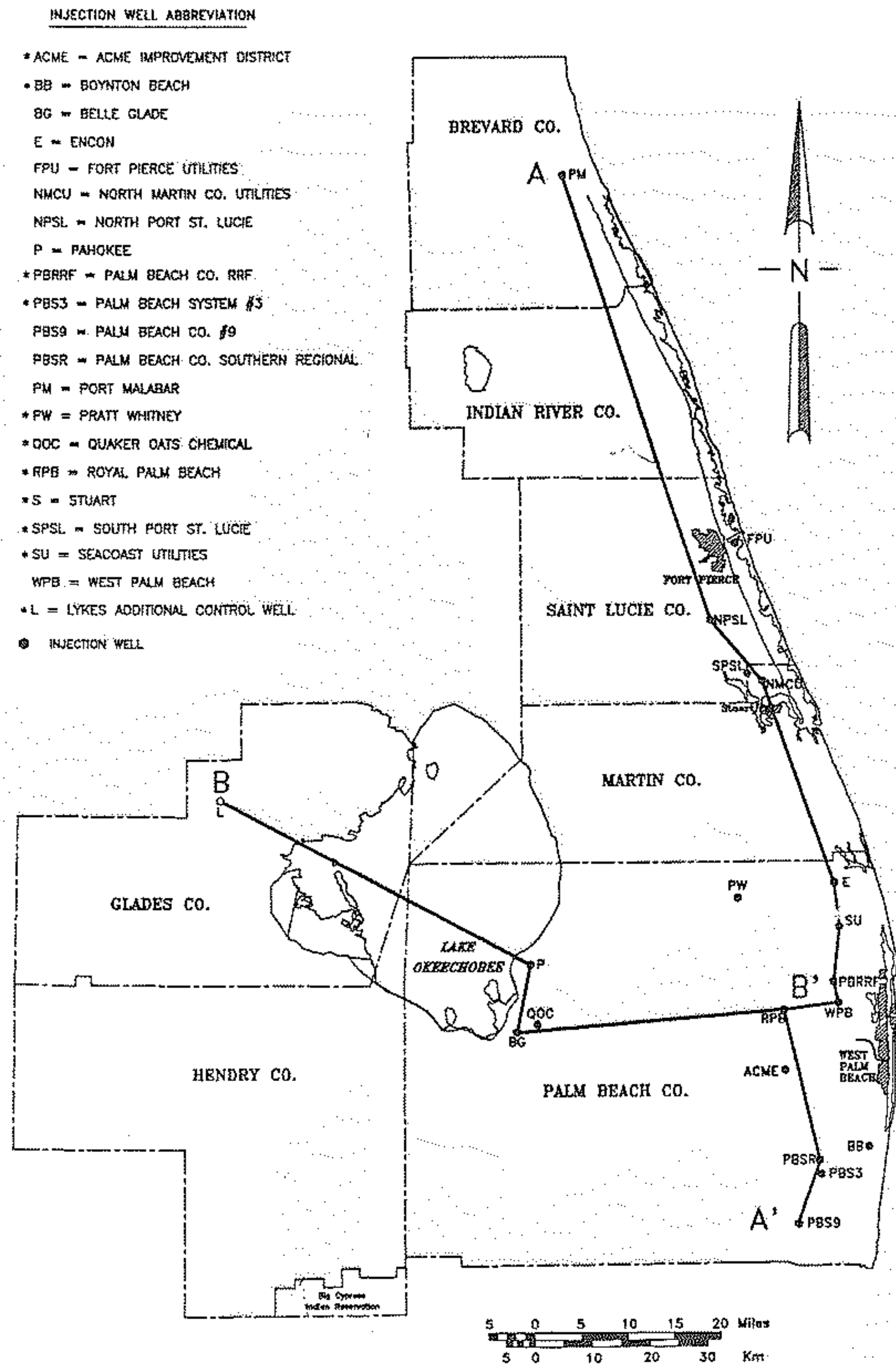


Figure 3. Location map showing cross-section lines A-A' and B-B' (Plates 2-5) and the injection wells.

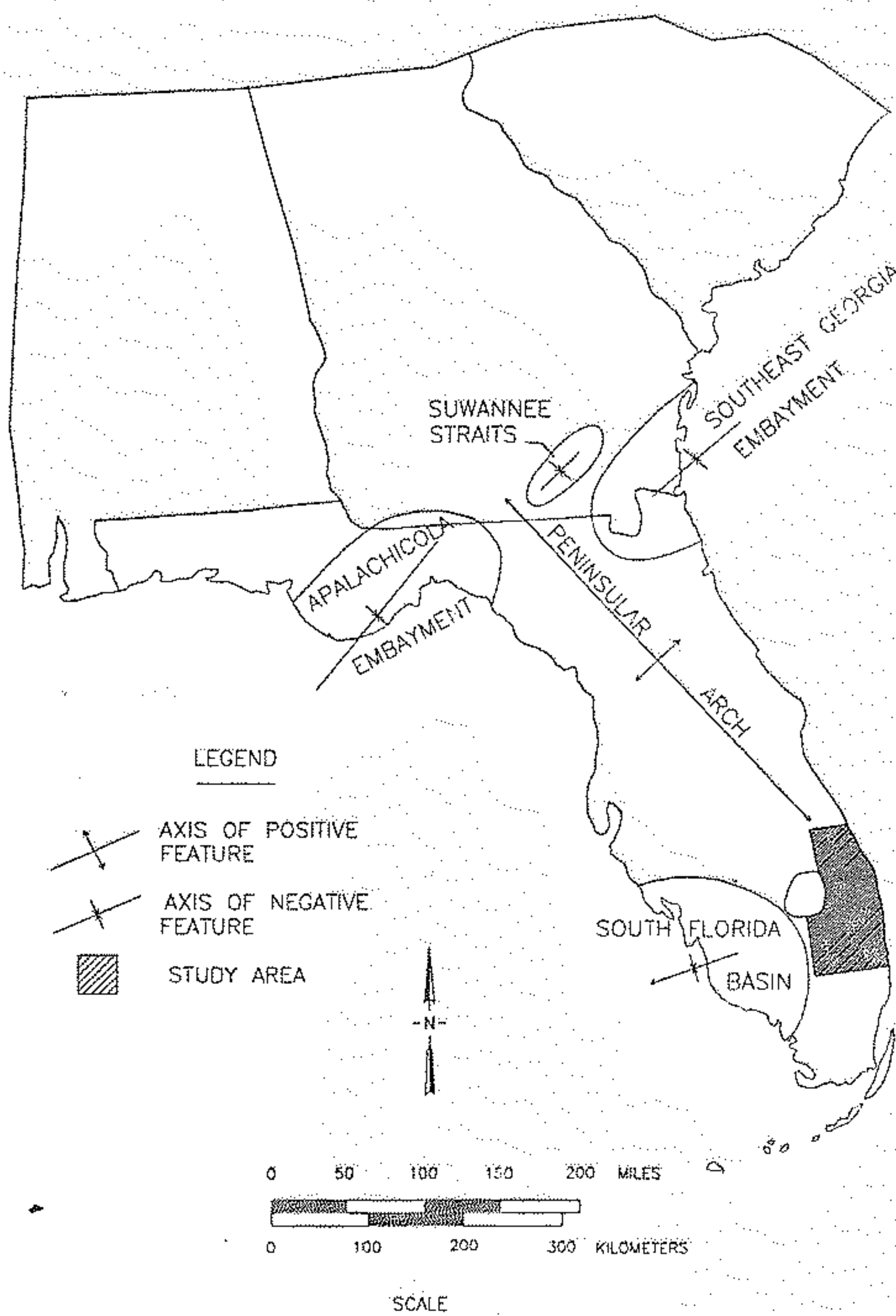


Figure 4. Pre-Cenozoic structural features of Florida and southern Georgia (from Scott, et al, 1991).

1983).

A significant basement fault-related crustal boundary referred to as the Bahama Fracture Zone by Klitgord et al. (1984), or the Florida Lineament by Christenson (1990) trends northwest-southeast across the Florida peninsula through central Palm Beach County (Figure 5). Klitgord et al. (1984) interpreted the feature as a Jurassic left-lateral transform fault that connected oceanic spreading ridges in the Gulf of Mexico with spreading ridges in the Atlantic Ocean. In contrast, Christenson (1990) postulated that the Florida Lineament was instead a Triassic-Jurassic extensional rift margin and a southeastward continuation of the Gulf peripheral fault system that trends from Texas southeast into Florida (Figure 6). Barnett (1975) also postulated a northwest-striking basement fault in southern Florida (Figure 7) similar in trend and location to that of Klitgord et al. (1984) and Christenson (1990).

The most recent tectonic event potentially affecting southern Florida was the collision of the Cuban island arc/margin with the North American plate (Figure 8) during the Late Cretaceous through Middle Tertiary (Sheridan et al., 1981; Hempton, 1991). Southern Florida and the Bahamas formed a carbonate foreland north of the Cuban arc/convergence zone (Hempton, 1991). 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 (Figure 8). Covergence-related stresses reactivated old (Jurassic) planes of crustal weakness (Sheridan et al., 1988) such as the Bahama

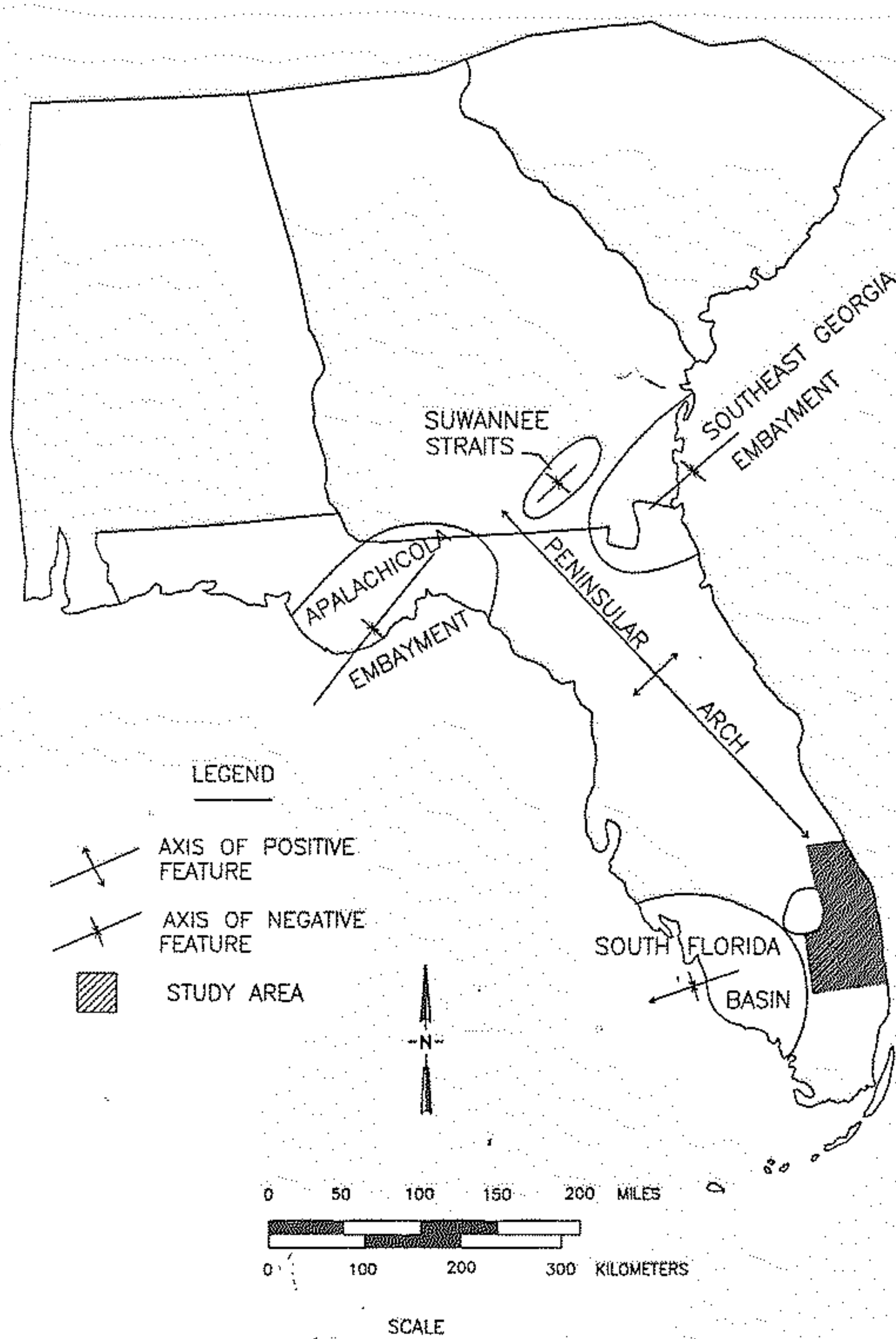


Figure 4. Pre–Cenozoic structural features of Florida and southern Georgia (from Scott, 1991).

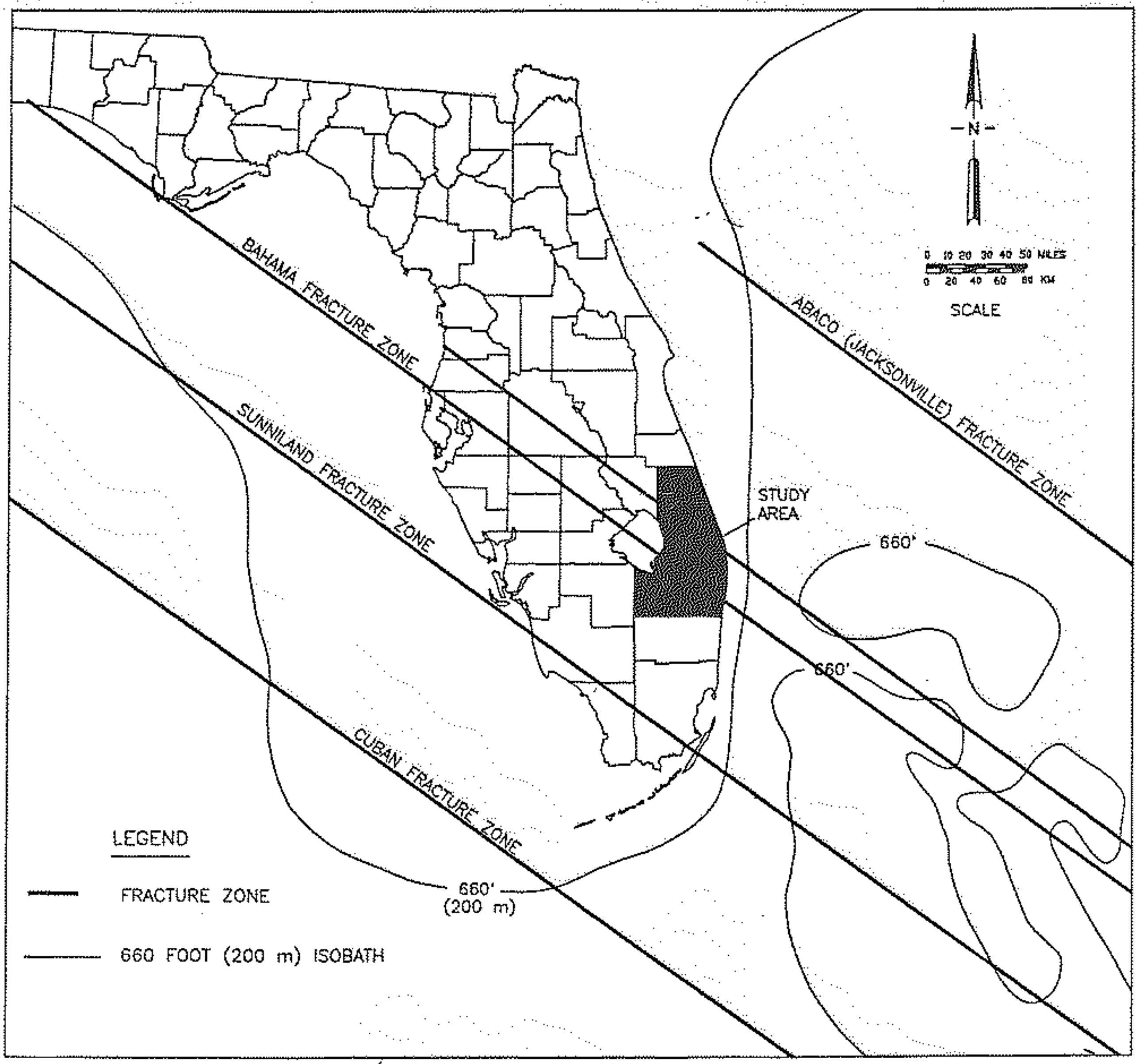


Figure 5. Basement (Jurassic) fracture zones of the Florida/Bahama region (after Klitgord et al., 1984).

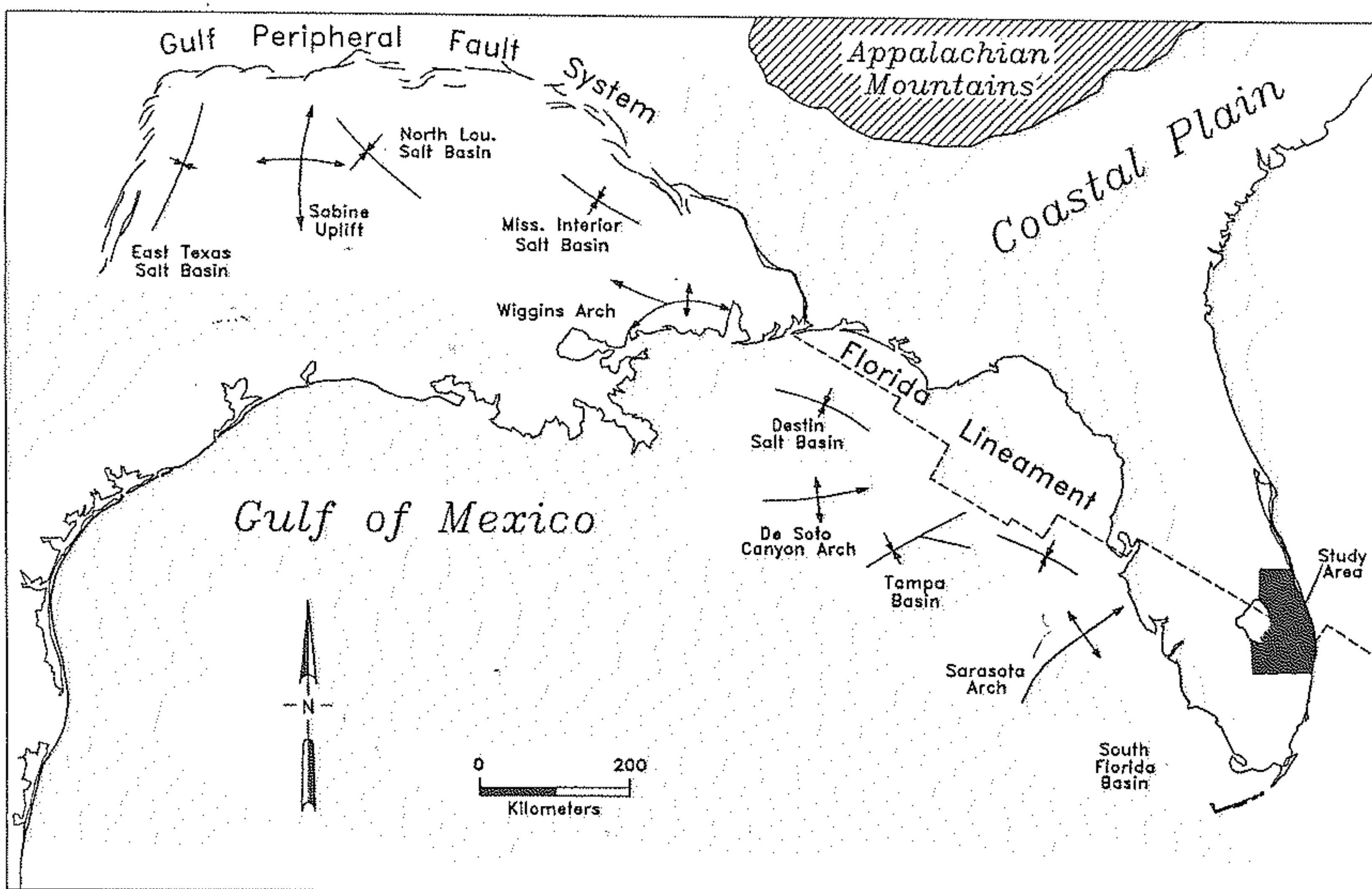


Figure 6. Simplified regional basement structural map of northern Gulf of Mexico, showing the relationship between the Florida Lineament and the Gulf Peripheral Fault System (modified from Christenson,1990).

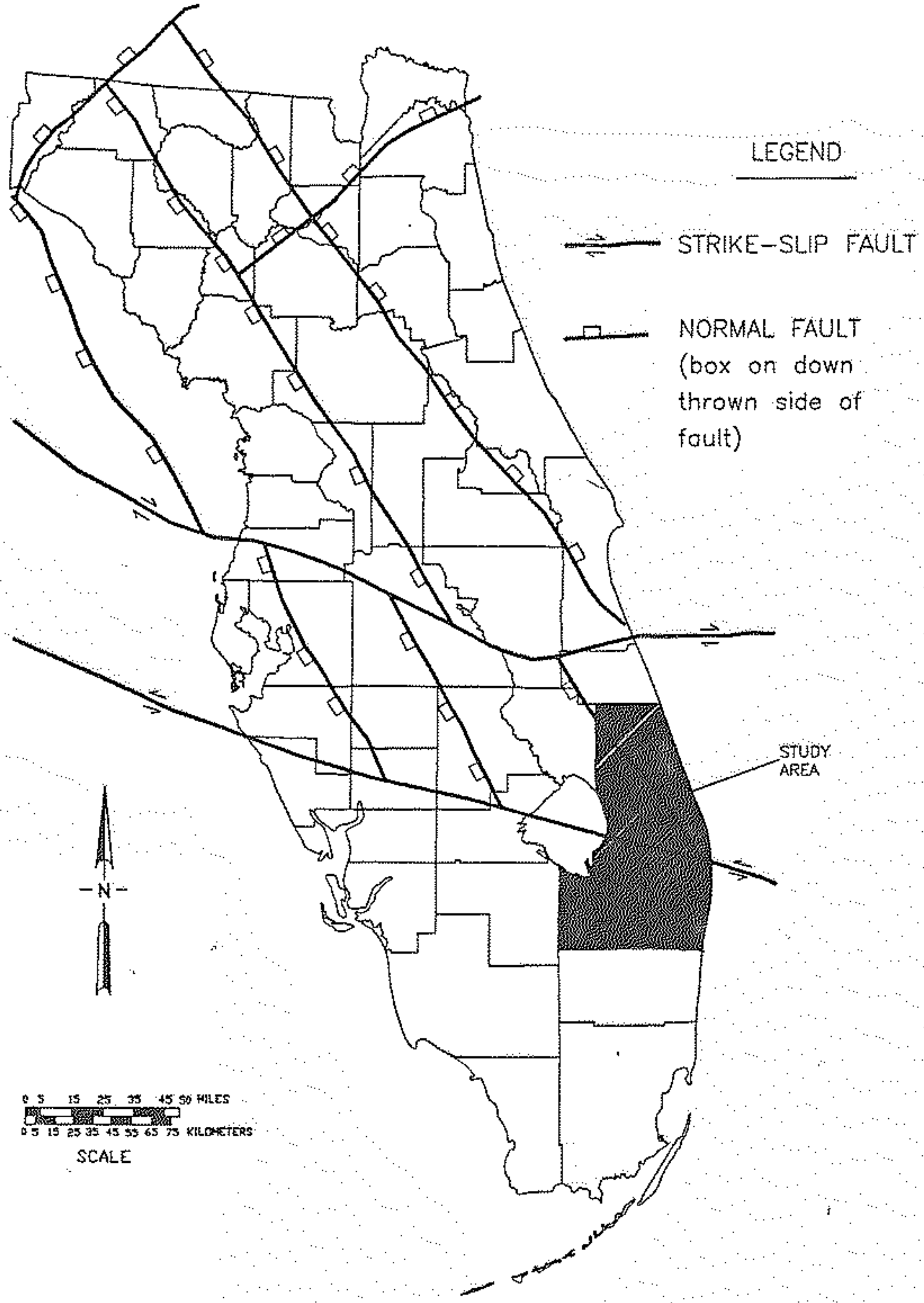


Figure 7. Basement faults of peninsular Florida (Modified from Barnett, 1975).

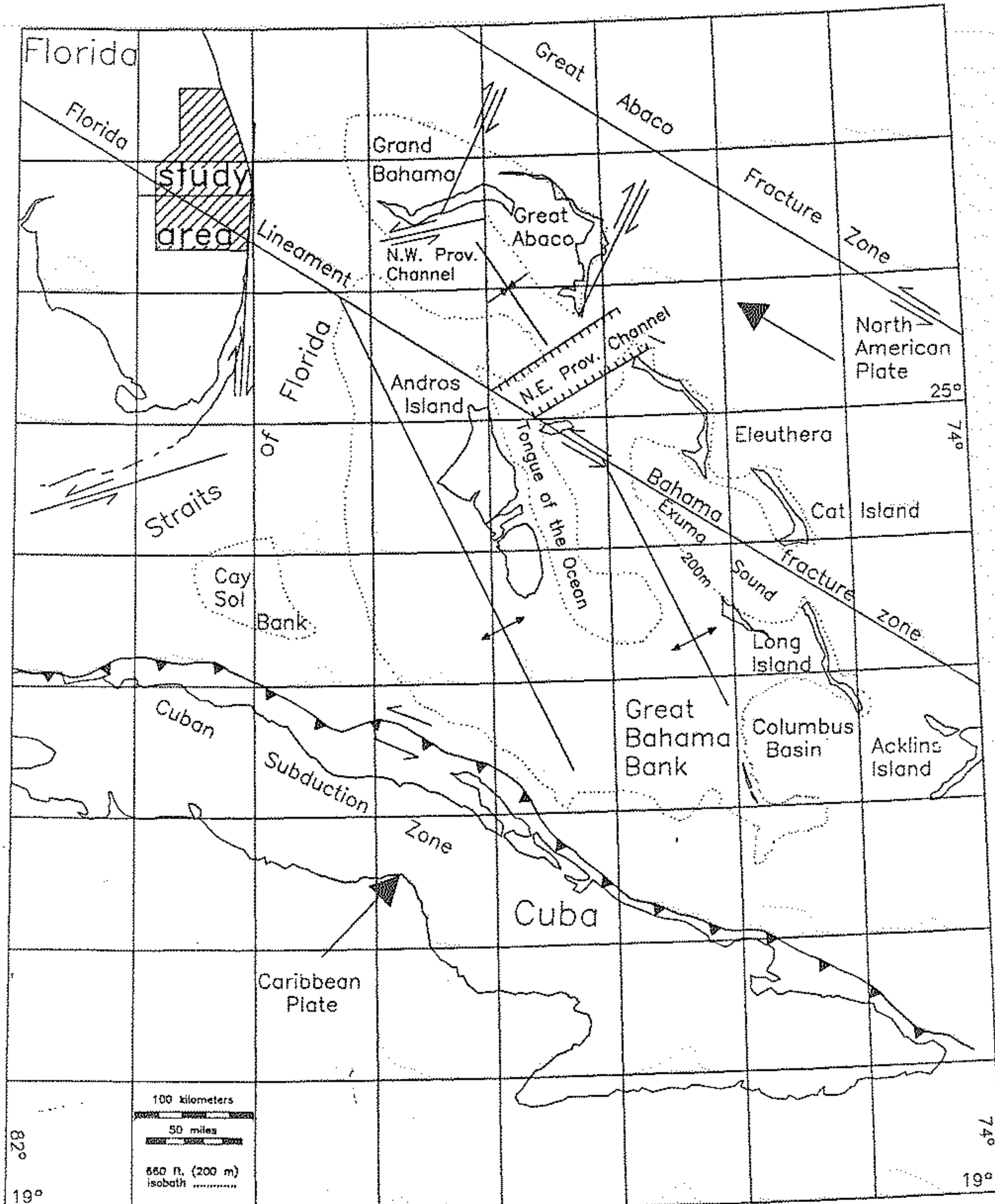


Figure 8. Tectonic map of the south Florida, Cuba and the Bahama region (Sheridan et al., 1988).

Fracture Zone (or Florida Lineament) with possible left-lateral shear displacement (Sheridan et al., 1981, 1988). Hempton (1991, 1993) interpreted anomalous vertical seismic features of southern Florida, commonly attributed to paleokarst or static problems, as true vertical faults that propagated upward from reactivated basement faults of the foreland into the overlying carbonate section during the Late Cretaceous through Middle Tertiary. In some cases, upward propagating faults created low-amplitude anticlinal closures in the overlying foreland carbonates (Hempton, 1991). Structural features in the study area could then be related to basement faults reactivated as a result of Cuban arc/North American plate convergence during the Late Cretaceous to Middle Tertiary (Figure 8).

The axis of the Peninsular Arch plunges southeastward toward the central portions of the St. Lucie, Martin, and Palm Beach Counties (Figure 4). The Peninsular Arch is cored by a large block Precambrian igneous and metamorphic rock covered by Paleozoic strata (Barnett, 1975), and has been a positive feature affecting sedimentation from the Jurassic into the early Cenozoic (Miller, 1986).

Middle Cenozoic structures in the study area include the Okeechobee Basin and Brevard Platform (Figure 9). The Okeechobee Basin is a Neogene depositional low that is defined by thick accumulations (greater than 700 feet) of Hawthorn Group sediments in the south Florida region (Riggs, 1979; Scott, 1988). The Brevard Platform is a low-relief ridge that plunges gently to the south-southeast and southeast (Scott, 1988). Both the Ocala

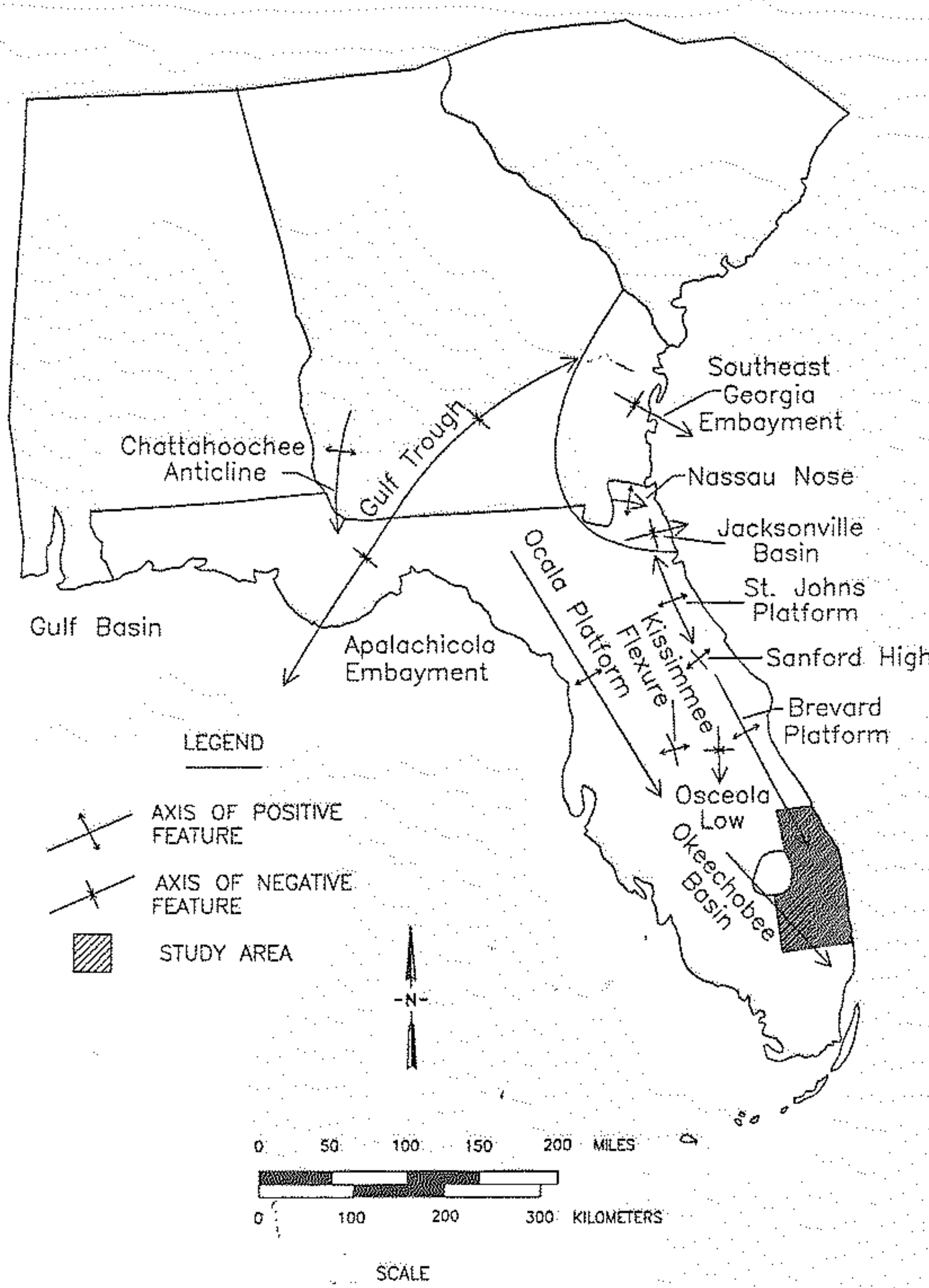


Figure 9. Mid–Cenozoic structural features of Florida and southern Georgia (modified after Scott et al, 1991).

Limestone and Hawthorn Group thin across the Brevard Platform and have erosional upper surfaces (Brown et al., 1962; Scott, 1988)

Several authors (e.g., Armstrong, 1980; Bond et al., 1981; Lichtler, 1960; Vernon, 1970; Miller, 1986; Tanner, 1965) have postulated subsurface Cenozoic faults in the study area several of which are located near injection well sites (Figure 10). Most of these faults were based on contour mapping the top of the Ocala Limestone (Lichtler, 1960; Armstrong, 1980) which is an erosional surface with the potential for significant paleotopographic relief. Without a reliable isopach of the Ocala Limestone, it is impossible to differentiate between steepening paleotopographic relief or true structural dip when using this datum. Thickness data for the Ocala Limestone (and other Eocene formations) have been historically lacking in this area because most wells are too shallow and do not penetrate the complete section.

Strata of the Floridan aquifer system in the study area dip regionally to the east-southeast at less than one half degree in the study area (Plate 4). The structure top of the Oldsmar Formation (or glauconite marker bed as defined in Brevard County by Duncan et al., 1994) indicates an area of much steeper dip and a dip reversal at both regional and local scales in northeast Palm Beach County near the West Palm Beach and Palm Beach RRF injection sites (Plate 1). Multiple three-point dip analyses were performed at the West Palm Beach site utilizing gamma-ray logs from six closely spaced (less than 600 feet apart) injection wells (Figures 11 and 12). Dip angles were computed for a gamma-ray marker located at the top of the Oldsmar Formation (glauconite marker bed)

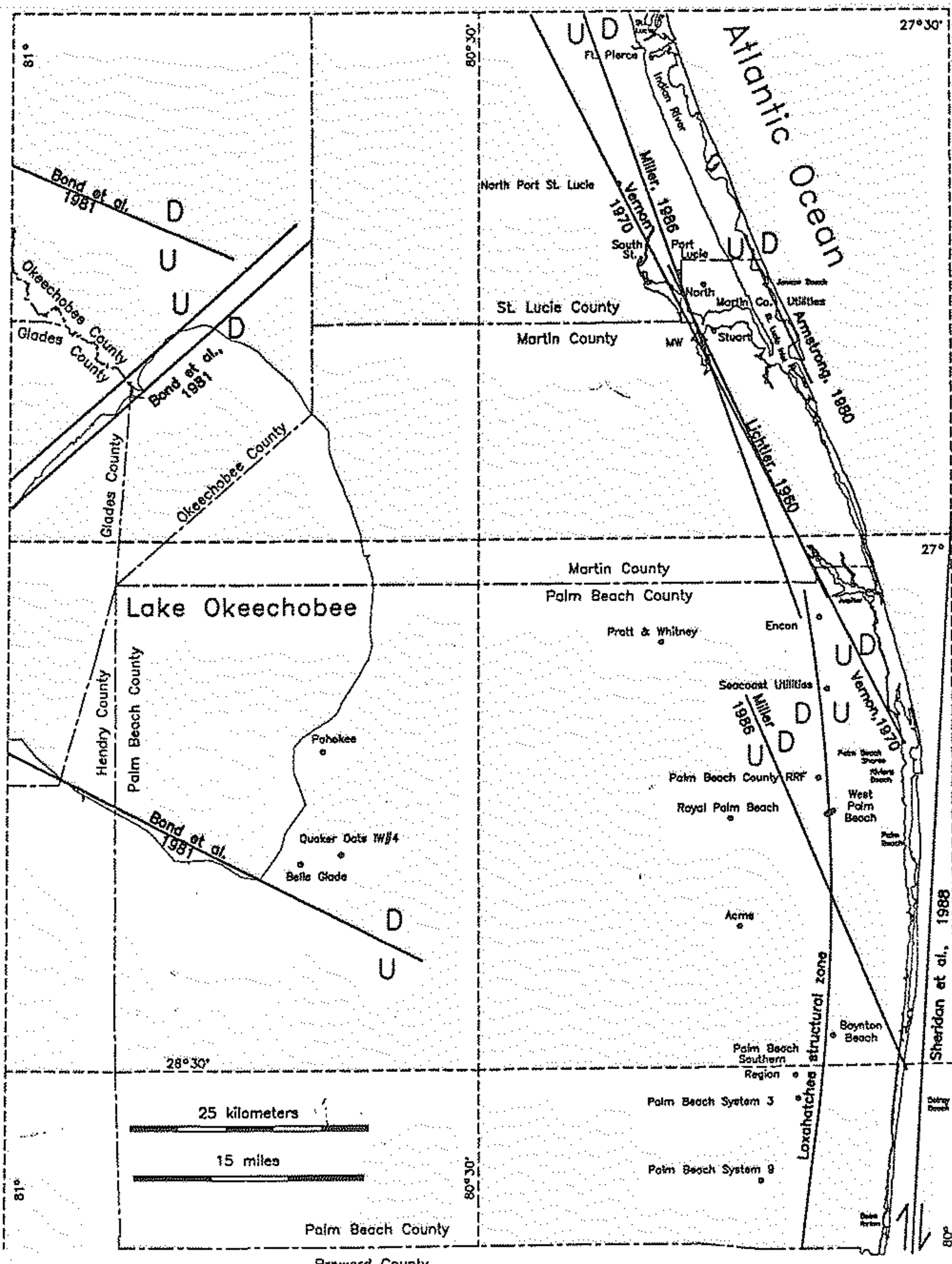


Figure 10. Present and previous interpretations of possible faulting that affects Paleogene and older strata in the study area.

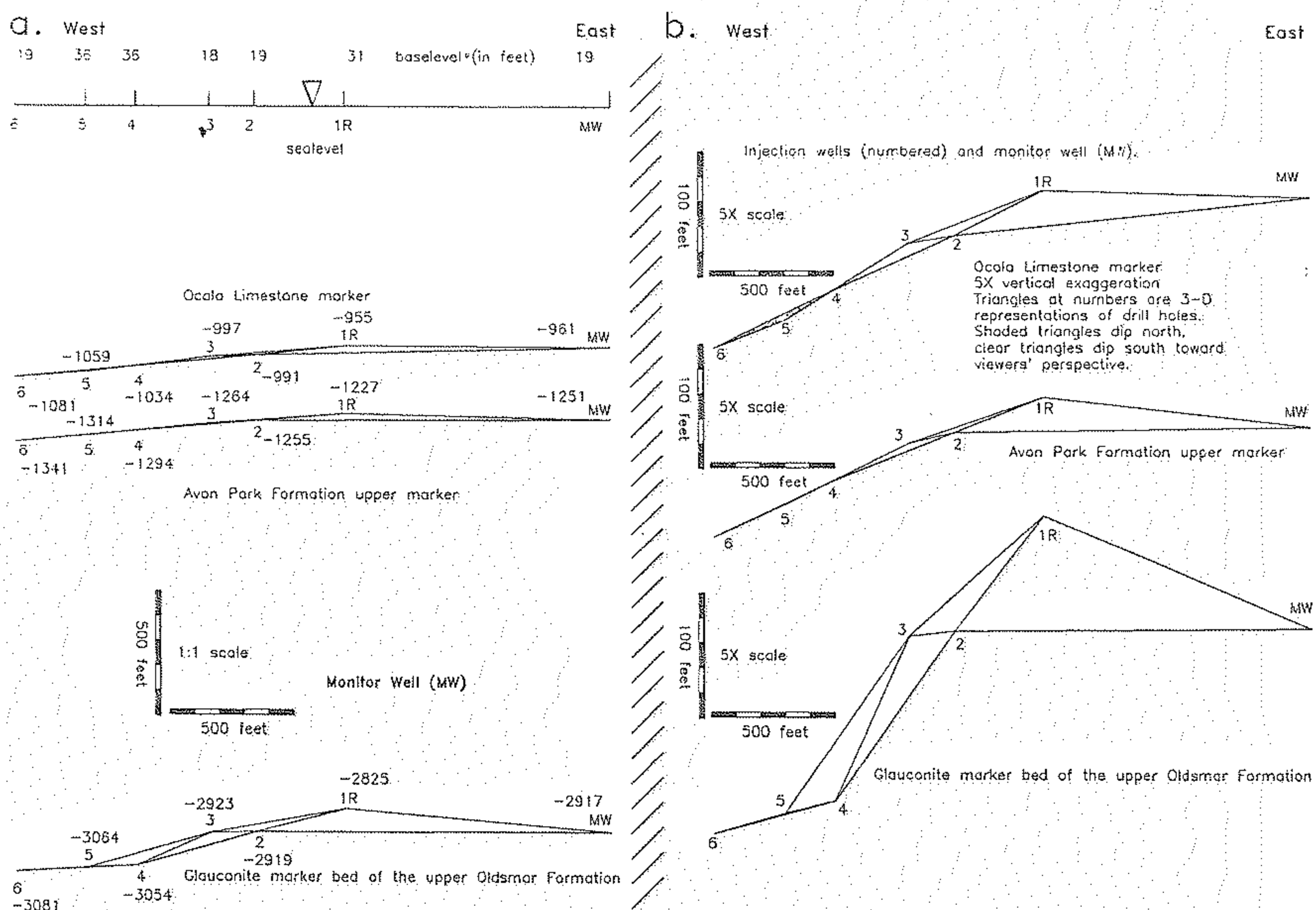
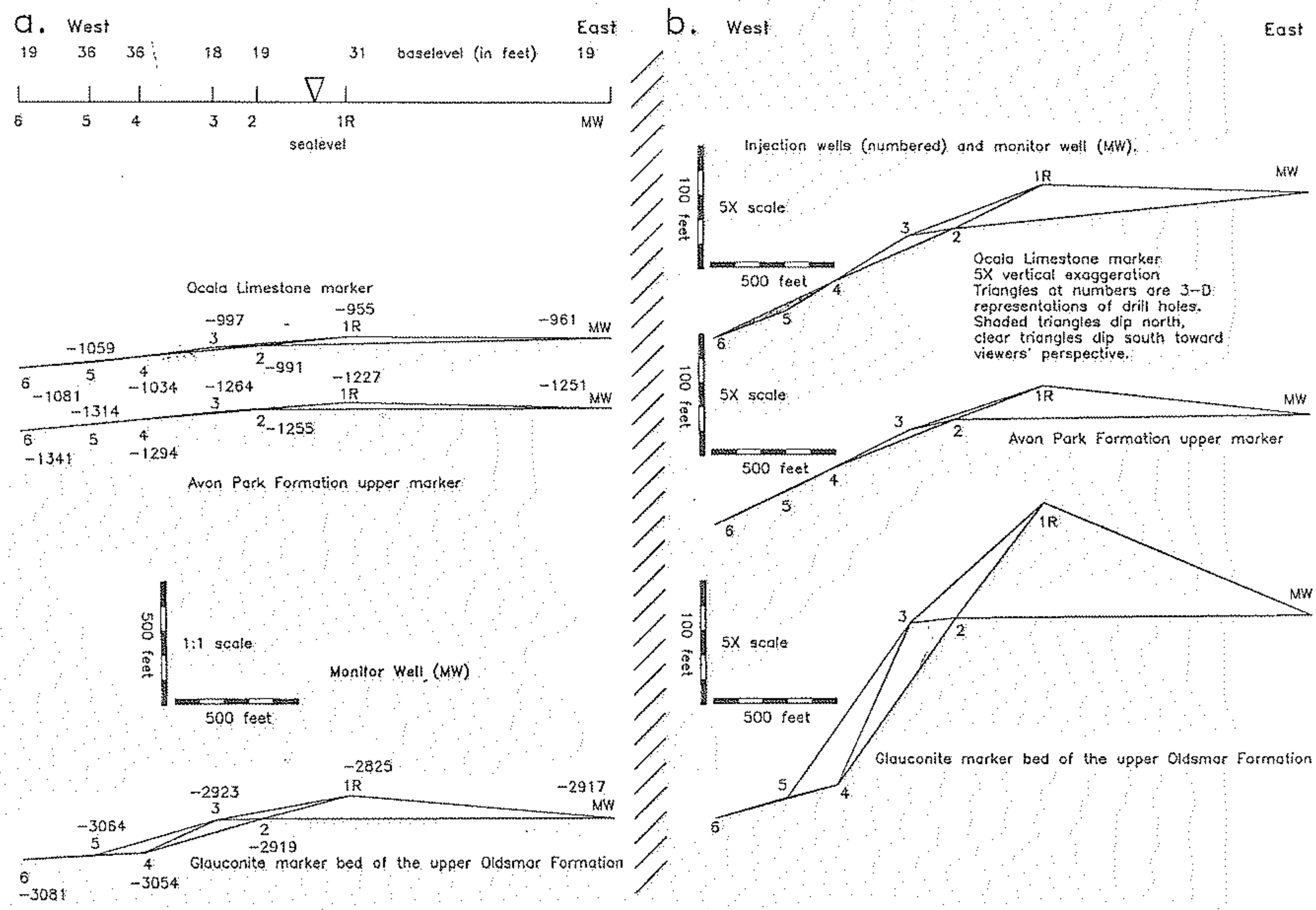


Figure 11. Three dimensional west–east cross section graphically illustrating multiple three–point problem solutions at the West Palm Beach Pollution Control Facility. a). 1:1 representation of markers and intervening stratigraphy. b). 5X vertical exaggeration of markers with no scaled intervening stratigraphy.



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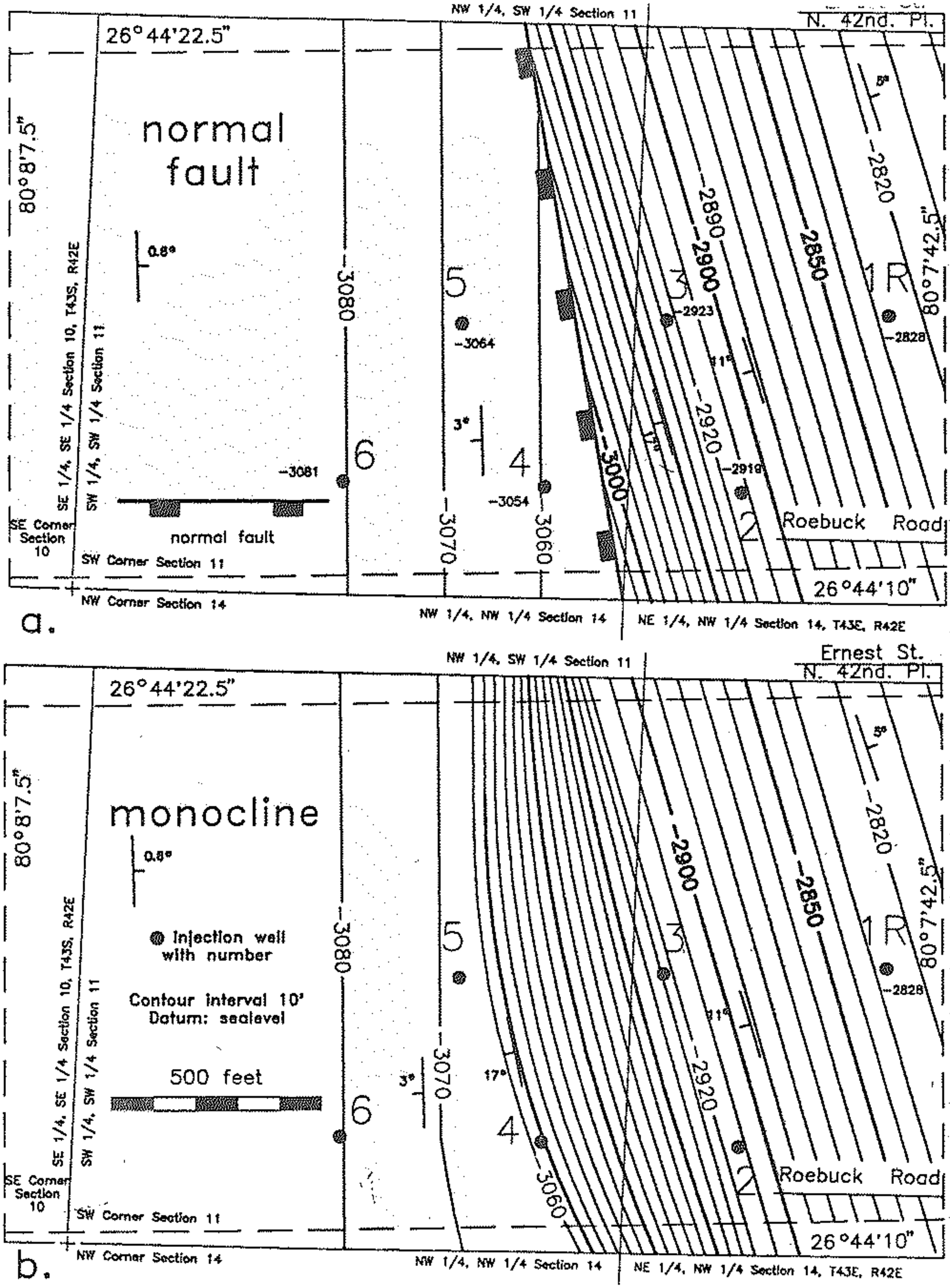


Figure 12. a.) Normal fault interpretation and b.) monocline interpretation based on the structural top of the glauconite marker bed of the Oldsmar Formation of injection wells located at the West Palm Beach Pollution Control Facility.

and a gamma-ray marker in the upper Avon Park Formation. Dip angles for the Oldsmar Formation/glauconite marker bed are 11, 17 and 3 degrees to the west-southwest and 5 and .6 degrees dip to the east-northeast (Figure 11 and 12). Calculations for the Avon Park Formation marker indicate that dip apparently decreases up the stratigraphic section varying from 4 to 6 degrees west-southwest and 0.6 to 1 degree to the east-northeast (Figure 11). Dip calculations by Geraghty and Miller Inc. (1978) utilizing borehole geophysical data from only three West Palm Beach injection wells are similar to the findings of this investigation. Apparent dip based on two wells at the Palm Beach RRF site is 5 degrees to the south.

The anomalously steep, counter-regional dip of the Oldsmar Formation at the West Palm Beach site can be explained by either normal faulting (Figure 12A) and/or monoclinal folding (Figure 12B). A north-northwest striking, down to the west normal fault with approximately 50 feet of throw at the Oldsmar Formation is indicated for the faulted interpretation as shown in Figure 12A. Decreasing dip up section (or increasing dip with depth) could be related to drag folding along the downthrown side of a normal fault, or asymmetrical folding. The abruptness of the dip-angle change suggests that faulting may be a more reasonable interpretation for the feature.

The apparent dip reversal and steepening contours between the Seacoast Utilities and the Palm Beach RRF sites indicates that the West Palm Beach structure is part of broader zone of structural deformation, herein named the Loxahatchee Structural Zone, that extends from the West Palm Beach site north-northwestward to at least the Martin County/Palm Beach County line and possibly south-southeast, to at least the Broward/Palm Beach County line (Plate 1; Figure 10). The North Port St. Lucie and North Martin County injection wells are located on a southeast plunging anticlinal nose that may be related to or an extension of the Loxahatchee Structural Zone (Plate 1). If faulting is presumed to be the more likely explanation for the Loxahatchee Structural Zone, as is suggested at the West Palm Beach site, then roughly 250 to 300 feet of throw is possible across a north-northwest striking, down to the west, normal fault or fault zone as depicted on Plates 1 and 2. The concept of a fault zone rather than a single fault is advanced if two shortened stratigraphic sections in the West Palm Beach 1R (35 feet short at -2840 NGVD and 30 feet short at -1446 feet NGVD) are interpreted as faults in addition to the postulated fault shown in Figure 12A. The Loxahatchee Structural Zone affects at least Upper Eocene and older stratigraphic units in eastern Palm Beach County. The Hawthorn Group thickens at its base by approximately 120 feet in the Palm Beach RRF and West Palm Beach over a structurally low area formed by the Loxahatchee Structural Zone (Plate 2). Faults postulated by Vernon (1970) and Lichtler (1970) for northern Palm Beach County and southern Martin County have strikes similar to the Loxahatchee Structural Zone. Thickness variations of the Hawthorn Group imply a probable Oligocene age for the structure.

A relatively broad and flat anticlinal nose that is present in western Martin and Palm Beach Counties (Plate 1) is possibly a southern extension of the Brevard Platform (Figure 9). The Ocala Limestone is thin or absent over much of this gentle structure. The Royal Palm Beach, ACME, Palm Beach Southern Regional and Palm Beach County System 9 injection wells are located on an apparent intermediate structural high where the Ocala Limestone is also thin or absent (Plates 1 and 2). The Ocala Limestone pinch-out is evident between the West Palm Beach and the Royal Palm Beach sites on cross section line A-A' (Plate 2) where the Ocala Limestone thins from 250 feet to zero as the Oldsmar Formation structural top (Plate 1) climbs higher by roughly 300 feet. The Hawthorn Group also thins over the structure (Plate 2). The Hawthorn Group and Ocala and/or Avon Park Formations are apparently separated by an angular, disconformable contact in association with this feature.

Geophysical correlations indicate that the Belle Glade well borehole, located on the southeast shore of Lake Okeechobee intersects two possible faults (Plate 3). Two shortened stratigraphic sections, one in the Oldsmar Formation (roughly 35 feet) at approximately -2681 NGVD and one in the lower Avon Park Formation (roughly 50 feet) at -2201 NGVD, could be due to faulting (Plate 3). Core from the Oldsmar Formation at the depth corresponding to the shortened section at -2681 NGVD consists of a one-half foot of muddy, rubbly or possibly brecciated, poorly indurated limestone with several clayey, slickensided surfaces (Appendix 1). Vertical fractures were present in moderately indurated limestone several feet above and below this depth. Sparse deep-well control in the area does not allow speculation on the orientation of the potential faults. Based on surface drainage patterns, Tanner (1965) and Bond and others (1981) proposed that Lake Okeechobee was a fault-bound depression (Figure 10). The proposed fault forming the southwestern boundary of the Lake Okeechobee depression trends very near the Belle Glade injection well site (Figure 10), possibly lending support to the notion of faulting in this area.

Cores from only two wells, the Belle Glade as described above, and the North Martin County (at 2692 and 2701 feet bls), exhibited any fractures. Most fractures are vertical and occur in moderately to highly indurated limestones and dolostones. The relative rarity of fractures in the study area as compared to that reported from Brevard County injection wells (Duncan et al., 1994) is a reflection of the poorly to moderately indurated lithologies selected for coring, which are less brittle than highly indurated dolostones and sparry calcite cemented limestones. Moreover, an overall lack of dolostone at some sites, specifically the Ft. Pierce and North Martin County wells, may explain the relative absense of fractures there. Structural interpretations in south Florida will remain problematic until seismic data are published or additional seismic and deep well control are acquired.

LITHOSTRATIGRAPHY

General Stratigraphy

Strata in the study area, ranging from Cretaceous to Holocene, 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 13) 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 carbonate mud-supported (mudstone/wackestone) and grain-supported (packstone/grainstone). The term mud, used in the following discussion, will refer to mud-size carbonate particles.

Formation boundaries within the Floridan aquifer system for this study are based out of necessity on traditional criteria used or established by earlier Florida stratigraphers that rely heavily on micro-faunal differences rather than recognizable lithologic differences. Often, in southeastern Florida, age-specific micro-faunal assemblages change abruptly with no or very little lithologic variation. This is commonly the case between the Avon Park/Oldsmar, and Ocala/Avon Park Formations. Also upper and lower dolomitization fronts related to mixing zone dolomitization vary in the vertical sense and cross cut apparent formation/lithologic contacts that might have existed prior to diagenesis. Even where lithologic changes are noted across formation boundaries, they are often very subtle and lithologies similar or identical to those above the contact commonly reappear with depth. The lack of

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

Figure 13. Lithostratigraphic/hydrostratigraphic nomenclature for southern Florida (modified from Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, SE Geologic Society, 1986).

distinctive lithologic breaks and the repetition of similar or identical lithofacies across apparent formation boundaries is to be expected of Paleogene formations as these rocks were deposited on the same carbonate platform in related depositional environments and were exposed to similar diagenetic processes that varied repetitively through time and space according to Walther's Law. The apparently distinctive lithologic/formation breaks recognized in northern peninsular Florida are most likely the result of unconformable contacts related to discontinuous sedimentation and/or erosion over the Ocala Platform whereas in southern Florida deposition was evidently more continuous.

Formation tops indicated in the text are based on combined geophysical and lithologic criteria and may differ slightly from those based solely on cuttings descriptions (Appendix).

Paleocene - Cedar Keys Formation

The Cedar Keys Formation is the sequence of interbedded dolostones and evaporites unconformably overlying the undifferentiated Cretaceous Lawson Formation and unconformably underlying the Lower Eocene Oldsmar Formation (Braunstein et al., 1988). 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 <u>Borelis</u> <u>gunteri</u> except in the highly recrystallized dolostones of the upper Cedar Keys section (Miller, 1986).

The top of the Cedar Keys Formation according to Chen (1965) ranges from approximately -3000 feet NGVD in northern St. Lucie County to -3700 feet NGVD in southern Palm Beach County. The Belle Glade injection well (Appendix 9; Plate 3) is the only well studied that encountered definitive Cedar Keys Formation. The interval between 3322 feet through 3422 bls consists of gray, microcrystalline dolostones interbedded with minor muddy limestones (Appendix 9). From 3422 to 3548 bls (total depth) the lithology changes to anhydritic shale and bedded anhydrite. Borelis gunteri was not identified in any of the cuttings examined probably due to extensive recrystallization associated with dolomitization.

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 underlying Cedar Keys Formation and overlying Avon Park Formation are unconformable (Braunstein et al., 1988). In the study area, the Oldsmar Formation top is based on the correlation and extension of lithologic and geophysical criteria established by Duncan et al. (1994) in Brevard and Indian River Counties. In this area the top of the Oldsmar Formation was established by the presence of a regionally correlative (lithologically and geophysically) glauconitic limestone or dolostone bed that coincides with a lithologic change from white to light gray, glauconitic, moderately indurated, and bioturbated wackestone or packstone of the Oldsmar Formation to cherty, brown dolostones of the overlying Avon Park Formation (Duncan et al., 1994). Duncan et al. (1994) called this stratigraphic unit at the top of the Oldsmar Formation the "glauconite marker bed" (GMB). The first occurrence of the Early Eocene index fossil Helicostegina gyralis also corresponded with the GMB in Brevard County. The top of the Oldsmar Formation in the study area ranges from - 2200 feet NGVD in northern St. Lucie County to - 3050 feet NGVD Palm Beach County (Plate 1). The Oldsmar Formation is 740 feet thick in the Belle Glade injection well which is the only well in the study area to penetrate the entire Lower Eocene section.

In southeastern Florida, lithologic associations in the Oldsmar Formation both similar to and different from those in Brevard and Indian River Counties are evident. Overall the Oldsmar Formation consists of a lower section of predominantly well-indurated, crystalline yellowish-brown dolostone and an upper section of interbedded white to light-gray, chalky packstone, wackestone, mudstone, and grayish-brown dolostone .

The lower Oldsmar Formation is characterized by yellowish-brown to grayish-brown, microcrystalline, dense, and generally non-fossiliferous dolostone. The contact between the more purely crystalline dolostones of the lower Oldsmar Formation with the limestones and calcareous dolostones of the upper Oldsmar Formation is gradational as the degree of dolomitization increases with depth from highly or partially dolomitic limestones to pure crystalline dolostone. The top of this sequence is readily identified on gamma-ray and sonic logs (Plates 2 and 3). Gamma-ray logs commonly show increased radioactivity below this horizon relative to the overlying limestones of the upper Oldsmar Formation. Sonic logs show a marked decrease in interval transit time at this level, which is indicative of the low porosities (less than 5%) and permeabilities prevalent throughout much of this interval.

Benthic foraminifera and echinoderm fragments are the principle allochems comprising packstones and wackestones of the upper Oldsmar Formation interbedded sequence. Minor amounts of slightly phosphatic clay are a common, but minor accessory mineral in the glauconitic wackestones and mudstones of the upper Oldsmar Formation. Limestones are moderately to well cemented with sparry calcite, calcilutite, and/or dolomite. Limestone porosity is variable but in general ranges from 15 to 25% and permeablity, based on visual estimates, is generally low except in the North Port St. Lucie well where permeability is high throughout most of the upper Oldsmar Formation. Higher permeability is more prevalent in mud-poor packstone and grainstone lithofacies than in mud-rich wackestones and mudstones.

Dolostones of the upper Oldsmar Formation are microcrystalline to finely crystalline and fossils are typically not preserved. Laminations, burrows, mottles, and spar-filled root tubes are common in dolostones and dolomitic limestones 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 dolomitization of limestones or incomplete dolomitization is common in the upper Oldsmar Formation and imparts a speckled nature to some calcareous dolostones in this interval. Cores and geophysical logs indicate the dolostone beds range from approximately five to ten feet thick.

The upper Oldsmar is increasingly dolomitic to the south from St. Lucie County to southern Palm Beach County where pervasive dolomitization ultimately obscures the contact between the Oldsmar Formation and the overlying Avon Park Formation. Such is the case in southern Palm Beach County at the Palm Beach County Systems 9 injection well (Plate 2) where a relatively thick dolostone sequence begins 370 feet above the glauconite marker bed and continues to 60 feet below and including the glauconite marker bed.

The glauconitic marker bed of the upper Oldsmar Formation has a characteristic gamma-ray and sonic log signature that is correlative from northern Brevard County into the extreme southern part of the present study area in southern Palm Beach County (Plates 2 and 3) and serves as an excellent datum for stratigraphic and structural analyses. <u>Helicostegina gyralis</u>, a common faunal constituent of the upper Oldsmar Formation in some areas of Florida, was not identified in the study area.

Middle Eocene-Avon Park Formation

Miller (1986) defined the Avon Park Formation as "the sequence of predominately 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 the study area, the Avon Park Formation is characterized by white to yellowish-gray limestones ranging from packstone to mudstone interbedded with very light orange to grayish-brown dolostones that commonly containing organics. Cherty dolostones are typical of the lowermost Avon Park Formation.

The top of the Avon Park Formation is frequently marked by a slight radioactive peak on the gamma-ray log that often coincides with the first occurrence of Dictyoconus sp. foraminifers (Plates 2 And 3). The top of the Avon Park Formation varies from -980 feet NGVD in the Ft. Pierce well to -1311 feet NGVD in the West Palm Beach # 4 well. Formation thickness averages approximately 1600 feet across the study area.

The typical Avon Park Formation section consists of a lowermost sequence characterized by intervals of nodular chert, cherty limestones and cherty dolostones. The chert is typically yellowish-gray to brownish-gray and highly brittle. The middle portion of the Avon Park Formation is characterized by crystalline, very-light orange to yellowish-brown dolostones with low porosity and low permeability that overlie another interval of foramiferal packstones and wackestones. The upper Avon Park Formation consists of very light orange to white to yellowish-gray, moderately indurated, Dictyoconus-rich wackestones and packstones interbedded with highly indurated dolostones and partially dolomitic limestones. The principal allochems are whole foraminiferal tests and echinoderm skeletal fragments.

Grain-supported limestones are only poorly to 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. The range of allochemical and textural alteration in dolostones varies from complete preservation to total destruction dependent on the particular diagenetic mechanism. Dolostones have generally subhedral to anhedral crystalline texture and have equigranular to inequigranular crystal fabric (Friedman and Sanders, 1967). Crystal size ranges from microcrystalline to coarse. Burrows in the lower Avon Park Formation are commonly dolomitized preferentially over the surrounding matrix. Burrows and vugs commonly contain coarser-grained dolomite crystals than 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 but are generally lower than that observed in non-dolomitic carbonates. 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.

A calcrete zone noted in the West Palm Beach #6 well at 2257 feet bls indicates a subaerial exposure surface at this level. Analysis of a petrographic thin section from core at this depth revealed an undulating, micro-karstic surface encrusted with Microcodium colonies, a calcified structure formed by a symbiotic association between soil fungi and higher-plant root cells (Scholle et al., 1983). Corroded clasts of a remnant foraminiferal limestone appear to "float" in a matrix of highly dolomitic, carbonate.

Upper Eocene-Ocala Limestone

The Ocala Limestone, as described by Applin and Applin (1944), consists of a lower member of cream to white, fined-grained, poorly to moderately indurated, micritic, milliolid-rich limestone and an upper member of white, poorly-indurated, porous coquina composed chiefly of foraminifera, bryzoan and echinoid fragments. The Ocala Limestone is unconformably overlain by the Oligocene-Pliocene Hawthorn Group in the study area (Scott et al., 1994; Missimer et al., 1994). The contact with the underlying Avon Park Formation is also unconformable (Braunstein et al., 1988). In much of the study area, however, the basal contact (if any) is conformable as there is no apparent lithologic break to separate Upper Eocene (Ocala Limestone) grainstones/packstones from those in the underlying Middle Eocene (Avon Park Formation). The typical microfaunal change from Lepidocyclina ocalanus to Dictyoconus sp., Lituonella sp. and other diagnostic Middle Eocene benthic forams is recognizable in the study area, but in several wells (Ft. Pierce, Appendix 1; North Port St. Lucie, Appendix 2; West Palm Beach, Appendix 5; Pahokee, Appendix 8) Ocala microfauna continues well into the cone-bearing Avon Park Formation or visa versa. Depositional environments were evidently continuous across the Middle Eocene-Late Eocene boundary in some areas of southern Florida.

In the study area, the Ocala consists of yellowish-gray to very light orange, coarse grained, poorly to rarely moderately indurated, interbedded packstone and wackestone with occassional grainstone and mudstone. The principal allochems are foraminfera and echinoderm fragments. The Ocala Limestone micro-fauna commonly includes Lepidocyclina ocalana, Amphistegina pinarensis, and various milliolids. 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).

Porosity and permeability are generally high throughout the Ocala Limestone, as 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 -700 feet NGVD at the Ft. Pierce site to -1050 feet NGVD at the West Palm Beach # 4 site.

Ocala Limestone thickness is highly variable throughout the study area ranging from zero to 270 feet thick. Thickness variations are structurally controlled in part as the Ocala Limestone apparently thins or pinches out over some anticlinal highs (Plate 2 and 3). In Palm Beach County, the Ocala Limestone thins and eventually pinches out to the west between the West Palm Beach and Royal Palm Beach injection sites (Plate 3) over a structural high in the Middle and Lower Eocene (Plate 1). The Ocala Limestone is thin in the Belle Glade and Pahokee wells (Plate 3), possibly in relation to the south-plunging anticlinal nose (Brevard Platform ?) located in central St. Lucie, Martin and Palm Beach Counties (Plate 1).

Winston (1993) explained the absence of typical Upper Eocene Ocala Limestone coquina and fauna in southeastern penisular Florida as the result of a facies change within the upper Avon Park Formation due to continuous deposition across the Middle Eocene/Upper Eocene boundary. Winston (1993) discounted any need or evidence for tectonic or structural uplifts as the cause for thickness variations, or pinchouts of the Ocala Limestone in southeastern Florida. The apparent "mixing" of Ocala Limestone microfauna with Avon Park microfauna observed in several wells reviewed for this study support the notion of at least some degree of lateral facies equivalency between the upper Avon Park Formation and the Ocala Limestone and that this facies relationship can in some cases explain the absence of typical Ocala Limestone. In Palm Beach County, however, there is evidence of some structural control over the Ocala thickness as indicated by the Ocala Limestone pinch-out between the West Palm Beach and Royal Palm Beach injection wells over a structural high in the Lower and Middle Eocene section (Plates 1 and 2).

Oligocene-Suwannee Limestone

Miller (1986) mapped a relatively thin (<100 feet thick) subcrop of Suwannee Limestone in extreme eastern St. Lucie and Martin Counties and in western Palm Beach County. Lithofacies characteristic of Suwannee Limestone were not, however, recognized in this study

Oligocene-Pliocene Hawthorn Group

The Hawthorn Group in the study area unconformably overlies the Ocala Limestone and consists of interbedded light olive to yellowish gray, poorly indurated calcareous silt, clay, quartz sand, and silty, sandy wackestone and mudstone. 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 southeastern peninsular Florida.

Hawthorn Group thickness is highly variable ranging from 530 feet at the West Palm Beach #4 site to 940 feet at the Palm Beach County Southern regional site. The top of Hawthorn Group ranges from -115 feet NGVD at the North Port St. Lucie site to -431 feet NGVD at the West Palm Beach #4 site.

Pliocene - Holocene Undifferentiated

Overlying the Hawthorn Group is a sequence of generally unconsolidated sandy shell beds, clays, and shelly quartz sands that range from Pliocene to Holocene in age (Brown et al, 1962). Cementation of the shell beds and shelly sands by calcite spar can result in highly indurated lithologies (coquina and sandstone). Total thickness of the Pliocene-Holocene section varies from 130 feet at the North Port St. Lucie site to 450 feet at the West Palm Beach #4 site.

DEPOSITIONAL ENVIRONMENTS OF THE OLDSMAR AND AVON PARK FORMATIONS

The thick sequence of limestones and dolostones comprising the Floridan aquifer system were deposited on an extensive carbonate platform that existed from Late Cretaceous through the 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 environmental interpretations in terms of subsurface studies. Drill cuttings are less useful because of their small size and because of the uncertainty associated with cavings. Severe limitations on the degree to which reasonable interpretations of lower Floridan depositional environments are posed by the lack of core in general, and the lack of stratigraphically-equivalent cored intervals in the available cores. Observations regarding depositional environments for purposes of this study were based entirely on information derived from core and thin section examination. Utilized cores include the Ft. Pierce, North Martin County, West Palm Beach #6, Belle Glade, and Pahokee injection wells and the Encon monitor well. Depositional-environmental interpretations herein 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

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

Much of the interbedded mudstones, wackestones, packstones and dolostones of the upper Oldsmar Formation 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 occurs in the Belle Glade well from 2708 feet bls to 2713 feet bls (Appendix 9) and in the Pahokee well (at approximately the same stratigraphic level as the

Belle Glade) 2597 feet bls to 2599 bls (Appendix 8). This section consists of light-gray mudstone interbedded with a pinkish-gray peloidal packstone. The mudstone is penetrated by numerous vertical tubes that represent roots that have long since decayed leaving molds. Algal-laminated and organic-rich, dolomitic limestones are noted in the Pahokee well at the equivalent stratigraphic interval.

Andros Island tidal flats serve as an excellent modern analog for the depositional environment of upper Oldsmar Formation 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 dolomitic limestones and dolostones of the Oldsmar Formation are comparable to recent supratidal dolomitic crusts that occur on Andros Island tidal flats (Shinn et al, 1969). Peloidal mudstones with root molds are similar to intertidal zone sediments of western Andros Island (Shinn et al, 1969). Duncan et al. (1994) found similar sedimentary structures indicative of tidal-flat deposition in the upper Oldsmar Formation in Brevard County injection wells.

The observed mineralogical suite of the uppermost Oldsmar Formation that includes glauconite, and phosphatic 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-half to as much as two percent of the total rock in the upper Oldsmar Formation. Glauconitization occurs at the sediment-seawater interface in marine waters where sedimentation rates are slow and bottom turbulence is minimal (Odin and Fullagar, 1988).

Phosphatic clay in micritic limestone is present in the upper Oldsmar glauconitic interval in the West Palm Beach site (3090 - 3130 feet bls). Phosphatization typically occurs where phosphate-rich water upwells adjacent to shallow shelves or platforms that border deep marine basins (Friedman and Sanders, 1978). Phosphate forms at the sediment-water interface under similar conditions to that of glauconite and consequently is commonly in glauconitic sediments.

The source of the clay is somewhat problematic given the apparent isolation of the carbonate platform from any potential siliciclastic source during this time period. The clay is possibly windblown, altered volcanic ash carried northward from erupting island arc volcanoes associated with subduction along the Caribbean/North American-plate boundary. Subduction and related island arc vulcanism occured from the Late Cretaceous through the Middle Tertiary (Sheridan et al., 1981; Hempton, 1991) which is consistent with the age of the upper Oldsmar Formation.

Avon Park Formation

A diversity of carbonate depositional environments are represented over the approximately 1600 feet of vertical sequence that comprises the Avon Park Formation in the study area. 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 mud-poor grainstone and packstone sequence in the middle to lower Avon Park Formation (below the Middle Avon Park Formation geophysical marker, Plates 2 and 3) is suggestive of higher-energy depositional conditions, however sedimentary structures indicative of a specific depositional environment are not observed due to very limited core representation across this section. Equivalent stratigraphic intervals that were cored more thoroughly in Brevard County injection wells contain sedimentary structures associated with beach and shoal type depositional environments (Duncan et al., 1994). High concentrations (50 to 80%) of coralline red algae (both encrusting and crustose varieties) or rhodoliths in a grainstone/packstone matrix at 2169 to 2179 feet bls and 2292 to 2303 feet bls in the North Martin County well (Appendix 3) suggest the possibility of a shallow water biostrome or coral-algal reef development at this location during the Middle Eocene. Red algal concentrations in the 10 to 20% range in the Ft. Pierce (Appendix 1) at 2300 to 2310 feet bls and a mixture of corals and coralline red algae at 2520 to 2525 feet bls may indicate a proximity to and possible size of the postulated reefal deposit.

Burrows are the most common sedimentary structure observed in cores from the lower Avon Park Formation of the southeastern Florida study area. Bioturbation typically signifies lower-energy conditions and slower sedimentation rates (Friedman and Sanders, 1978). The absence of bedding in core from this interval suggests that energy conditions were typically low allowing burrowing organisms to rework and completely homogenize the substrate. It is possible that some of the extensively burrowed grainstones and packstones were deposited as tempestites under episodic high-energy conditions and later reworked by burrowing organisms during normal periods of lower current energy and slower deposition.

Randazzo and Cook (1987) studied approximately 450 feet of upper Avon Park Formation core from west central Florida and conlcuded 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. Many of these sedimentary structures are found in the lower Avon Park Formation of the study area indicating a similar depositional origin.

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 in the study area.

Poorly to moderately indurated limestones can 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 high 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 salt-water 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 2 and 3). Glauconite and phosphatic clay are common accessory minerals the uppermost Oldsmar. The gamma-ray log, in response to this mineralogy, shows an abrupt increase of gamma-ray activity across the zone that can be identified and traced from northern Brevard County (Merrit Island injection site) to southern Palm Beach County (Palm Beach County Systems 9 site). This geophysically and lithologically distinctive zone is informally referred to as the glauconite marker bed. The sonic-log response across this interval, although not directly related to this mineralogy, is correlative to a lesser degree (at least locally) among many of the injection wells. Sonic-log interval transit times are highly variable throughout the uppermost Oldsmar, apparently reflecting porosity differences between the more porous limestones (approximately 30% porosity) and less porous dolostones (approximately 15% 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. In such cases, dolostones have sonic-log curves that peak in the low-porosity direction (generally 20% or less porosity). Sonic-log curves in limestones, on the other hand, peak in the high-porosity direction (30% or greater). This relationship is especially true of upper Avon Park Formation.

Induction-resisivity logs can be useful in distinguishing relatively low-porosity zones from relatively high-porosity zones within the lower Floridan aquifer system. Low-porosity, salt-water saturated carbonates are highly resistive and are typically indicative of dense dolostones or possibly calcite spar cemented limestones. Highly porous, salt-water-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, approaching, if not corresponding to, that of the formation water alone.

Several sections of the Floridan aquifer system have gamma-ray signatures that are correlative throughout the study area (Plates 2 and 3), especially the Eocene section. An example of this remarkable degree of correlation is illustrated in Figure 14, which compares the gamma-ray and sonic-log character of the Encon and Sea

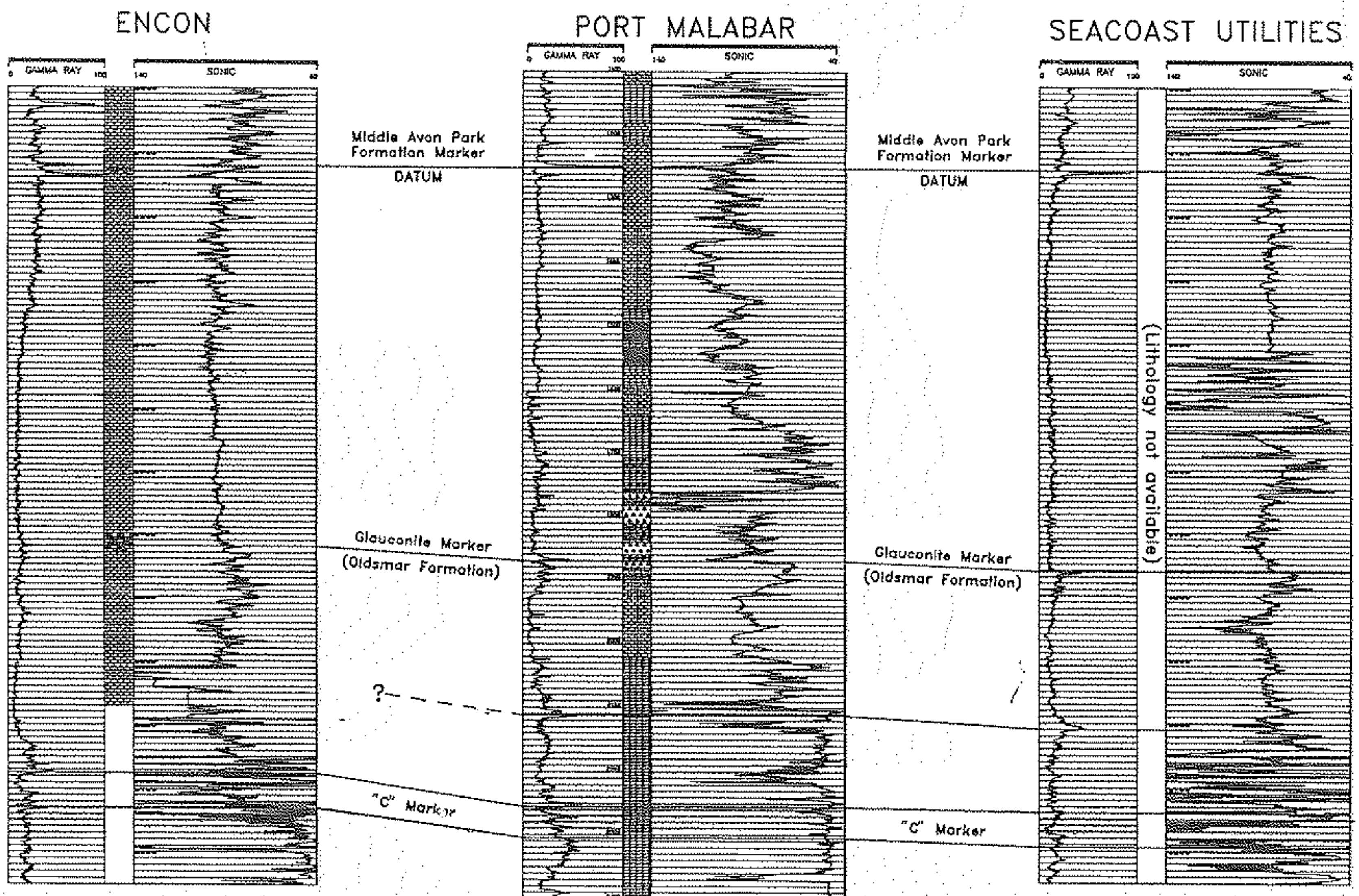


Figure 14. Geophysical comparison of the Port Malabar injection well, Brevard Co. with the Encon and Seacoast Utilities in Palm Beach County, Florida.

Coast Utilities injection sites in Palm Beach County with the Port Malabar injection site in Brevard County. The Brevard County well, located roughly 80 miles to the north, has gamma-ray and, to some degree, sonic-log signatures that are close duplicates of the Palm Beach County well logs.

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), Randazzo et al. (1977, 1978, 1987), and Cander (1991) relate to the lower Floridan aquifer system and are summarized in the following discussion.

Hanshaw et al. (1971) hypothesized a mixing-zone dolomitization model for the regionally extensive Floridan aquifer system dolostones. In this 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 salt water 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 salt-water/fresh-water interface due to sea-level variations, climatic changes, and/or platform uplift or subsidence has also facilitated dolomitization within much of the Floridan aquifer system (Hanshaw et al., 1971).

Randazzo et al. (1977), in their study of upper Avon Park Formation dolostones of west-central Florida, recognized three principal textures indicative of different dolomitization processes: 1) dolomitizat' 46
^T (otal replacement, 2) dolomitization by aggrading porphyroid and coelescive 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 et al. (1978) acknowledged the mixing-zone model's role in dolomitization of Avon Park Formation carbonates in west-central Florida. They concluded that some Avon Park Formation 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-fresh water interface and a ground-water mixing zone (Randazzo et al., 1978).

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 87Sr/86Sr isotopic compositions, indicating that the Avon Park Formation underwent massive dolomitization by normal to hypersaline seawater during the Middle Eocene, essentially contemporaneous with deposition." Cander (1991) concluded that the Avon Park Formation in central penisular Florida was deposited in a tidal-flat environment (sabkha) under arid climatic conditions analogous to the modern Persian Gulf.

Cander (1991) recognized a late stage of mixing-zone dolomite that is present locally in more coastal Avon Park Formation areas. 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).

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 objection 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 dolomite replacement 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).

Dolomitization within the Floridan aquifer system is variable throughout the study area. The Ft. Pierce and North Martin County sites have atypical Lower and Middle Eocene lithostratigraphic sections in that little or no dolostones are present in the Avon Park and upper Oldsmar Formations (Plate 2). The amount of dolostone appears to increase in an inland direction in St. Lucie County.

Both penecontemporaneous and diagenetic dolomitization processes have apparently affected lower Floridan aquifer system carbonates in southeast Florida. Dolostones having similar texture and color to mixing-zone dolostones described by Cander (1991) are present in the Avon Park Formation of the southeastern Florida study area. 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 Floridan aquifer system is best explained by marine dolomitization, probably penecontemporaneous with deposition in a tidal flat environment.

HYDROGEOLOGY OF THE FLORIDAN AQUIFER SYSTEM

General Hydrogeologic Summary

Four major hydrogeologic units occur in peninsular Florida (Southeastern Geological Society (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 13). 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 St. Lucie, Martin and Palm Beach Counties, the surficial aquifer system is a permeable unconfined aquifer. This unit is contiguous with land surface and varies in thickness.

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. The intermediate aquifer system is not well developed in eastern, central and southeastern peninsular Florida and is not an important source of drinking water (Scott et al., 1991). Locally, the intermediate confining unit may be breached due to karst (sinkhole) formation, fracturing, or erosion; thus, the upper Floridan aquifer system may be under confined, semiconfined, or unconfined conditions.

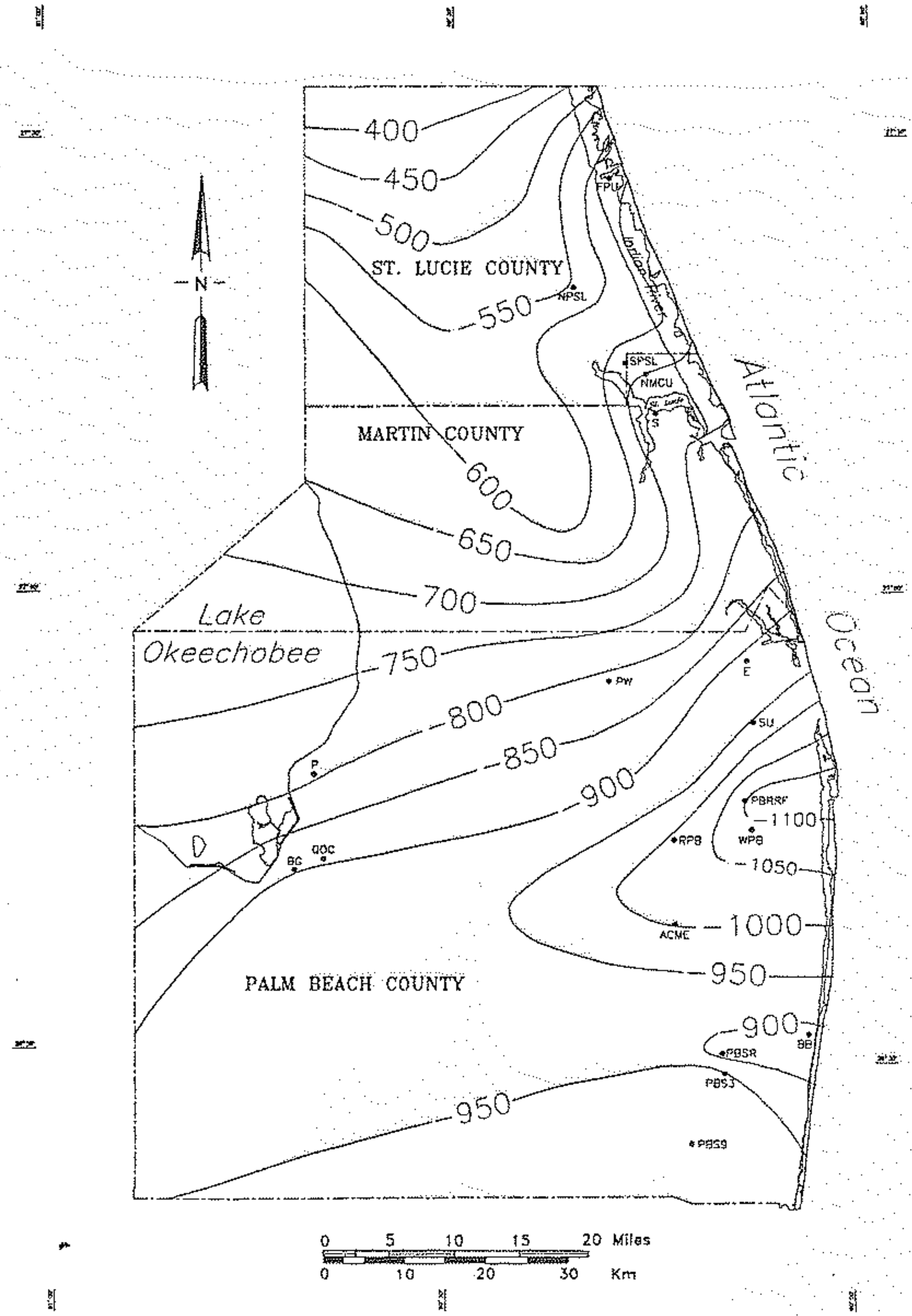
The Floridan aquifer system, as defined by Miller (1986), is a vertically continuous sequence of carbonate rocks of generally high permeability. These middle to upper Tertiary carbonates are hydraulically connected to varying degrees. Permeability is typically several orders of magnitude greater than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

In St. Lucie, Martin, and Palm Beach Counties, the Floridan aquifer system generally consists of two major permeable zones (Plates 4 and 5) 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 cavernous and fractured nature of the dolostone commonly causes boulder-sized 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 exceeds 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 2). 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 15) 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, in general, contiguous with the top of the Eocene Ocala Limestone (Plates 4 and 5) and occurs at elevations ranging from -400 to greater than



Contour Interval = 50 ft.

Figure 15. Top of the Floridan aquifer system in St. Lucie, Martin and Palm Beach Counties.

-1,100 feet NGVD (Figure 15). In some areas the top of the Floridan begins in continuous carbonate sequences in the lower Hawthorn Group (Plates 4 and 5). The thickness of the Floridan aquifer system in the study area ranges between 2,700 to more than 3,400 feet and generally increases to the south (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 occur where the Floridan aquifer system is unconfined or poorly confined. Karst features (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 depending upon the potentiometric gradient between the systems.

Artesian conditions are present over most of the study area (Scott et. al., 1991). In areas where there is relatively poor or non-existent confinement, and where the water table is higher than the potentiometric surface, artesian conditions are absent and recharge to the Floridan aquifer system may occur. Transmissivity of the upper Floridan aquifer system (Figure 16) 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 is defined in terms of a permeability contrast that limits the depth of active ground-water circulation

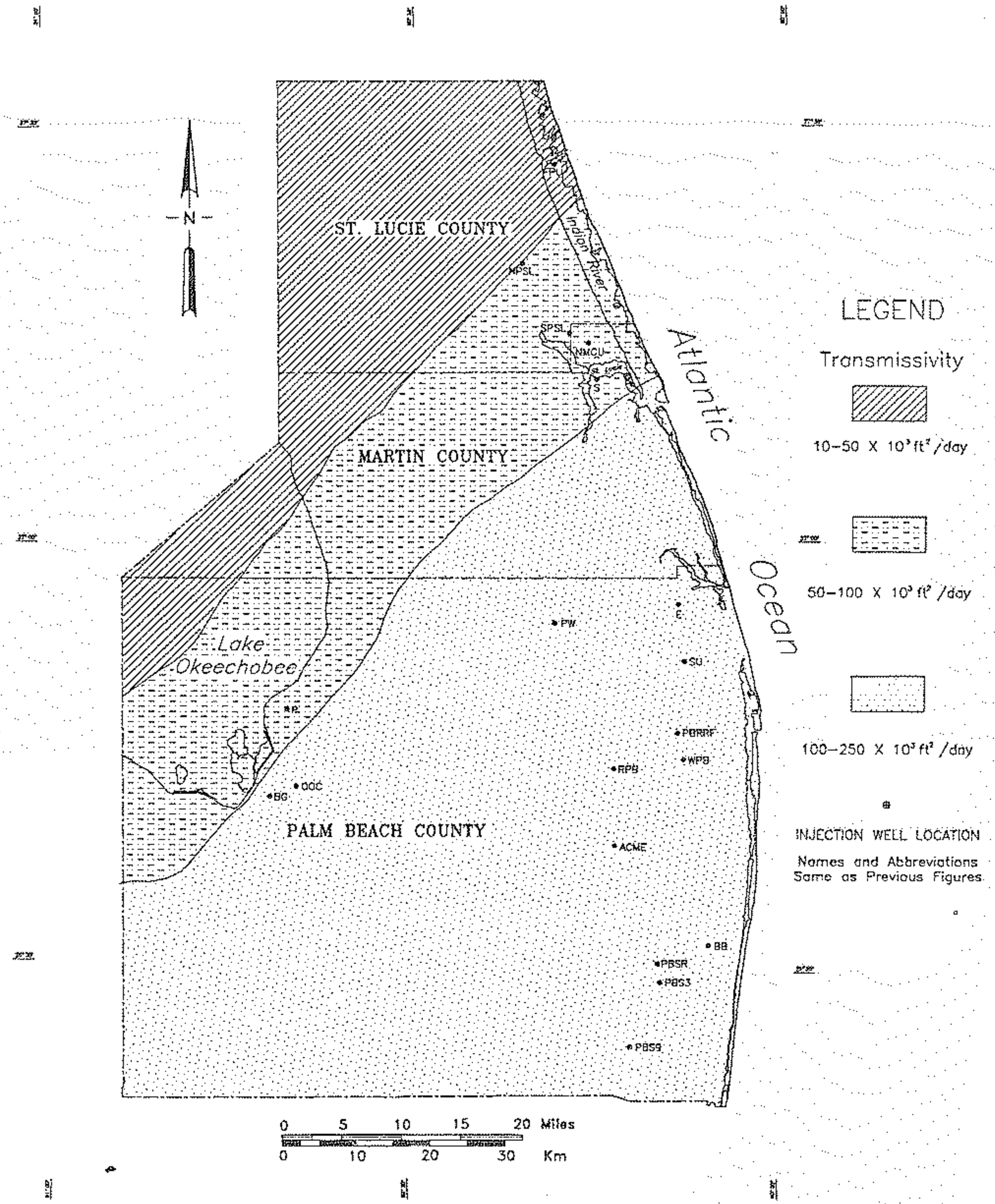


Figure 16. Estimated transmissivity of upper Floridan aquifer system, St. Lucie, Martin and Palm Beach Counties (after Miller, 1986).

and generally is associated with the Upper Paleocene Cedar Keys Formation (Figure 13). The injection and monitor wells in the study area are not deep enough to encounter the sub-Floridan confining unit except in the Belle Glade injection well. The top of the sub-Floridan is approximately 3400 feet NGVD in this well (Plate 2).

Hydrogeology of the Middle Confining Unit

The upper and lower Floridan aquifer systems are separated by a middle confining unit (Miller, 1986) (Plates 4 and 5). 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 (Miller, 1986) are 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 and may be associated with the Avon Park marker bed (Plates 4 and 5). 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 (Plates 4 and 5).

The middle confining unit is recognized on geophysical logs by a slight increase in gamma-ray activity (when the carbonates are not fractured). The sonic log exhibits a decrease in interval transit time as the limestones of the upper Floridan aquifer system abruptly grade into low porosity (less than 20 percent), dense, microcrystalline dolostones that make up the middle confining unit (Plates 4 and 5).

The top of the middle confining unit in the study area is between -1,600 to -2,000 feet NGVD (Plates 4 and 5). The thickness of the middle confining unit ranges from 0 to 800 feet, attaining its greatest thickess in eastern Palm Beach County (Figure 17). Based on lithologic criteria, it appears that the middle confining unit is absent at the North Port Saint Lucie and North Martin County Utilities injection wells in the northern portion of the study area. This is due to lack of dolomitization (see Dolomitization section for further discussion) and demonstrates the significance of local geologic variation (Plates 4 and 5).

Quantitative field data and aquifer tests (straddle-packer tests) that describe the water-transmitting characteristics of the middle confining unit were analyzed for the Pahokee and Belle Glade injection wells (Table 1). Hydraulic conductivity is estimated at 8.2×10^{-2} cm/s at the Pahokee site (an interval of 1,776 to 1,821 feet below pad surface) and transmissivity is 78,185 gpd/ft (Geraghty and Miller, 1991). At the Belle Glade site, hydraulic conductivity is estimated at 3.4×10^{-4} cm/s at the interval of 1,960 to 1,980 feet below pad surface and 1.1×10^{-2} cm/s at 1,994

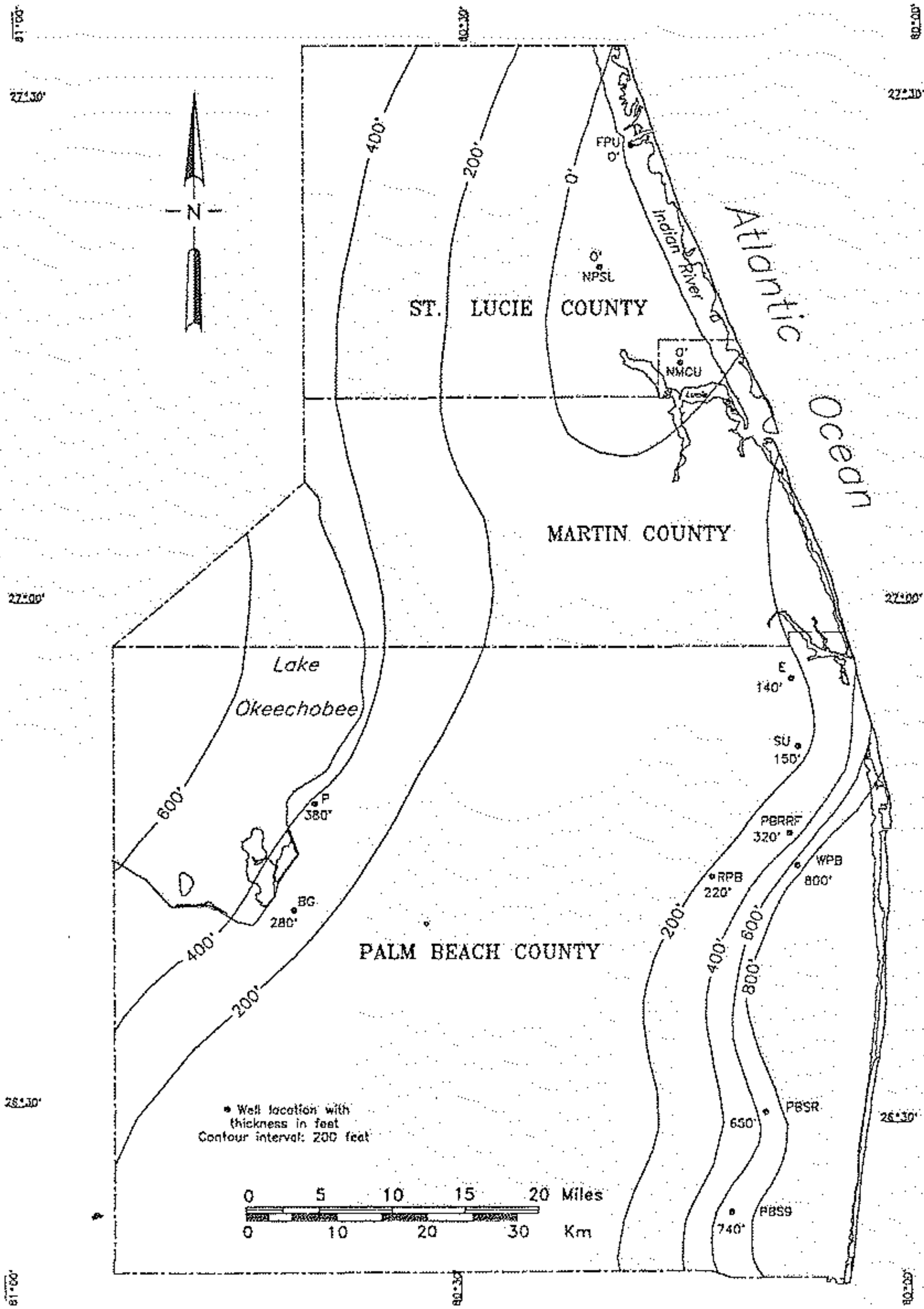


Figure 17. Thickness of the middle confining unit of the Floridan aquifer system in St. Lucie, Martin, and Palm Beach Counties.

Table 1. Transmissivity and hydraulic conductivity from straddle packer tests.

Site	depth in feet below pad level	interval thickness (feet)	calculated transmissivity (gpd/ft)	hydraulic conductivity (cm/sec)	consultant
North Martin County Utilities	1720 - 1740	20	4325	3.0E-02	Geraghty & Miller, Inc. 1988, Table 3
	1895 - 1915	20	5169	3.4E-02	
	2186 - 2206	20	1615	1.2E-02	
	2576 - 2596	20	522	3.8E-03	
	2723 - 2743	20	261	1.9E-03	
Pahokee	1776 - 1821	45	78185	8.2E-02	Geraghty & Miller, Inc. 1991, Table 1
	2350 - 2370	20	1377	3.2E-03	
Belle Glade	1960 - 1980	20	143	3.4E-04	Geraghty & Miller, Inc. 1991, Table 2
	1994 - 2024	30	7166	1.1E-02	
	1610 - 1640	30	94	1.5E-04	
	2756 - 2774	18	160	4.2E-04	
	2513 - 2531	18	170	4.5E-04	

to 2,024 feet below pad surface. Transmissivity values for these two intervals are 143 gpd/ft and 7,166 gpd/ft respectively. Geophysical evidence coupled with borehole video observations indicate that the middle confining unit contains fractures at several of the well sites (Plates 4 and 5). Locally, vertical fractures may hydraulically connect the upper and lower Floridan aquifer system; however, the available data is insufficient to accurately make this determination.

Lower Floridan Aquifer System

The lower Floridan aquifer system consists of all beds that lie below the middle confining unit (Plates 4 and 5) and above the sub-Floridan confining unit (Miller, 1986). If the middle confining unit is absent, the upper boundary of the lower Floridan can be geochemically defined . 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 (Plates 4 and 5).

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 (Plates 4 and 5).

Geophysical and lithologic evaluations of the injection wells indicates that the top of the lower Floridan aquifer system is located between -1,600 to 2,00 feet NGVD. The injection wells are not deep enough to fully penetrate the lower Floridan aquifer system except at Belle Glade. The lower Floridan is approximately 1,580 feet thick at the Belle Glade site.

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). Direction of water movement, however, 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 by the circulation of cold sea water inland through the lower part of the Floridan aquifer system (see Geothermal Gradient Section). 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 numerous fracture zones in the lower Floridan aquifer system exist (Plates 4 and 5).

The quantitative methods used to describe aquifer parameters usually assume homogeneous, isotropic conditions in a granular medium that assumes laminar flow. On a regional scale these methods may be satisfactory (Bush and Johnson, 1988). Locally, however, the lower Floridan aquifer system is heterogeneous. 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 conductivity 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) (Tables 1 and 2). Hydraulic conductivity analyses reported by various consulting firms (Table 2) indicate that vertical ground water movement in the lower Floridan aquifer system is generally low with values less than 10^{-4} cm/s in the vertical direction (Table 2). Horizontal hydraulic conductivity (when analyzed) values are no greater than 1.2×10^{-3} cm/s (Table 2). Transmissivity values for the lower Floridan aquifer system above the Boulder Zone have been reported only in the North Martin County, Pahokee and Belle Glade injection wells. Transmissivity estimates are variable and range between 143 to 78,185 gpd/ft (Table 1).

Boulder Zone

The Boulder Zone (Kohout, 1965) is a subzone 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 paleo-water tables were at a level that resulted in karstification of the upper part of the carbonate sequence (Vernon, 1970; Puri and Winston, 1974). However, a study of four injection sites along the east coast of Florida by Safco and Hickey (1992) concluded that

Table 2. Core permeability and porosity analyses from selected injection sites.

Site	depth (feet) below pad level (bpl)			vertical permeability (cm/sec)	horizontal permeability (cm/sec)	total porosity percent	consultant
West	2085.0	-	2086.5	2.0E-07	no data	18	Geraghty &
Palm	2154.0	-	2154.5	1.9E-07	no data	16	Miller, Inc.
Beach	2207.9	-	2208.5	1.4E-07	no data	17	1987, Table 1
#6	2257.0	-	2257.4	1.2E-07	no data	23	
	2335.6	-	2336.3	1.4E-05	no data	31	
	2446.5	-	2447.0	1.7E-07	no data	17	
	2541.3	-	2541.9	4.3E-07	no data	34	
	2653.4	-	2654.0	2.3E-05	no data	36	
Palm	2066.0	-	2067.0	1.1E-10	2.1E-08	10	CH2M Hill,
Beach	2101.5	-	2102.5	2.9E-10	4.8E-10	12	Inc., 1991,
County	2196.0	-	2197.0	1.5E-06	1.1E-06	17	Table 4-1
Southern	2296.5	-	2297.5	3.8E-06	9.0E-06	26	
Region	2400.0	-	2400.7	1.1E-04	7.9E-05	32	
IW2	2512.0	-	2513.0	1.1E-05	1.1E-05	29	
	2625.0	-	2626.0	1.3E-06	3.7E-06	24	
Palm	1891.0	-	1891.8	4.0E-05	no data	no data	CH2M Hill,
Beach	1893.0	-	1895.0	2.0E-06	2.0E-05	23	Inc., 1986,
County	1893.0	-	1897.6	2.0E-05	3.0E-08	4	Table 3-1
System 9	2015.0	-	2015.6	5.0E-06	no data	29	
North	2019.1	-	2019.7	2.0E-05	5.0E-06	30	
	2023.4	-	2024.0	3.0E-10	2.0E-07	6	
	2374.7	-	2375.5	2.0E-09	no data	no data	
	2375.5	-	2376.0	2.0E-10	no data	1	
	2505.6	-	2505.8	4.0E-09	no data	no data	
	2510.6	-	2511.0	no data	no data	27	
	2516.0	-	2516.6	2.0E-05	no data	no data	
	2517.4	-	2518.1	1.0E-05	no data	no data	
	2518.3	-	2518.7	1.0E-05	no data	no data	
	2520.4	-	2520.8	7.0E-07	no data	no data	
	2590.5	-	2590.9	5.0E-06	no data	no data	
	2591.5	-	2591.8	3.0E-05	no data	no data	
	2592.4	-	2592.9	2.0E-05	no data	no data	
	2594.2	-	2594.7	no data	no data	29	

Table 2 (cont.). Core permeability and porosity analyses from selected injection sites.

Site	depth (feet) below pad level (bpl)	vertical permeability (cm/sec)	horizontal permeability (cm/sec)	total porosity percent	consultant
Pahokee	2366	3.2E-05	2.4E-05	no data	Geraghty & Miller, Inc. 1991, Table 2
	2367	3.8E-05	3.3E-05	no data	
	2411	1.0E-04	5.1E-05	no data	
	2412	1.3E-05	2.2E-05	no data	
	2414	3.2E-05	7.9E-06	no data	
	2592	4.6E-05	1.2E-05	no data	
	2597	7.6E-07	6.8E-05	no data	
	2603	1.5E-06	1.8E-04	no data	
	2637	1.6E-05	4.8E-05	no data	
	2644	2.2E-06	1.5E-05	no data	
	2648	6.2E-06	6.2E-05	no data	
	2747	2.4E-05	5.5E-04	no data	
Belle Glade IW1	2410	7.9E-06	3.1E-06	24	Geraghty & Miller, Inc., 1991, Table 1
	2411	1.6E-05	1.2E-05	23	
	2418	4.4E-06	1.2E-05	26	
	2459	1.2E-05	1.4E-05	26	
	2460	5.9E-05	6.7E-05	24	
	2462	2.4E-06	4.6E-05	24	
	2520	1.3E-05	9.4E-06	17	
	2522	2.3E-05	4.2E-06	18	
	2523	8.7E-06	2.5E-05	25	
	2524	4.7E-06	6.9E-06	20	
	2525	5.9E-07	9.2E-06	19	
	2603	6.7E-05	3.2E-05	21	
	2670	4.7E-05	5.9E-06	11	
	2671	6.6E-07	4.9E-06	23	
	2672	7.1E-06	2.8E-06	21	
	2711	3.5E-06	1.0E-05	27	
	2756	8.0E-04	1.3E-03	37	
	2757	7.8E-04	7.6E-04	35	
	2758	4.5E-04	6.1E-05	38	
	2763	1.2E-03	2.7E-03	33	
	2764	6.9E-04	1.6E-04	33	

Table 2 (cont.). Core permeability and porosity analyses from selected injection sites.

Site	depth (feet) below pad level (bpl)			vertical permeability (cm/sec)	horizontal permeability (cm/sec)	total porosity percent	consultant
Fort Pierce	2136			5.2E-04	1.3E-04	35	CH2M Hill, Inc., 1993, Table 4-1
	2140			3.0E-04	6.3E-04	35	
	2201			1.9E-05	1.1E-05	37	
	2213			3.4E-05	1.8E-05	38	
	2251			3.1E-05	8.0E-06	37	
	2259			1.6E-05	2.5E-05	38	
	2301			7.1E-06	1.6E-05	35	
	2309			7.4E-06	7.0E-05	37	
	2432			2.8E-06	3.5E-06	34	
	2515			1.1E-05	2.6E-04	28	
	2592			1.6E-05	3.0E-07	18	
North Port Saint Lucie	2101.0	-	2101.8	4.5E-05	5.4E-05	35	CH2M Hill, Inc., 1987, Table 3-2
	2108.2	-	2109.0	4.4E-05	3.3E-05	31	
	2249.0	-	2250.0	3.5E-07	1.4E-07	11	
	2253.5	-	2254.0	2.8E-03	1.2E-03	35	
	2425.0	-	2426.2	6.7E-04	5.7E-04	35	
	2430.0	-	2431.0	1.6E-05	3.4E-04	35	
	2449.0	-	2450.0	3.5E-06	8.9E-05	37	
	2451.0	-	2451.8	2.3E-05	1.1E-05	31	
	2628.0	-	2629.0	4.1E-05	1.9E-04	27	
	2632.5	-	2633.0	5.0E-04	1.5E-04	31	
North Martin County Utilities	2171.3	-	2172.0	2.2E-04	5.3E-07	15	Geraghty & Miller, Inc. 1988, Table 2
	2296.4	-	2297.0	4.9E-04	3.5E-05	38	
	2413.4	-	2413.9	6.3E-07	2.0E-06	20	
	2549.5	-	2550.2	1.7E-04	3.1E-04	32	
	2695.1	-	2695.6	3.3E-06	2.7E-05	27	
Encon	2058.9	-	2059.4	8.3E-07	no data	29	Geraghty & Miller, Inc., 1986, Table 2
	2151.5	-	2151.9	4.2E-05	no data	31	
	2247.0	-	2247.6	3.8E-05	no data	31	
	2346.6	-	2347.2	1.4E-04	no data	39	
	2443.0	-	2444.2	1.1E-05	no data	37	
	2545.7	-	2546.6	1.9E-05	no data	36	
	2641.2	-	2642.0	6.7E-06	no data	34	
	2748.3	-	2748.7	6.0E-07	no data	28	

fracture porosity is the principle type of secondary porosity within the Boulder Zone. Duncan et al., (1994) and the present study, utilizing core samples, borehole videos and geophysical logs, support this hypothesis. The Boulder Zone has no stratigraphic significance and can exist at any level or locale where paleo-conditions allowed for the formation of fracture porosity.

The Boulder Zone in the study area is generally located in the Lower Eocene Oldsmar Formation at a depth of approximately -3,000 feet NGVD which is below the glauconite marker bed and is generally associated with the "C" marker bed (Figure 18 and Plates 4 and 5). Thickness of the Boulder Zone is locally variable and ranges between 60 to 364 feet (Plates 4 and 5). The Boulder Zone in peninsular Florida diminishes northward (Miller, 1986).

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 (Plates 4 and 5).

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, 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

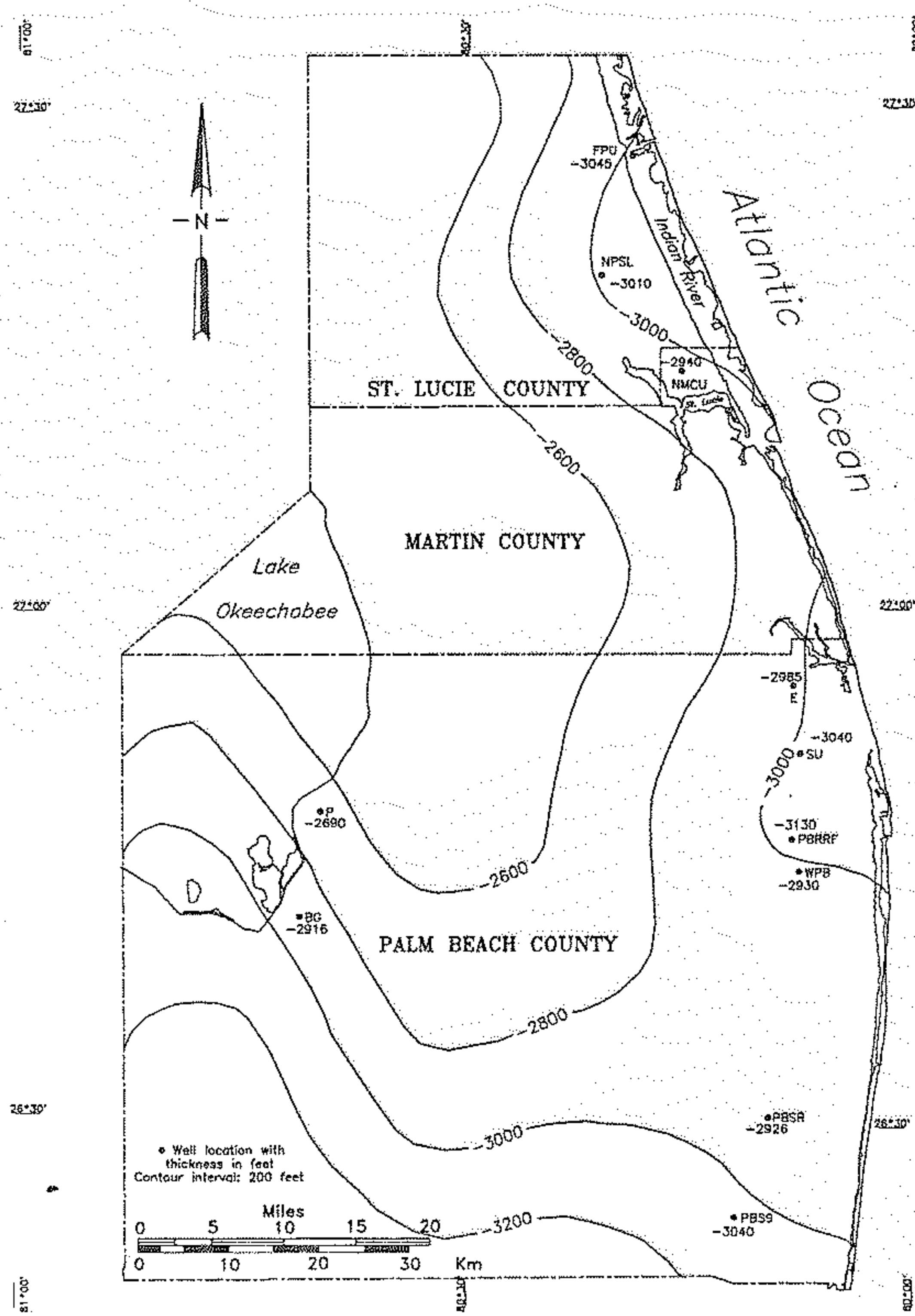


Figure 18. Top of the Boulder Zone in St. Lucie, Martin, and Plam Beach Counties.

videos and geophysical logs, supports this hypothesis.

Confining Layers

Possible confining layers above the Boulder Zone, within the lower Floridan aquifer system, are defined conservatively in this study and are not always in agreement with confining layers delineated by the various consulting firms (Plates 4 and 5). 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 and lithologic cutting's permeability estimates are less than 20 percent, that are traceable and correlative in the subsurface between the injection wells, are defined as confining layers.

The rocks underlying the Boulder Zone are dense microcrystalline dolostones with porosities less than 15 percent. These dolostones are locally fractured in places and extend below the total depth of the injection wells. These carbonates, in general, appear to be a layer of confinement (Plates 4 and 5).

Fractures and Vertical Flow

As previously noted, analysis of geophysical logs, lithologic samples and borehole videos indicate that numerous fractures exist throughout the lower Floridan aquifer system (Plates 4 and 5). 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 appropriate 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 19). 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 and bedding planes. Analyses of geophysical logs and borehole videos indicate fractured dolostones in and above the injection zone (Boulder Zone) (Plates 4 and 5). Normal faulting in the area where the Sea Coast and Palm Beach County RRF wells are located (Plate 4) could result in increased secondary porosity along the fault plane (or within the fault zone) and locally enhanced fracturing (see Structural Geology section for further discussion).

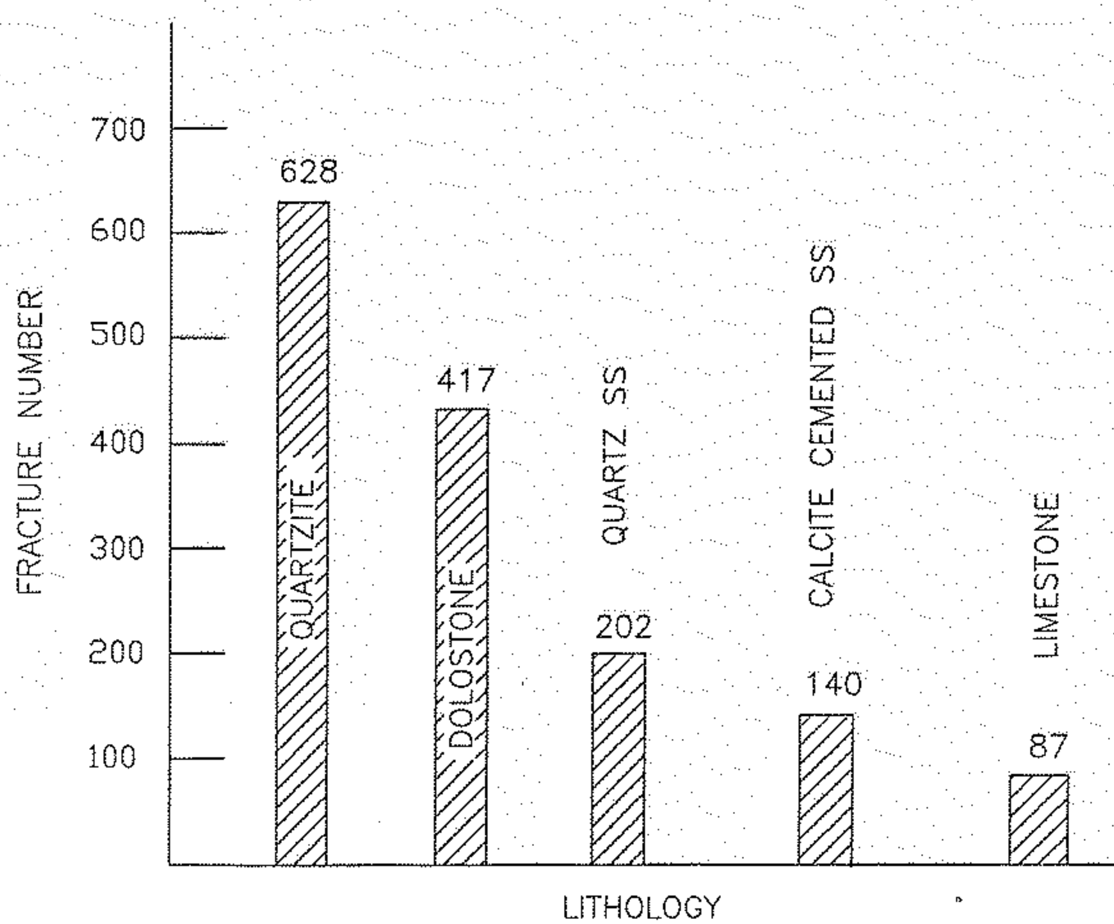


Figure 19. Average fracture density for several common rock types naturally deformed in the same physical environment (after Stearns, 1967)

Hydrogeologically, the most important fracture properties are orientation, density, aperture opening, smoothness of fracture walls, and the degree of connectivity (Domenico and Schwartz, 1990). If a given set of fractures does not extend through a confining layer or is 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. However, 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 20 is a schematic diagram demonstrating these phenomena.

Hydraulic Head in Wells

By definition, an 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

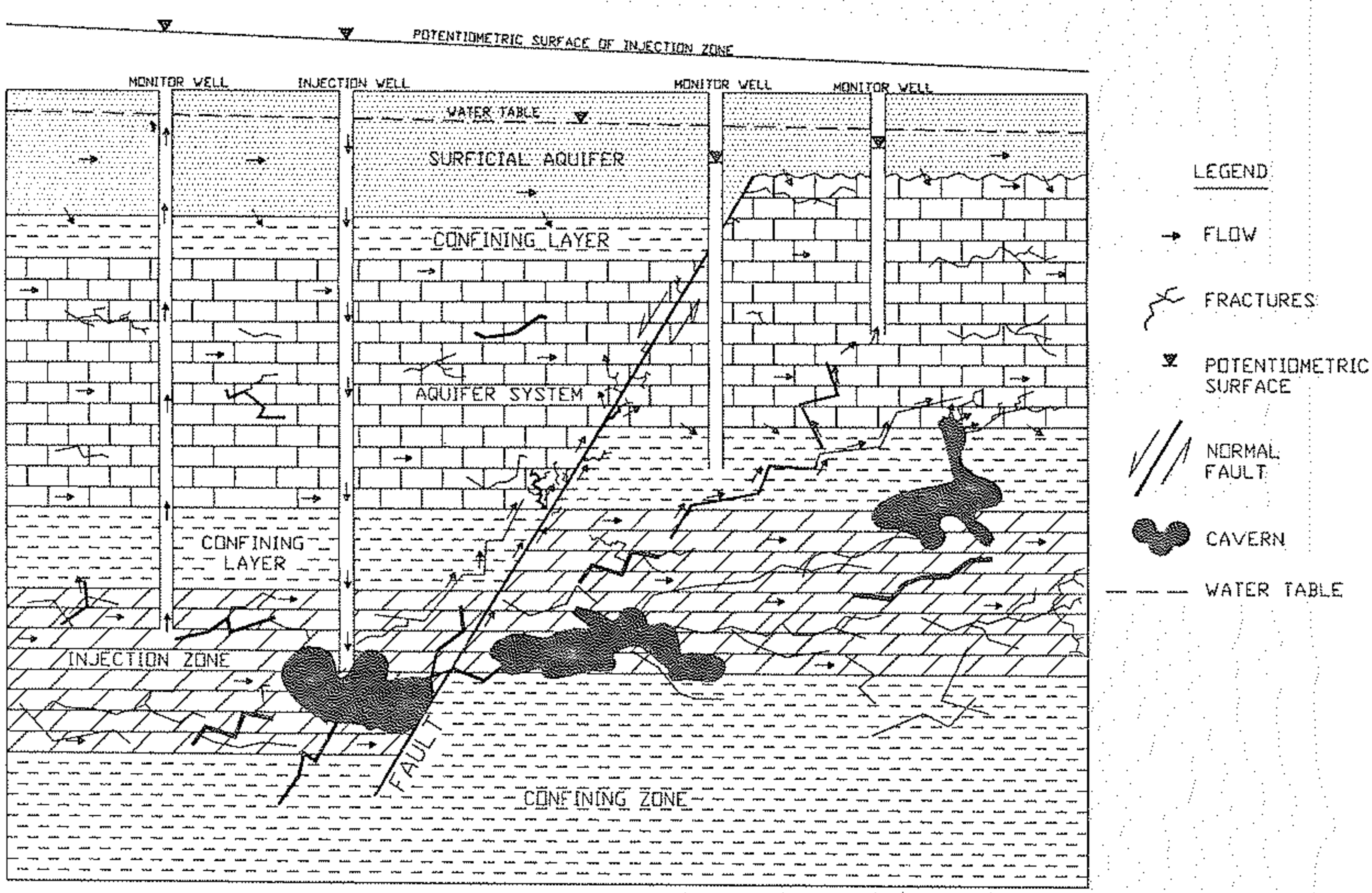


Figure 20. Hypothetical hydrogeologic conditions which could result in vertical flow of different waters (after Duncan et al, 1994).

similar pattern a hydraulic connection could be present and vertical flow may be occurring.

Confined aquifers, however, 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 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 the study area 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 (Enright, 1990):

1. Mechanical loading of the aquifer at its oceanic extension;
2. Propagation and attenuation of the pressure wave inland through the aquifer; and
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 distances between well and ocean increase, the inland transfer of the pressure wave through the aquifer propagates with diminishing amplitude and increasing time lag (Enright, 1990) (Figure 21).

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 are typically 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 overlying 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. The well, however, 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).

If a well system is monitored continuously, 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

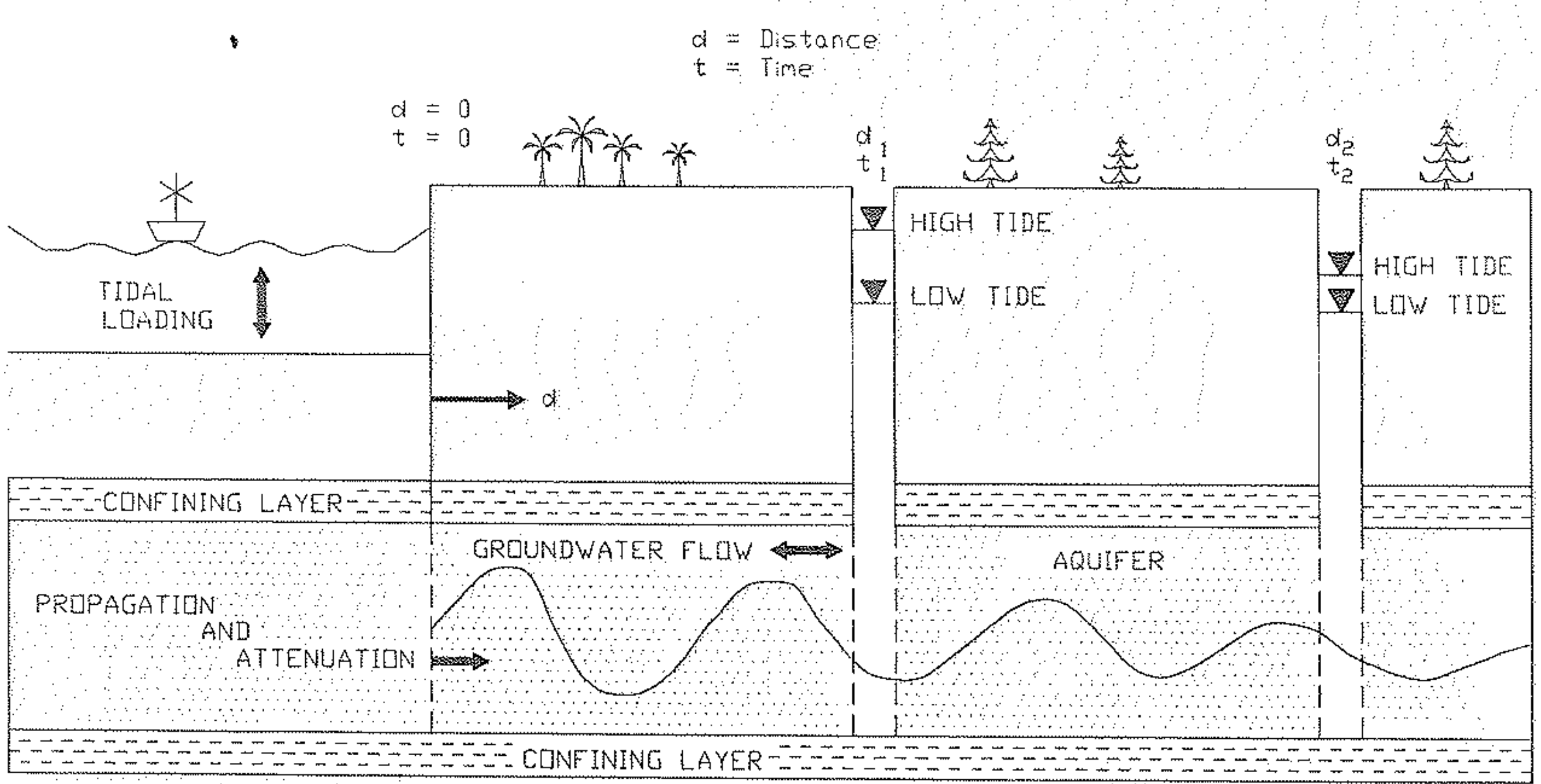


Figure 21. Response of water in a well penetrating a confined aquifer to oceanic tidal loading (modified from Enright, 1990).

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) responses 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 Jacob (1940) and Domenico and Schwartz (1990).

The availiable data does not adequately address the effects of aquifer loading on the injection well sites in the study area. Duncan and others (1994) provide a detailed example of aquifer loading effects on injection and monitor wells at the D. B. Lee site located at Melbourne, Florida.

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° F and increases to 108° F along the central axis of the Florida Plateau

(Kohout et al., 1977)(Figure 22). 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 22).

Borehole temperature logs, provided by the various consulting firms were closely inspected 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. There were slight variations in temperature that were associated with fractures (Safko and Hicky, 1992). 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

Water-quality data, injection zone and monitor zone information for six injection sites in Palm Beach County (Belle Glade, Palm Beach Southern Region, Palm Beach County Sytems 9, Pahokee, Encon, and West Palm Beach Pollution Control Facility) and one in St.Lucie County (North Port St. Lucie) were analyzed for

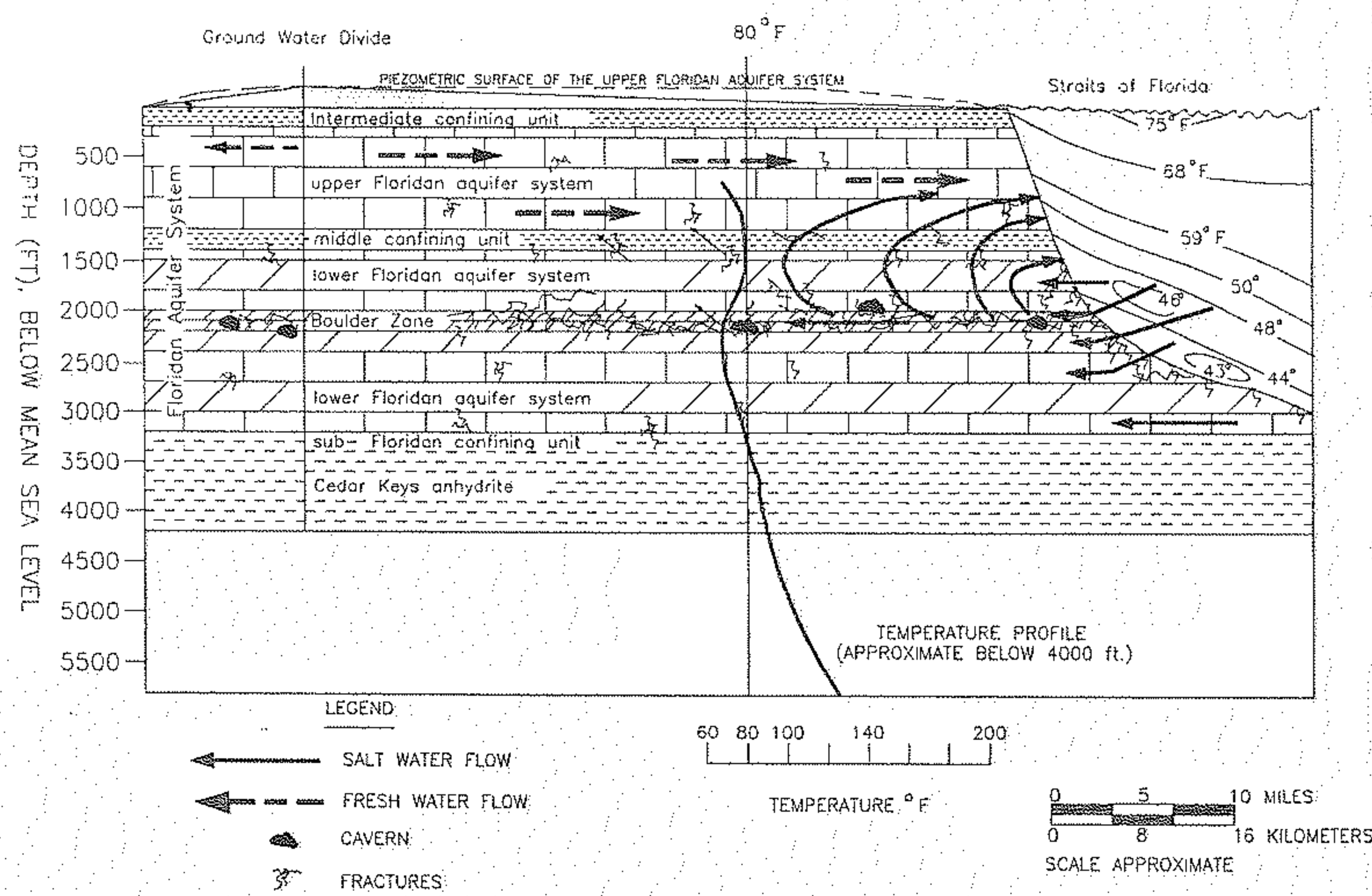


Figure 22. Hypothetical hydrogeologic cross section through peninsular Florida demonstrating the concept of cyclic flow of seawater induced by geothermal heating (modified from Kohout et al, 1977).

this study (Figure 1). The Palm Beach Southern Region (IW-1) and the Belle Glade (IW-1), both in Palm Beach County, were selected for detailed review because of apparent water-trends noted at these injection sites.

The primary injection interval of all the injection wells in the study area is the Boulder Zone of the Upper Oldsmar Formation (Figure 23; Plates 4 and 5). The Boulder Zone is generally highly fractured and cavernous with transmissivity values of up to 21 million gpd/ft (Haberfeld, 1991). The high transmissivities in the injection zone, and the 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 waters are circulating freely. Fractures, discontinuities, and cavities in designated confining zones of the injection wells could provide conduits for the circulating water.

The injected fluids are generally low-salinity, treated municipal waste water. Injected waters are less dense than formation water, and since fluids in the injection and deep monitor zones are highly saline, "contamination" from injected fluids will be seen as freshening trends in monitor well data. For example, such trends are indicated by a decrease in total dissolved solids (TDS) and/or chloride concentration. Occassionally, marked increases in these parameters are observed and are attributed to the upward displacement of deeper saline waters by the less dense injected fluids (J. Haberfeld, DEP, personal communication, 1991)

Nitrogen content is monitored because treated waste water generally has higher nitrogen concentrations than ambient formation

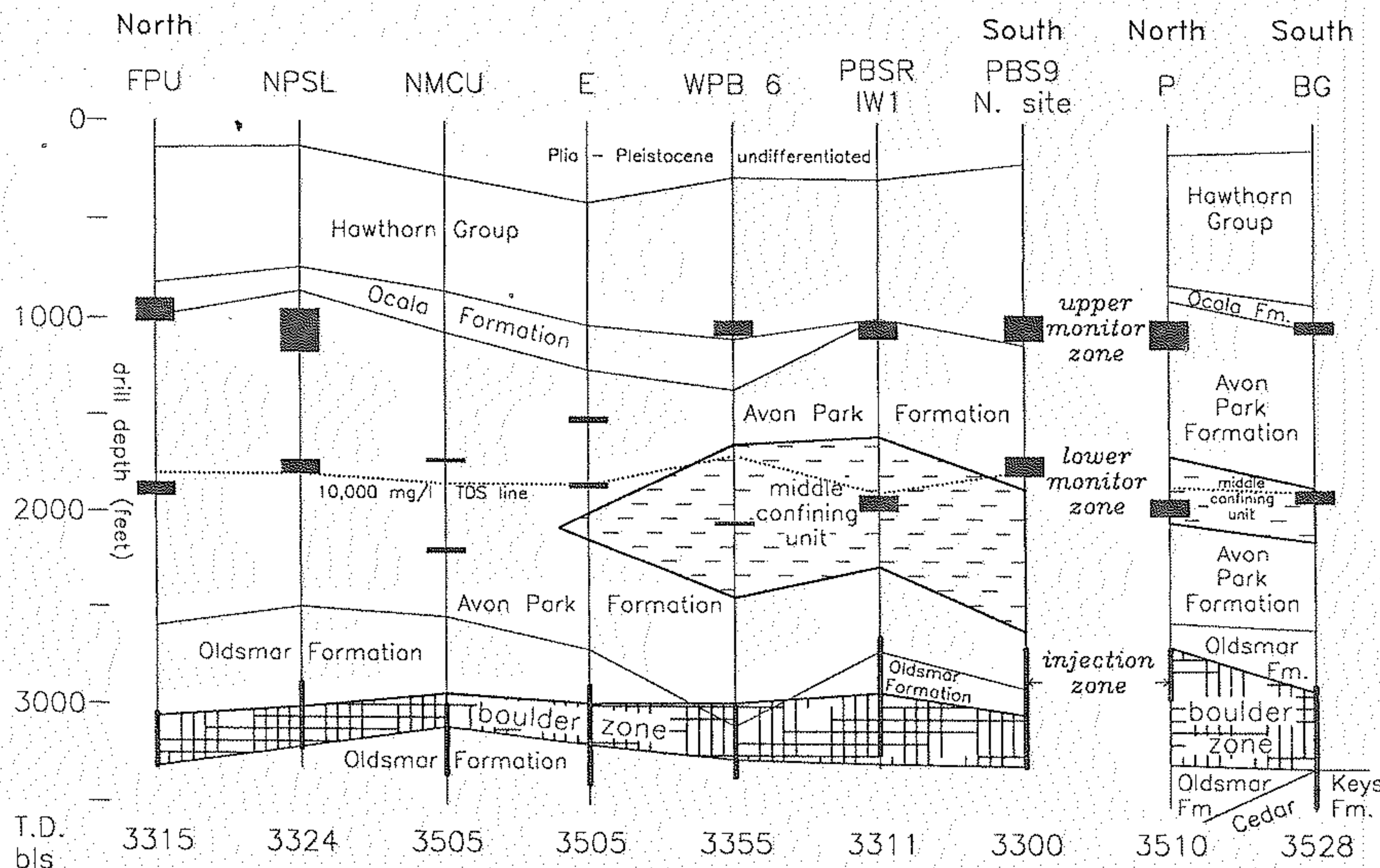


Figure 23. Relationships of formations, monitor zones, middle confining unit, and injection zones (data from consultant-engineering reports). Well-name abbreviations are listed in Figure 1.

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 require that the formation water TDS in injection zones must exceed 10,000 mg/L, so consultants note the depth at which the transition occurs (Figure 23).

The TDS, chloride, and TKN are among the parameters tracked in the various monitor zones and were chosen for close investigation because time series data on them are available for the monitor zones of the injection wells. Regression analyses were performed on the time series data from deep monitor zones to determine the significance of of the observed trends. A high R-squared value, or coefficient of determination (R is the correlation coefficient), indicates low scatter of data, or a definite relationship between time and concentration values.

The Palm Beach County Southern Region well (IW1) reached a total depth of 3311 feet bls. The injection zone is at 2660 to 3300 feet bls in the upper Oldsmar Formation and lower Avon Park Formation. The injection interval consists of dolostone and dolomitic limestone in the Oldsmar Formation and highly dolomitized limestone and dolostone in the Avon Park Formation. A deep monitor well (1984 feet bls) has dual monitor zones at 1900 to 1984 feet bls and 1000-1096 feet bls (Figure 23).

Background water-quality data for the Palm Beach County Southern Region well shows that the ambient water quality before injection was 36548 mg/l TDS, 23040 mg/l chloride, and 0.92 mg/l

TKN for the deep monitor zone and 6941 mg/l TDS, 3800 mg/l chloride, and 2.28 mg/l TKN for the shallow monitor zone (CH2M Hill, 1991, Appendix N). For comparison, water containing more than 2000-3000 mg/l TDS is too salty to drink, and sea water has approximately 35000 mg/l TDS.

During an injection program from January, 1992 to July, 1993 chlorides decreased from 15,500 mg/l to 13,500 mg/l, TDS decreased from 35,000 to 26,000 mg/l, and TKN increased from 0 to 7 mg/l (Figures 24-26) in the deep monitor zone (Figure 23) at the Palm Beach County Southern Region IW-1. Concentrations of chloride (3000 mg/l) and TDS (5,000 mg/l) remained constant, and TKN increased from 1.3 to 3 mg/l in the shallow monitor zone. Based upon r^2 coefficients of the deep monitor zone data, a correlative relationship exists for time versus chloride at 0.7, TDS at 0.86, and TKN at 0.56.

The injection zone of the Belle Glade IW1 is located between 2890 and 3500 feet bls, which spans the Oldsmar Formation-Cedar Keys Formation contact (Figure 23, Plate 3 and 5). A deep monitor well (1940 feet bls), located about 100 feet south of the injection well, has dual-monitor zones at 1871-1940 feet bls and 1001-1940 feet bls (Figure 23). During July of 1990, the background water-quality data showed concentrations of 4830 mg/l chloride, 10,160 mg/l TDS, and 1.23 mg/l TKN for the deep monitor zone and 852 mg/l chloride, 3351 mg/l TDS, and 1.09 mg/l TKN for the shallow monitor zone (Geraghty & Miller, 1991, Appendix E).

During an injection program from August, 1991 through January, 1994 at the Belle Glade IW-1, chlorides increased from 4500 mg/l to

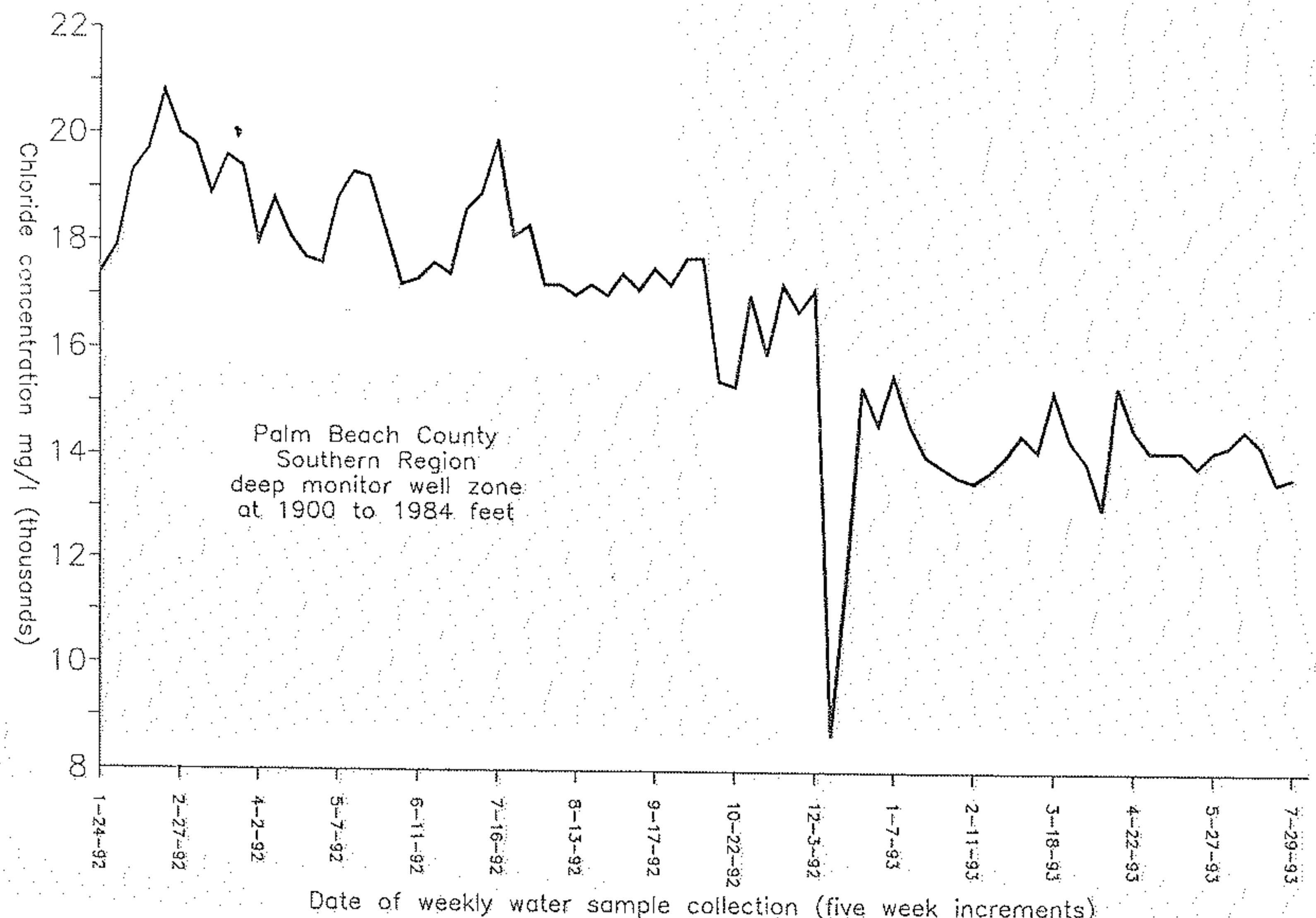


Figure 24. Cloride concentrations of the Palm Beach County Southern Region deep monitor zone (data from Department of Environmental Protection, Bureau of Drinking and Ground Water Resources, Underground Injection Control).

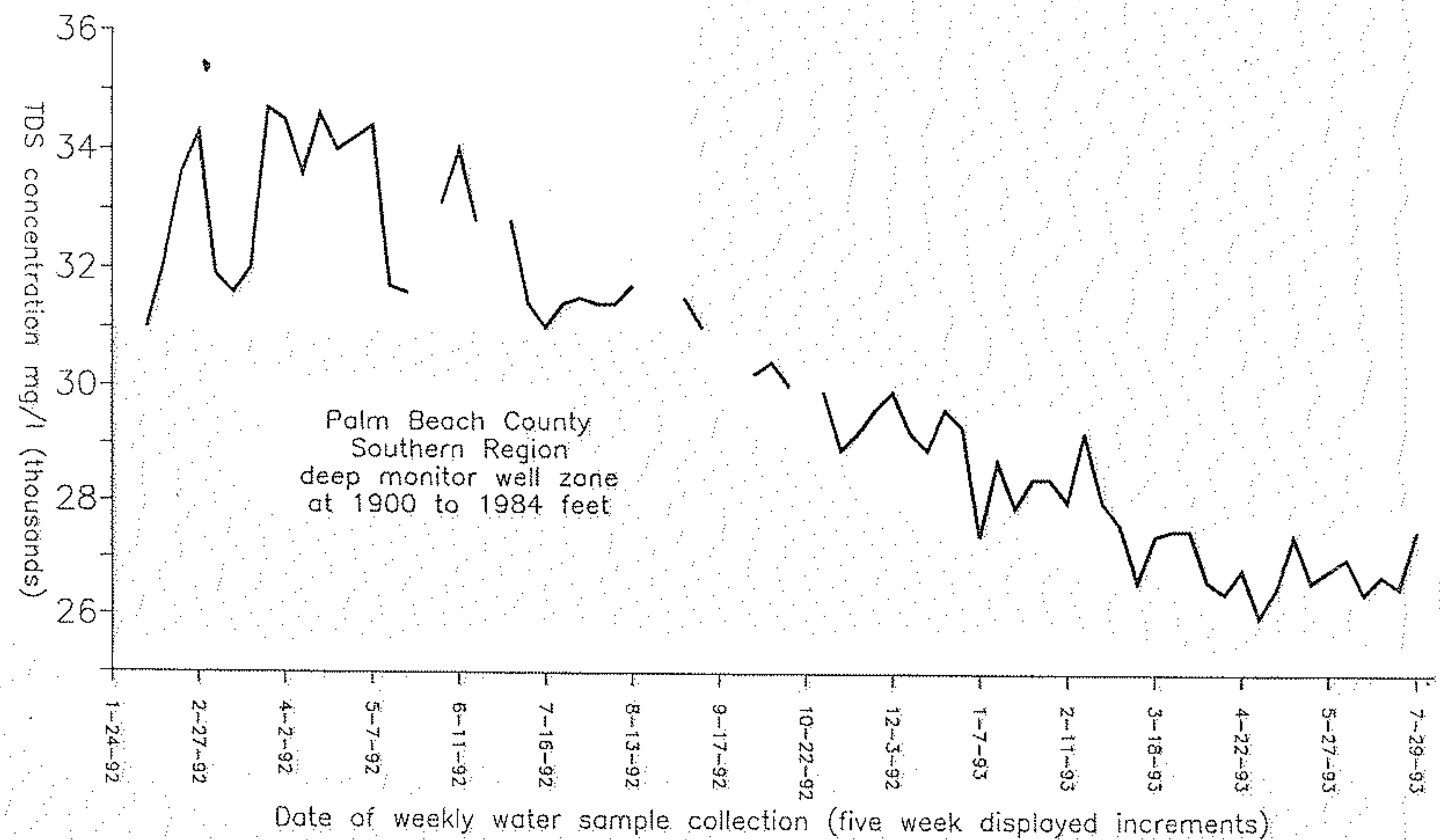


Figure 25. Total dissolved solids (TDS) concentrations of the Palm Beach County Southern Region deep monitor zone (data from Department of Environmental Protection, Bureau of Drinking and Ground Water Resources, Underground Injection Control).

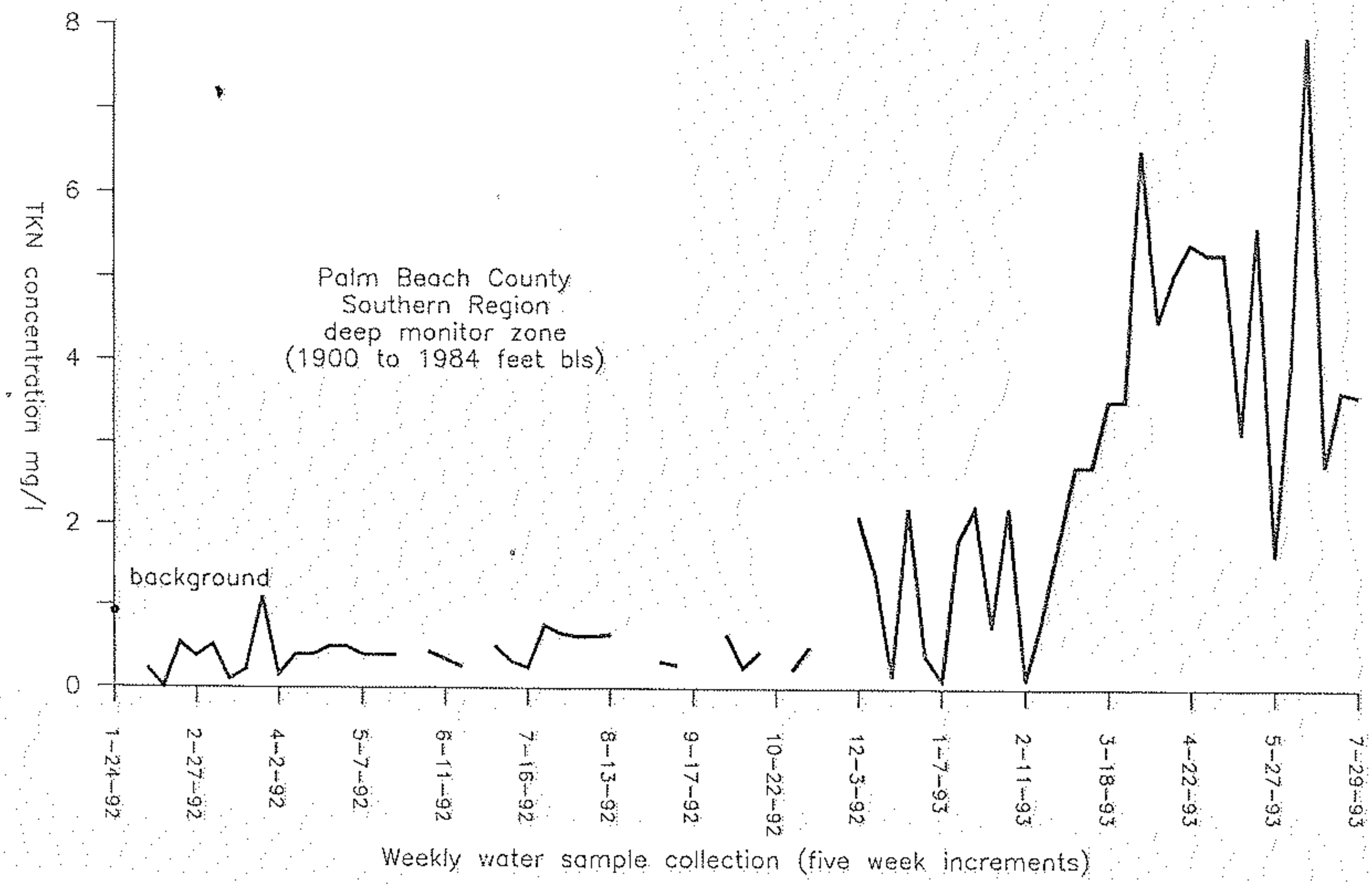


Figure 26. Total Kjeldahl Nitrogen (TKN) concentration of the Palm Beach County Southern Region deep monitor zone (data from Department of Environmental Protection, Bureau of Drinking and Ground Water Resources, Underground Injection Control).

9000 mg/l and TDS increased from 8000 mg/l to 15000 mg/l in the deep monitor zone (Figures 23, 27-29). TKN remained constant at 0.8 mg/l in the deep monitor zone. Based upon r^2 coefficients, a correlative relationship exists for time versus chloride at 0.81 and TDS at 0.56 in the deep monitor zone.

Data from the shallow monitor zone in the Belle Glade IW-1 remain fairly constant for the same injection period, with approximate concentrations of chloride at 1200 mg/l, TDS at 3000 mg/l, and TKN at 0.8 mg/l.

The Belle Glade deep monitor zone results have chemical trends similar to post-injection of the D.B. Lee injection well from April, 1989 to December, 1991 at Eau Gallie in Brevard County where both sites exhibited an overall increase of chloride and TDS content (Duncan et al., 1994, p. 68). The meaning of the Belle Glade deep monitor zone trends are unclear, but possibly indicate enrichment in chlorides and TDS concentrations from deeper levels other than the injection zone because injecting fluids are generally of low salinity.

DISCUSSION AND CONCLUSIONS

The geologic framework of the lower Floridan aquifer system in St. Lucie, Martin and Palm Beach Counties 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 of these components can result in considerable differences in local lithofacies, porosity, permeabilty, and the hydrogeologic character

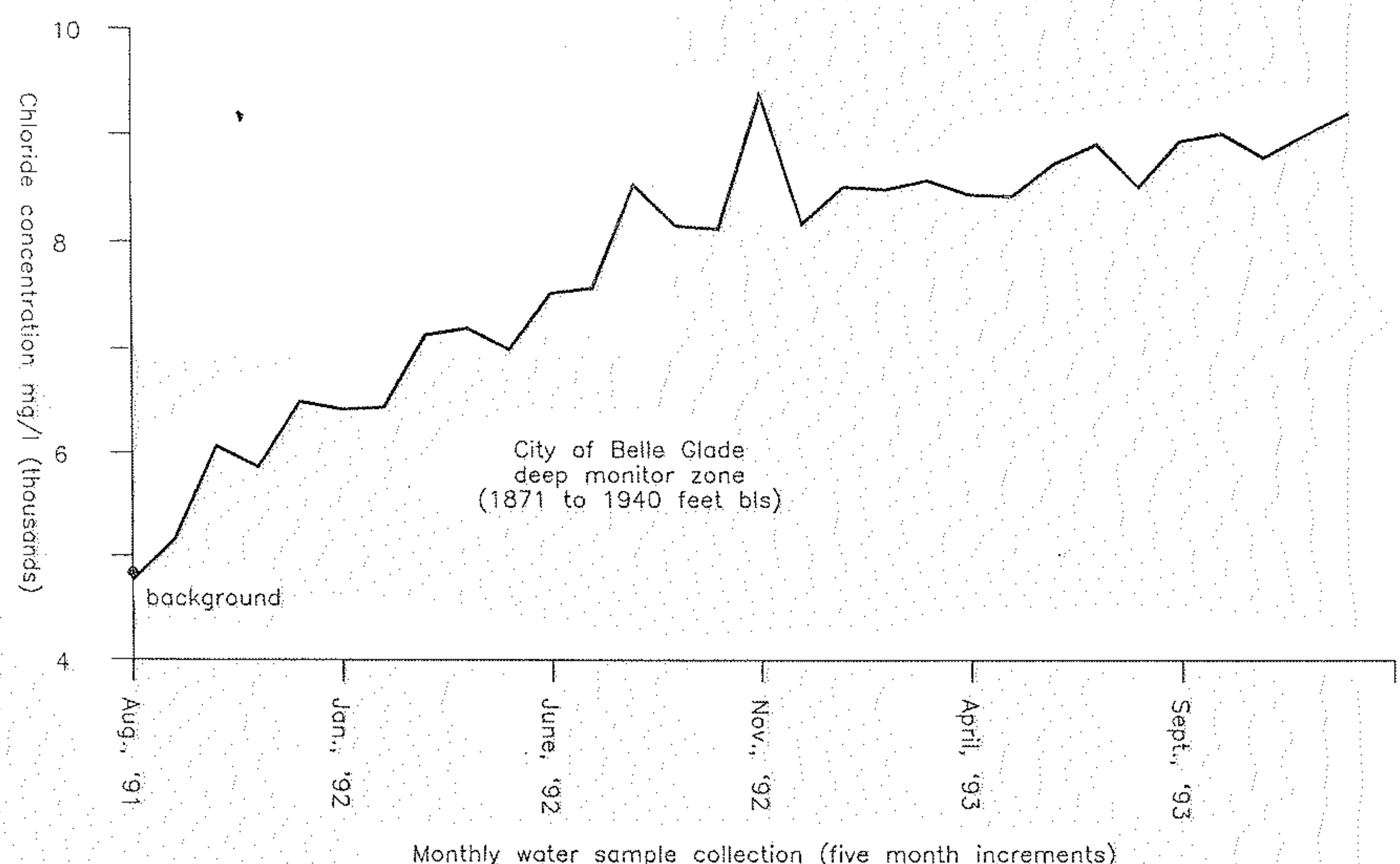


Figure 27. Chloride concentration of the Belle Blade Wastewater Treatment Plant deep monitor zone (data from the Department of Environmental Protection, Bureau of Drinking and Ground Water Resources, Underground Injection Control).

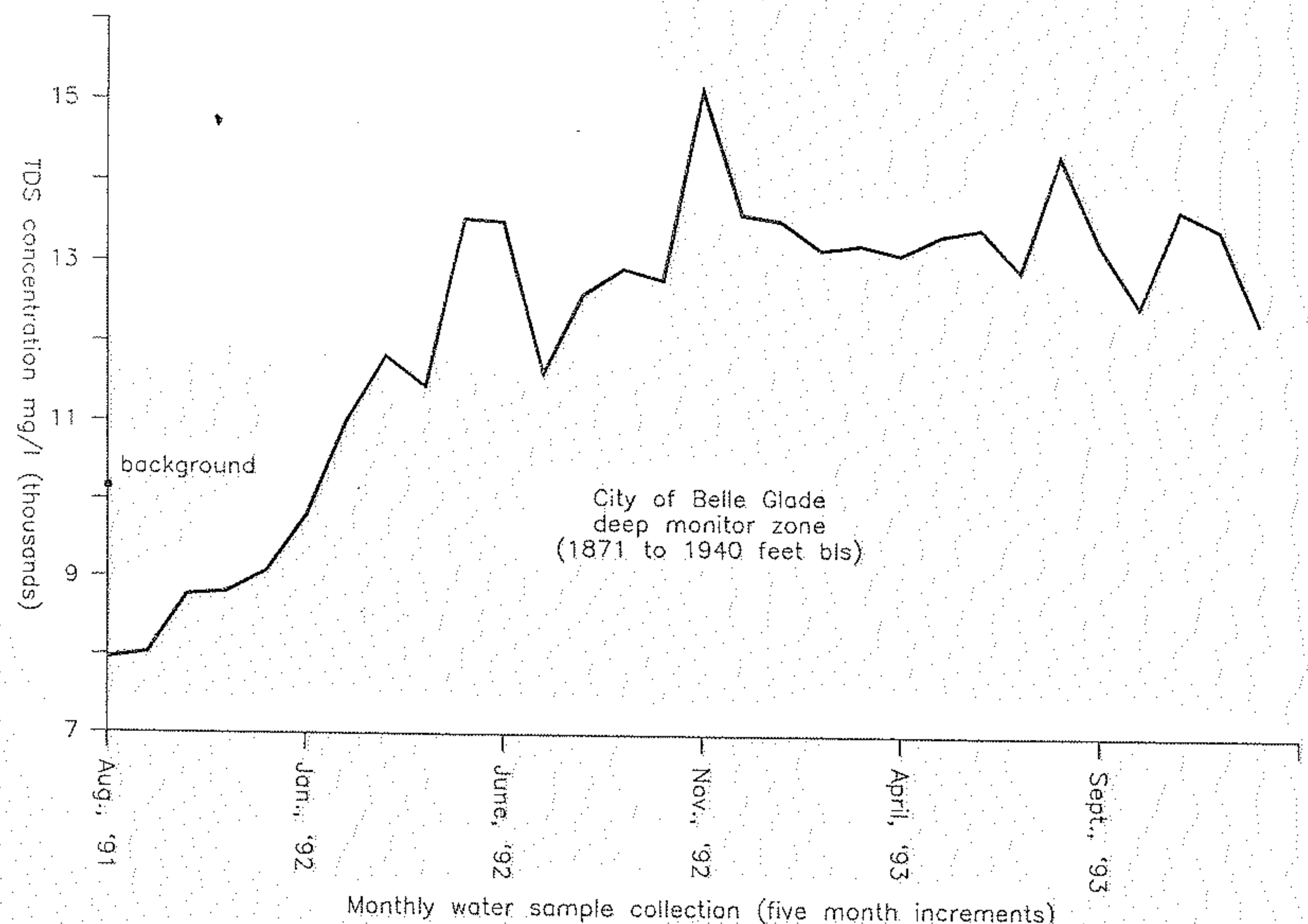


Figure 28. Total dissolved solids (TDS) concentrations of the Belle Glade Wastewater Treatment Plant deep monitor zone (data from Department of Environmental Protection, Bureau of Drinking and Ground Water Resources, Underground Injection Control).

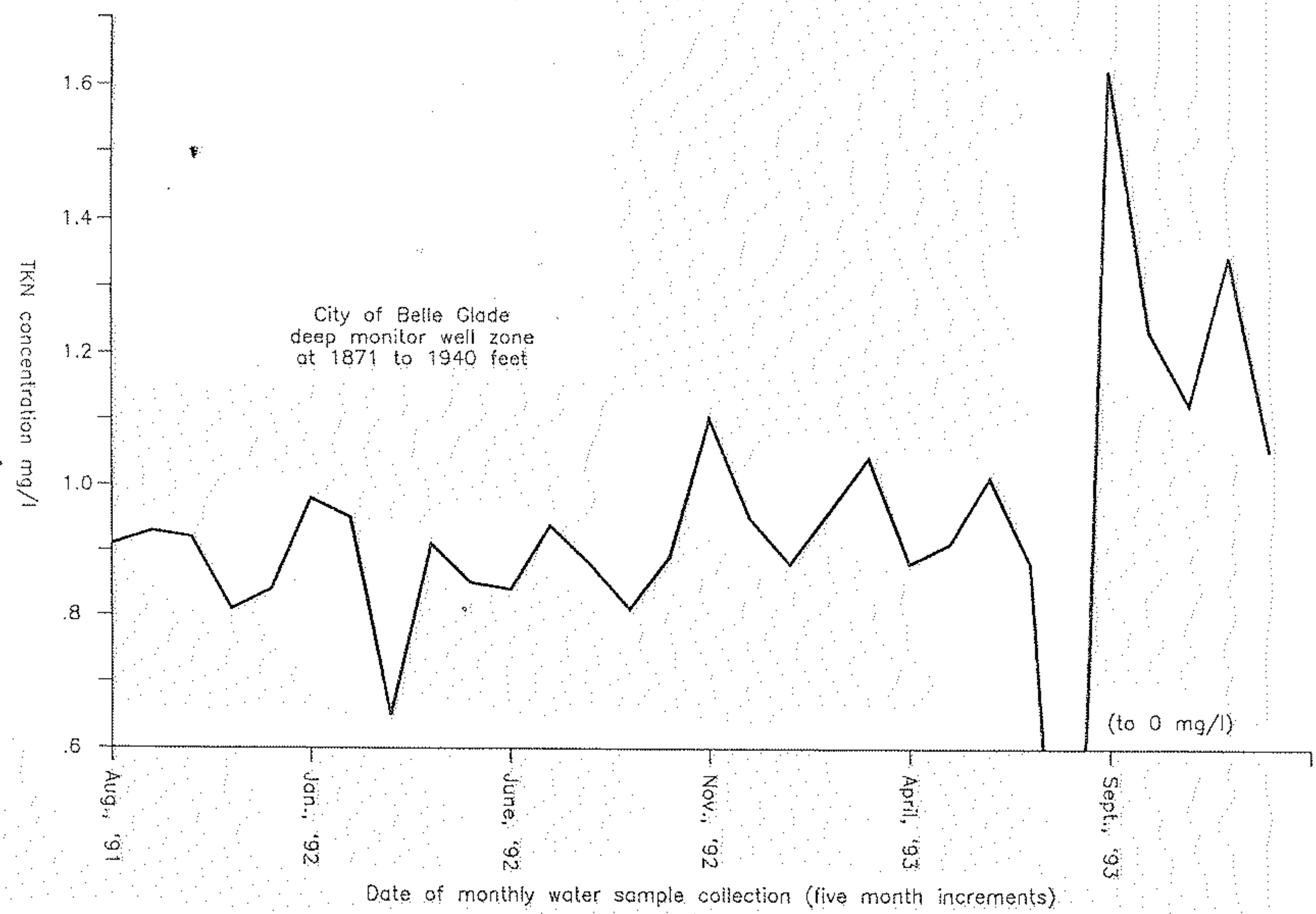


Figure 29. Total Kejldahl Nitrogen (TKN) at the Belle Glade Wastewater Treatment Plant deep monitor well zone (data from the Department of Environmental Protection, Bureay of Drinking and Ground Water Resources, Underground Injection Control).

of the aquifer.

Ground-water chemistry trends for the Belle Glade and Palm Beach County Southern Region injection wells, barring any well mechanical problems, indicate that injected waste liquids are possibly migrating upward through the "confining" rocks immediately above the injection zones at these sites. Since apparently low-permeabilty dolostones and some low-permeabilty limestones are common in the "confining" sequence, injected waste waters are probably moving vertically along fractures and possibly along fault planes where present. Observed fractures justify this supposition.

Given the similarity of the lithostratigraphy throughout the study area, the findings of this study do not resolve why ground-water chemistry trends indicative of leaky or poor confinement are apparent at two injection sites and not in others. For example, no chemical trends indicative of upward fluid migration are evident at the West Palm Beach site where structural deformation due to possible faulting and/or folding would possibly locally enhances fracturing locally and perhaps breachs the confining sequence. More detailed analysis accomplished by thorough coring and hydrologic testing of the confining sequence is necessary in order to ascertain a plausible explanation for these variations.

Significant differences between the geologic framework of the study area and Brevard County (Duncan et al., 1994) are not apparent. The general lack of ground-water chemistry trends in the study area as compared to Brevard County, where several wells exhibit strong trends indicative of upward fluid migration (Duncan et al., 1994), may be related to some degree to the depth of the deep monitor zone relative to the top of the Boulder Zone (injection zone). Deep monitor zones in Brevard County are typically located 500 feet (most less than 300 feet) or less above the Boulder Zone (see Figure 36, p.58 in Duncan et al., 1994) and below the middle confining unit, whereas in Palm Beach County the deep monitor zone is typically located 1000 feet or more above the Boulder Zone, above the middle confing unit (Figure 23). It is uncertain whether or not more wells in the study area would exhibit trends if the deep monitor zones were positioned nearer the top of the Boulder Zone and below the middle confining unit.

A more adequate comprehension of southern Florida's Cenozoic geologic history is highly desirable for further understanding the complexities of the Floridan aquifer system in the region. Specifically, detailed regional investigations of the depositional, diagenetic, and tectonic evolution of the Florida Platform during the Paleogene and early Neogene are much needed. Such studies will require an expanded data base that should include additional and more thorough coring of the lower Floridan aquifer system, regional seismic grids, and complete open-hole borehole video surveys.

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