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CENTRAL AND SOUTHERN FLORIDA PROJECT

COMPREHENSIVE EVERGLADES RESTORATION PLAN

LINEAMENT ANALYSIS
SOUTH FLORIDA REGION

AQUIFER STORAGE AND RECOVERY
REGIONAL STUDY

U.S. Army Corps of Engineers
Jacksonville District

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Abstract

The purpose of this investigation was to identify surface lineaments in south Florida, show possible relationships between the lineaments and known geologic structure, and to help identify structural features that may impact hydraulic parameters of the Floridan Aquifer System (FAS) and confining units. The study area consisted of the southern peninsular portion of Florida, from approximately 35 miles north of Lake Okeechobee to the south tip of the peninsula.

This investigation involved identifying lineaments (photolinears) on Landsat imagery, and comparison of lineaments with published geologic structural data to help provide interpretations of possible correlations to known regional hydrogeologic trends and anomalies. Because of the low topographic relief, the primary surface features used to identify lineaments were sinkholes and solution depressions, stream segment alignments and fluvial patterns, and tonal changes. Azimuths and lengths of each lineament were measured and rose diagrams and histograms created. Digital orthophoto quadrangle (DOQQ) aerial photos were also viewed as part of the analysis for aquifer storage and recovery (ASR) pilot project sites. The size of the study area limited the field proofing of potential lineaments.

The FAS is a thick sequence of Paleocene to Miocene-age carbonate units underlying the entire State of Florida. It is the primary source of water supply for the northern counties of Florida and is a source of supplemental irrigation water as far south as Martin County. In south Florida, it is the primary target zone for aquifer storage and recovery operations. Depth to the top of the FAS in south Florida ranges from approximately 700 feet to 1,000 feet.

The present day Florida Platform is generally considered to be part of a relatively stable setting on the passive margin of the North American plate. However, the basement rocks underlying Florida reflect a complex tectonic history. A total of 548 lineaments have been mapped in the study area. Of these, 63 are equal to or greater than 25 miles in length. Many lineaments observed on DOQQ photo mosaics at each of the ASR pilot project sites coincided with those identified on the Landsat images, thus adding confidence to the significance of the photolinear. Further confidence was gained by the repeatability of lineaments identified by other authors.

The findings show the regional geologic structure and hydrogeologic character tend to parallel surface lineament trends. The data for the south Florida region suggest that many lineaments are indicative of fractures (or perhaps faults in some cases) extending from the basement structures through the overlying rock, and are reflected on the ground surface. One of the most noteworthy findings of this investigation is the concentration of northeast trending lineaments along the northern Caloosahatchee River corridor and the northwest side of Lake Okeechobee, in which the lineaments seem to correlate to a possible basement hinge zone or other geologic structure at depth. Chloride concentrations in the Upper FAS also increases significantly south of these features. A recently completed test well at the Kissimmee River ASR pilot site at the mouth of the Kissimmee River also shows uncharacteristic highly fractured sections in the upper FAS.

Other noteworthy findings are: 1) Lineaments coinciding with a mapped fault and in areas of higher chloride concentrations and higher Upper Floridan aquifer groundwater temperatures in the northeast study area; and 2) The northwest-trending lineaments in the southwest portion of

the study area, which appear to correlate with reports of upward leakage through semi-confining and confining units, and inferred faulting and structure in the FAS, Hawthorn Group, and Surficial Aquifer System.

Further investigation, is necessary to verify the presence of the lineaments identified during this study, and their relationship to geologic and hydrogeologic features. Results of such investigations will likely show many of these lineaments do not have any relationship to the subsurface conditions. Others will be shown to be the surface manifestation of fractures and/or faults extending far up into the sedimentary section, or to have an effect on the local and regional hydrogeology.

Introduction

The concept of linear topographic, geologic, or biologic elements reflecting the bedrock or geomorphic characteristics of an area has been recognized by geologists for well over one hundred years. However, the practice of mapping lineaments and fractures received little attention until after World War II. Using aerial photography, geologists in the oil industry began incorporating lineament and fracture trace analysis in their research to identify joint and fracture patterns, faults, and other geologic and geomorphic features. By the early 1960s, photogeologic features were being used to help guide water-supply development. Today, these analyses use a variety of aerial photographs, false-color imagery, and other remotely sensed imagery.

Fracture traces and lineaments often reflect geologic structural features such as fracture zones and faults in the subsurface. Geologic structures parallel to the preferred fracture trace and lineament orientations are more likely to be manifested at the surface because they represent the effects of the various associated stress fields. These features can have a significant impact on the hydrogeology since they typically reflect evidence of zones of enhanced permeability and porosity. Additionally, it has been found that well yields are typically significantly enhanced in carbonate rock settings where wells are sited on fracture traces or fracture trace intersections. Full discussion of the various stress mechanisms, stress vectors, and associated lithology and dissolution along structural fractures is outside the scope for this work and will not be discussed further in this document. However, these would be worthwhile objects of future investigation.

Implementation of the Comprehensive Everglades Restoration Plan Aquifer Storage and Recovery (ASR) component will result in a tremendous amount of surface water being stored in the Floridan Aquifer System (FAS) and pumped out during times of need. In order to build confidence on hydrogeologic factors such as leakance and potentiometric head changes, the regional geologic and hydrogeologic setting must be understood. A lineament analysis to identify potential areas of concern has been planned as part of this effort.

Purpose

The purpose of this investigation was to identify surface lineaments in south Florida, show possible relationships between the lineaments and known geologic structure, and to help define structural features that may impact hydraulic parameters of the FAS and confining units. Features identified by surface lineaments in this investigation are possible fracture or fault zones, which could act a conduits or barriers for groundwater flow.

Location of Study Area

The study area consists of the southern peninsular portion of Florida, extending south from a line trending east-northeast across central Sarasota, Hardee, Highlands, Okeechobee and Indian River Counties (Figure 1). The western part of Sarasota County was not included in the study area because of its distance from Lake Okeechobee and it was covered by the available Landsat imagery used for this project.

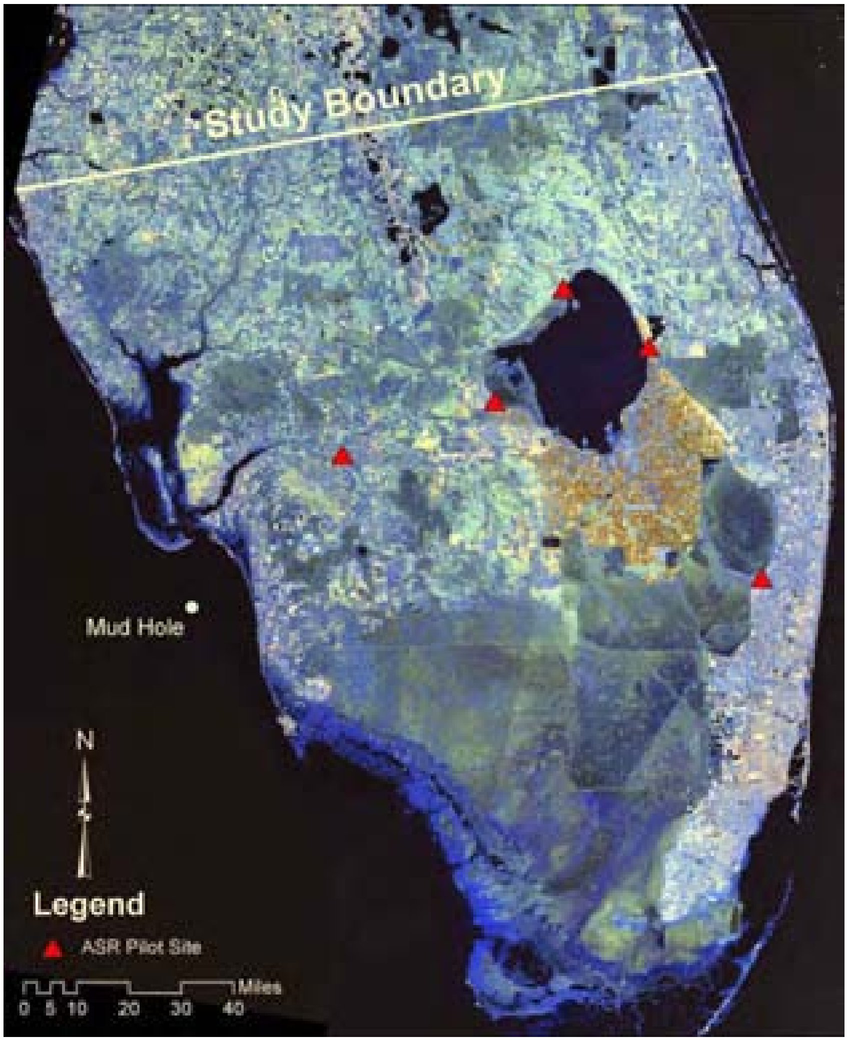


Figure 1. Location map of the lineament analysis study area.

Summary of Fracture Traces and Lineament Analysis

Studies of lineaments (photolinears) discernable on aerial photographs have revealed that these linears are abundant natural, and are systematically oriented in four principal groups of external stresses in the WNW, NNW, NNE, and ENE directions. Fractures are formed predominately by terrestrial or earth tides due to gravitational effects of the moon and sun, tectonic forces, diagenetic, or weathering processes (Blanchet, 1957).

Numerous investigations have shown that most of the fractures and faults identified as photolinears are vertical or near-vertical zones of fracture concentrations (Kaiser, 1950; Blanchet, 1957; Lattman, 1958; Lattman and Matzke, 1961; Lattman and Parizek, 1964).

The following paragraphs present excerpts of a good summary on fracture-trace mapping principles by Diodato (1999):

> Photolinear analysis is a type of remote sensing analysis wherein investigators map linear features ("photolinears") observable on aerial photographs or other remotely-sensed images. The use of photolinears for ground-water well siting was pioneered by Lattman and Parizek (1964). For linear features of geologic origin, *lineaments* are defined as those photolinear features greater than one mile in length, whereas *fracture traces* are the same type of feature having a total length of less than one mile. The width of these zones of fracture concentration can vary from a few to tens of meters. In general, longer lineaments tend to have wider surface expressions of the zone of fracture and wider zones of fracture concentration at greater depths. Because the fracture trace is the surface expression of the vertical zone of fracture concentration, Parizek has suggested the "*fracture zone trace*" might be a more appropriate descriptive term (Parizek and Diodato, 1995).
>
> Zones of fracture concentration in soluble rocks such as carbonates and evaporates can lead to enhanced dissolution of these rocks due to accelerated chemical and physical weathering. In the case of rocks prone to karstification, White (1999) has determined that the development of karst conduits begin when fracture apertures reach about one centimeter.
>
> In south Florida, linear features (photolinears) are detected and identified based primarily upon indicators such as aligned solution depressions, surface ponds, vegetation, and variations in soil tone (Trainer and Ellison, 1967, Parizek, 1975). Doline (sinkhole) development can be expected to follow orientation of photolinears, as these represent areas of higher permeability and porosity.

For this study, the term "lineament" will be synonymous with "photolinear" when discussing such features identified on remote sensing imagery (Landsat or aerial photography).

Previous Work

Not many fracture or lineament studies in Florida have been documented. The reasons for this are uncertain but probably reflect the assumption that Cenozoic-age strata in Florida have had little geologic structural influences as well as the many factors complicating the delineation of structural lineaments in south Florida. These factors include low topographic relief, man-made features and disruption of natural features, natural stratigraphic and erosional features.

Paleohurricane tracks have been reportedly documented to leave long-lasting linear scars on the landscape in this region, which may look like fractures on photos (Diodato, 1999). White (1970) aptly stated that throughout the Florida peninsula confusion arises in recognizing structural lineaments because one of their two principal trends, as presented by Vernon (1951), is the same as the relic and present oceanic shorelines of the east coast. He also noted that most of the contacts between formations follow lineaments of one or the other of the two main sets.

Several authors have compiled data on regional terraces or surface lineaments in Florida, and have proposed various tectonic solutions to account for the observed patterns (Schmidt, 1997). Tanner (1965) and Bond et al. (1981) suggested a fault-control origin for Lake Okeechobee in which the lake occupies a down-faulted depression, based on geomorphic evidence and a postulated vertical offset observed in wells north and east of the lake.

White (1970) observed structural lineaments in the Everglades area, including what he referred to as the Shark Creek lineament, a major feature that can be traced from the Gulf Coast immediately north of Cape Sable to the Atlantic Coastal Ridge near Fort Lauderdale. He identified this as one of the major lineaments along which the several Pleistocene formations are juxtaposed. White also noted several short lines of tree islands that are notably straight and parallel.

Table 1 summarizes the findings of detailed fracture trace and lineament studies performed in Florida. The findings of these studies show the primary and secondary sets of fractures or lineaments typically trend either to the northeast or northwest, with the fracture sets in south Florida trending between 40°-55° and 310°-340°.

Table 1
Previous Fracture Trace and Lineament Studies in Florida

Author, Date	Location	Primary Set(s)	2nd-ary Sets	Images Used	Scale	# Photo-linears Mapped	Length Range (ft)	Average Length (ft)
Diodato, 1999	Eldridge-Wilde Well Field, Pinellas Co	41° to 50°	331° to 340°	Four aerial photographs	1:20,697	43	883-8,300	3,576
Culbreth, 1988	South Florida	45°-50°, 315°-325°	55°-65°, 25°-45°, 295°-305°	Landsat MSS bands 5&7; false color composite MSS bands 5,6,7	---	290 linea-ments	1.43-130.5 miles (2.3-210 km)	---
Watkins & Ruth, 1983	East Central Lee County (Southwest Regional Airport)	35°, 65°, 315°	325°, 345°	Landsat MSS false color composite, NASA IR photo B&W panchromatic aerial photo	1:250,000 1:60,000 1: 24,000			
Hazlett, 1989	Crescent City Ridge, Putnam & Volusia Co.	40°-50° 310°-320°	30°-60°, 300°-330°, 80°-90°, 270°-280°	B&W panchromatic aerial photos	1:20,000	172 linea-ments, 278 fx traces*	368-27,831 (112m-8483m)	
Williams, 1985	Cross-Bar Field, Pasco Co	25°-65°, 300°-340°	280°-300°, 350°-10°, 85-95°	B&W panchromatic areial photos, Color IR & color IR diapositive aerial photos	1:24,000 1:80,000 1:130,000	618	<1640 ft to ~6.25 mi	1640-4921 ft (0.5-1.5 km)
Moore, 1981	Cross-Bar Field, Pasco Co	333°, 70°, 38°		IR photos - stereo	1:80,000	3		1-2 km
Vernon, 1951	North & central FL	NE and NW	WNW	?	?			
Barksdale, 1988	Leon and Wakula Co	NE and NW		B&W aerial photos	1:24,000	9		

MSS – multi-spectral scanner

Vernon (1951) completed the first detailed lineament map in north and central Florida (Figure 2). The lineaments he observed showed a northeast by southwest symmetric orthogonal pattern. Since then, several fracture trace and lineament analyses have been performed in localized investigations primarily in central and northern Florida. The Florida Department of Transportation prepared a lineament map of the entire state, which shows many lineaments in central and south Florida. Figure 3 shows a copy of the map contained in Hazlett's (1989) graduate thesis. A copy of the original map could not be located for review, so no further discussion on this work is presented in this report.

Figure 2. Fracture pattern of the northern portion of the Floridan Peninsula (from Vernon, 1951).

- Lineaments mapped in the state of Florida by the Florida Department of Transportation (FDOT, 1973).

Figure 3. Lineament map of Florida by the Florida Department of Transportation (FDOT, 1973). (Modified from Hazlett, 1989).

There were only two other published fracture trace or lineament studies located within the ASR study area. These studies were a regional study completed by Culbreth (1988) and a localized investigation by Watkins & Ruth (1983). Culbreth's work is most relevant to the subject study because it covers the entire south Florida area (Figure 4), and is focused on lineaments identified on Landsat imagery rather than shorter fracture zone traces. Culbreth also performed gravity profiles across several lineament traces, which help to validate the lineaments identified in his study.

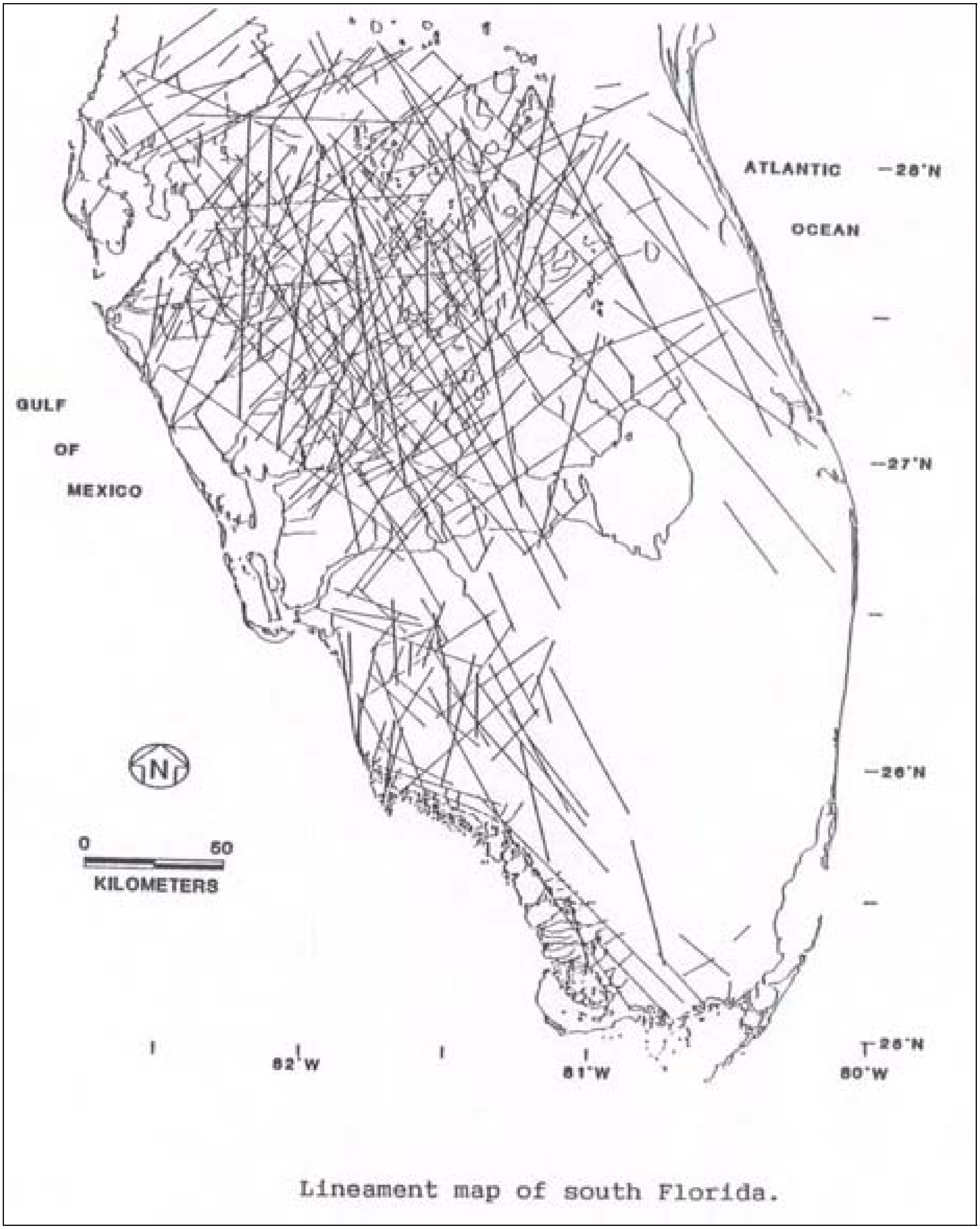


Figure 4. Lineament map of south Florida (from Culbreth, 1988).

Methodology

The work for this task involved conducting the following tasks: 1) Literature review, 2) Identify lineament/fracture zone traces (or photolinears), 3) Limited field proofing of apparent lineaments, 4) Comparison of lineaments with published geologic and hydrogeologic data, and 5) Preparation of a technical memorandum.

The primary remote sensing imagery used in this study consisted of Landsat multi-spectral scanner (MSS) false color images, with a resolution of about 98 feet (30 meters), cover the south Florida region. Six Landsat images were used to create a mosaic covering the south Florida area. The path, row and acquisition dates of the images are:

Path	Row	Acquisition Date	Path	Row	Acquisition Date
15	41	5 February 2000	16	40	26 December 1999
15	42	5 February 2000	16	41	26 December 1999
15	43	5 February 2000	16	42	26 December 1999

The images were manipulated to show various MSS band combinations, with bands 4, 5 and 7 showing the best contrast for identifying lineaments. This is consistent with the findings of previous lineament studies and published documents such as Salomonson et al. (1983), who indicated MSS bands 5 and 7 have been recognized as typically presenting the best images for mapping lineament (Culbreth, 1988).

The lineament analysis was performed using ArcMap™ geographic information system (GIS) and mapping software, with which lineaments were mapped as a separate coverage layer. The Landsat image was viewed at various scales of 1:1,000,000 to as high as 1:125,000, below which the image became pixilated. Contrast and brightness of the image were adjusted as necessary to enhance linear features. Printed images were also viewed at various angles to corroborate lineaments observed on the digital images viewed on the computer, as well as identifying other lineaments. Portions of a few images selected at random, were reviewed by a second analyst to check the traces observed by the main analyst.

The analysis involved mapping of lineaments (traces greater than one mile) because longer lineaments have the greatest potential of being more fully developed and of penetrating greater depths. Because of the significant amount of linear features observed on the images, shorter lineaments were highly scrutinized. Many were not added because of the uncertainty of whether these were fracture zone traces or some other man-made or natural feature. An attempt was made to map only lineaments that were observable at various scales. Using this method resulted in some possible apparent larger lineaments seen on the smaller scales not being identified at the larger scales. In most of these instances, numerous smaller lineaments parallel to or en-echelon to the apparent major lineament trends were identified within these larger trends at all scales and were thus mapped.

Several primary criteria were utilized to identify the lineaments. These were grouped in five sets: Stream segment alignment; ponds and lakes; sinkholes and solution depressions; vegetation/soil tonal changes; and drainage patterns and topographic relief. Ponds and lakes are larger water bodies that may have karst or other origins, whereas smaller ponds are grouped with the sinkholes and solution depressions. The criteria by which each lineament was identified were recorded and tabulated. Each lineament was then ranked according to a low, medium or high level of 'confidence' of the lineament identification based primarily on the number of criteria being identified for each lineament. Lineaments identified with stream segment alignment being one of the criteria were automatically given a "High" ranking because this criteria is essentially the most obvious indication lineation. Other lineaments having a "High" ranking have at least for criteria. "Medium" ranking was given to lineament with three criteria and a "Low" ranking for lineaments having one or two criteria.

Digital orthophoto quadrangle (DOQQ) photography mosaics were used to help identify lineaments in the ASR pilot project areas. A 1995 DOQQ color infra-red aerial photography mosiac was used for the Port Mayaca, Kissimmee River and Hillsboro ASR pilot sites. A 1999 DOQQ color infra-red aerial photography mosaic was used for the Caloosahatchee River and Moore Haven ASR pilot sites because this area was not in the coverage of the 1995 set. The 1995 mosiac was selected because it had better quality images for this study than the more recent set. Both mosaics have resolution of five meters. The DOQQ images were viewed on ArcMap™ GIS and mapping software at various scales of 1:80,000 to as high as 1:20,000, with an average of 1:40,000. Lineaments were mapped and overlaid on the lineaments identified on the Landsat images to compare repeatability.

After mapping the lineaments, a comparison was made to the original images with lineaments identified by Culbreth (1988). The images used by Culbreth were obtained for review as part of this study. These images have a scale of 1:500,000 and cover the entire study area. The following identifies the images reviewed:

Path	Row	MSS Band	Acquisition Date
16	41	FCC	22 March 1973
16	42	7	16 May 1978
16	42	FCC	16 May 1978
17	41	FCC	15 January 1979

Path	Row	MSS Band	Acquisition Date
17	41	FCC	15 January 1979
17	42	7	8 December 1980
17	42	FCC	8 December 1980

The large size of the project area, along with time and budget constraints, limited the field proofing effort to selected locations to verify that the mapped lineaments were not man-made or other recognizable natural features. Because of this and other factors described below, some lineaments may actually be some other feature than being indicative of an actual fracture zone or fault trace.

The azimuths and lengths of each lineament were measured and rose diagrams and histograms created. The lineament maps were compared to published maps (discussed in Findings and Discussion section) to evaluate consistencies and trends, which help to provide interpretations of potential correlations to known regional hydrogeologic trends and anomalies.

Regional Geologic Setting

Florida lies within the Coastal Plain of the southeastern United States, and its present-day landforms reflect the dominant effect of marine forces in shaping the land surface (Schmidt, 1997). However, the peninsular Florida basement was formed as a result of tectonic activity associated with the opening of the Atlantic Ocean and Gulf of Mexico basins.

The Florida basement can be recognized as those rocks underlying the coastal plain sequence of Cretaceous through Holocene sedimentary deposits and the post-rift sediments that begin with the Jurassic Louann and Werner evaporates (Smith, D.L. & Lord, K.M, 1997). Overlying the basement rocks are principally limestone and dolostone, with minor amounts of evaporates and clastics in the younger deposits. The summary of the stratigraphy and lithology in this memorandum covers only those units making up the principal aquifer systems in south Florida. Figure 5 shows the regional stratigraphy with hydrostratigraphic relationships.

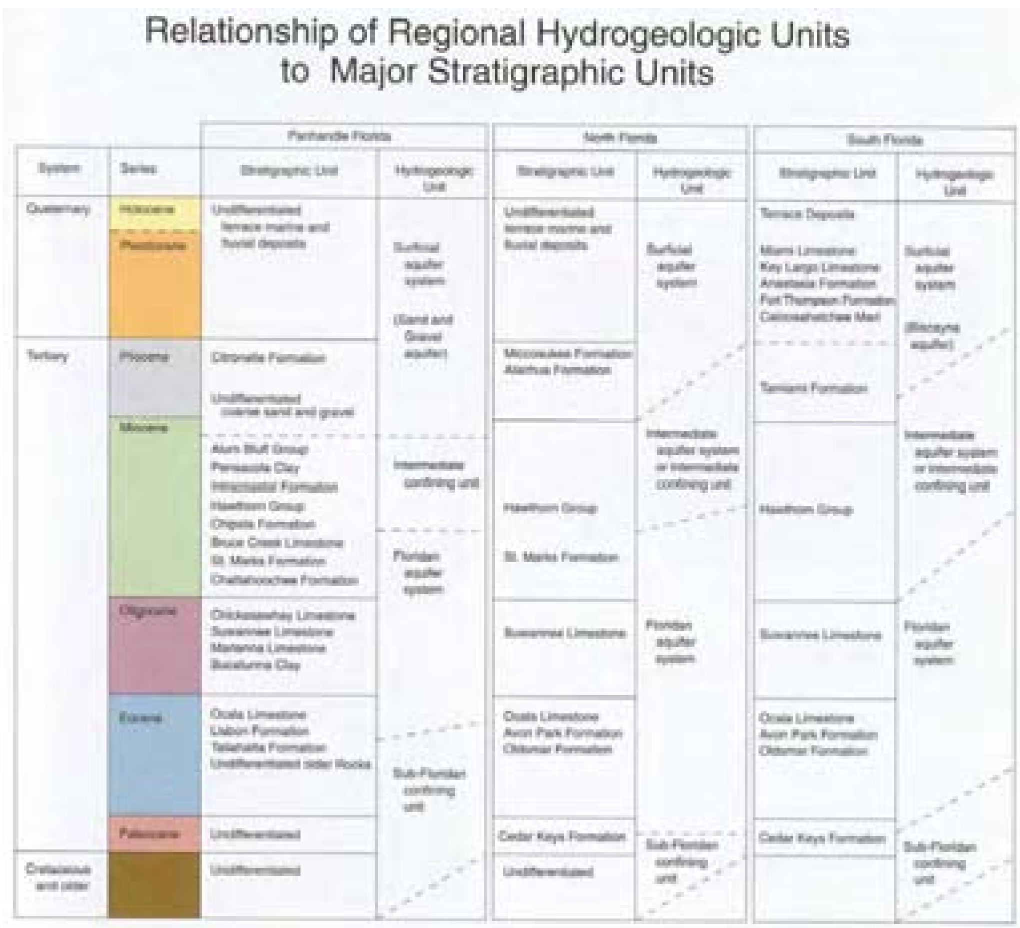


Figure 5. Regional stratigraphy with hydrostratigraphic relationships (from Bernt, M.P., Oaksford, E.T., Mahon, G., Schmidt, 1998).

Stratigraphy and Lithology of South Florida

Basement Rocks

The basement rocks underlying most of the study area consist of Mesozoic sequences of variably deformed rhyolitic and calc-alkaline andesitic rocks. Underlying the northeastern portion of the study area is a diorite to granodiorite batholith referred to as the Osceola Granite (late Proterozoic to Early Cambrian Period of the Paleozoic Era), and immediately south of, and associated with the Osceola Granite is the St. Lucie Complex, which consists of an amphibolite-grade metamorphic sequence. These two units make up the Osceola complex (Smith, D.L. & Lord, K.M., 1997). The Bahamas Fault Zone (also known as the Jay fault) separates the Osceola granite from the south Florida volcanic and St. Lucie Complex rocks. Figure 6 shows a Geologic map of pre-Cretaceous rocks in the basement of Florida and surrounding areas.

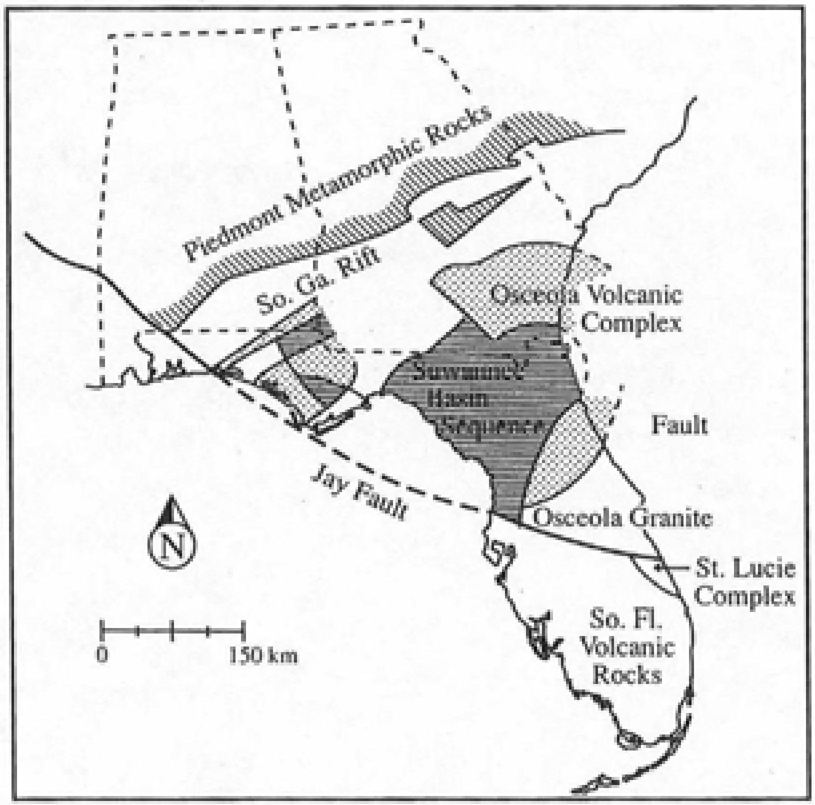
Depths to the basement rock in Florida varies from less than 3,300 feet (1 km) below land surface (bls) in the northwest and panhandle parts of the State, to greater than 17,000 feet in south Florida (Barnett, 1975). The average depth to the basement in the study area appears to be approximately 11,000-12,000 feet bls.

Paleocene Series

The Paleocene sediments of the Cedar Keys Formation lie beneath the “Boulder Zone” of the Oldsmar Formation. This unit is categorized as the sub-Floridan Confining Unit, also known as the “base of the Floridan Aquifer System”, includes dolomite and dolomitic limestone with massive beds of anhydrite at increasing depths.

Eocene Series

Lying below the Hawthorn Group and Suwannee Limestone sediments at depths of approximately 600 to 900 feet bls are the Eocene-aged Oldsmar Formation, Avon Park Formation, and Ocala Limestone. These formations are typically characterized by pale orange to brown, poorly-cemented, granular limestone, and are occasionally micritic. The fossil content of the Eocene Series is not significant, although foraminifera, irregular echinoids and algae debris are commonly observed. The Oldsmar Formation contains significant quantities of hard, yellowish brown finely crystalline to saccharoidal dolomite, and is present to depths of nearly 3,500 feet bls. Anyhdrite is also found to be present in some local areas. The lower 300-600 feet of the Oldsmar Formation, called the “Boulder Zone”, is predominately dolomite and contains massively bedded, cavernous or fractured dolomite of high permeability, and dense, recrystallized dolomite of low permeability (Reese and Memberg, 2000). Overlying the Oldsmar Formation if the Avon Park Formation, which is typically recognized as white to cream foraminiferal limestone, with the majority of foraminifers being Dictyconus. These Avon Park Formation is present to a depth of approximately 1,900 feet bls. Lying over the Avon Park Formation is the Ocala Limestone. The lithology of the Ocala Limestone varies from micritic or Chalky limestone, to a medium frained calcarenitic limestone, to a coquinoid limestong. THis formation is characterized by abundant larger benthic foraminifera, such as Operculinoides sp., Camerina sp., and Lepidocyclina sp. (Reese, 2000).



Geologic map of pre-Cretaceous rocks in the basement of Florida and surrounding areas (adapted from Dallmeyer et al. 1987 and Thomas et al. 1989). The Suwannee Basin sequence of undeformed Ordovician to Devonian sedimentary rocks is shown by horizontal lines. The Osceola complex includes the Osceola Granite, the St. Lucie metamorphic rock sequence, and the Osceola volcanic complex (stippled). Where present in the panhandle, the Osceola volcanic complex includes undelineated granitic subcrops. The South Florida volcanic rocks are Mesozoic. The South Georgia Rift area is occupied by Mesozoic sedimentary rocks. The boundary of Piedmont metamorphic rocks is indicated by diagonal lines.

Figure 6. Geologic map of pre-Cretaceous rocks in the basement of Florida (from Smith & Lord,1997).

Oligocene Series

The Suwannee Limestone is interpreted to be present in the western half of south Florida, pinching out in a generally northwest-southeast trend through the northeast portion of Glades County and trending diagonally through the west and central part of Palm Beach County (Miller, 1986). The depth to the top of the Suwannee range from approximately 600 to greater then 900 feet bls. The dominant lithology of this unit in the project area is pale-orange to tan, fossiliferous, medium-grained calcarenite with minor amounts of quartz sand and little or no phosphatic mineral grains (Reese, 2000).

Miocene Series

The Plio-Pleistocene sediments unconformably overly the dense, phosphatic clays and limey silts of the Miocene-aged Hawthorn Group. However, recent work indicates the Peace River Formation component of the Hawthorn Group may range in age from late Miocene to early Pliocene (Missimer, 1997). The Hawthorn Group sediments extend from between 200 to 900 feet bls. Near the base of the Hawthorn Group, the limestone and phosphate content of these sediments increases, causing the natural gamma ray log to record high emissions through this interval. These characteristic log signatures may be used as “marker beds” that can be correlated throughout the area (Reese, 1994 and 2000). The Hawthorn Group is variable in lithology and generally consists of interbedded sand, silt, clay, dolostone, and limestone, with a characteristically high phosphate content. In the Lake Okeechobee area, the thickness of the Hawthorn Group deposits thicken from approximately 300 feet northwest of the lake to greater than 800 feet southeast of the lake.

Hydrostratigraphy

There are three principal aquifer systems in south Florida: Surficial aquifer system (SAS), Intermediate aquifer system, and the FAS.

Surficial Aquifer System

The SAS consists of typically hydraulically connected unconfined and semi-confined aquifers above the intermediate confining unit, and consists of Pleistocene and Pliocene age deposits. This system is comprised primarily of loose, sandy material and porous limestone with a wide range of permeability, and is divided into distinct aquifers that are separated by less permeable or semi-confining units. The discontinuous and locally productive nature of the shallow water bearing units reflect the complex interfingering of lithologic units throughout southern Florida (Causarus, 1985, 1987; Fish and Stewart, 1991; Knapp et.al, 1986; Smith and Adam, 1988; Shine et.al., 1989; Weedman and others, 1997). The principle surficial aquifers of southern Florida include: the Biscayne aquifer, the undifferentiated surficial aquifer, the coastal aquifer of Palm Beach and Martin Counties, the Gray Limestone aquifer of south-central Florida (Reese and Cunningham, 2000) and the shallow aquifer of southwest Florida. The thickness varies from approximately ten feet at some locations in the western part of the State to greater than 400 feet along the southeastern coastline. These units consist of sands, sandy and shelly limestone, sandstone and silts.

Intermediate Confining Unit

Separating the SAS from the FAS is the Intermediate Confining Unit, which consists predominately of Miocene-aged Hawthorn Group deposits. In Miami-Dade and Broward Counties, the lower portion of the Miocene-Pliocene Tamiami Formation is included in the Intermediate Confining Unit because of its low permeability (Fish, 1988; Fish and Stewart, 1991).

Intermediate Aquifer System

In southwest Florida, the intermediate aquifer system is present within the Hawthorn Group. It consists of beds of sand, sandy limestone, limestone, and dolostone of Oligocene to Pliocene age that dip and thicken to the south and southwest. These aquifers are typically leaky artesian aquifers with moderate transmissivity and are located primarily in Polk, Sarasota, Highlands, Hardee, DeSoto, Hendry, Lee, and Collier Counties.

In southwestern Florida (Lee, Hendry, and Collier Counties), the IAS is under confined conditions and is used as a source of potable water. The aquifer system pinches out to the south and east as the clay content increases.

Floridan Aquifer System (FAS)

The FAS is a thick sequence of Paleocene to Miocene-age carbonate units underlying the entire State of Florida. The upper part of the Cedar Keys Formation (Paleocene), Oldsmar Formation (early Eocene), Avon Park Formation (middle-Eocene), the Ocala Limestone (late-Eocene), the Suwannee Limestone (Oligocene age), and lower portion of the Arcadia Formation (Hawthorn Group-Oligocene to Miocene age) are included in the FAS (Reese, 2000; Miller, 1986, 1997). Low permeable anhydrite units in the lower Cedar Keys Formation constitute the base of the FAS.

The FAS is the primary source of water supply for the northern counties of Florida, and is used as a source of supplemental irrigation water as far south as Martin County. The system receives direct recharge along a structural high, known as the “Ocala High”, which occurs in the west central part of the State. From this area, the FAS dips southward where it is overlain by clays and silts of the Hawthorn Group, which form a relatively thick confining layer over the FAS. The groundwater potentiometric surface is also highest in the central portion of the State and decreases in a radial pattern to the south, east and west.

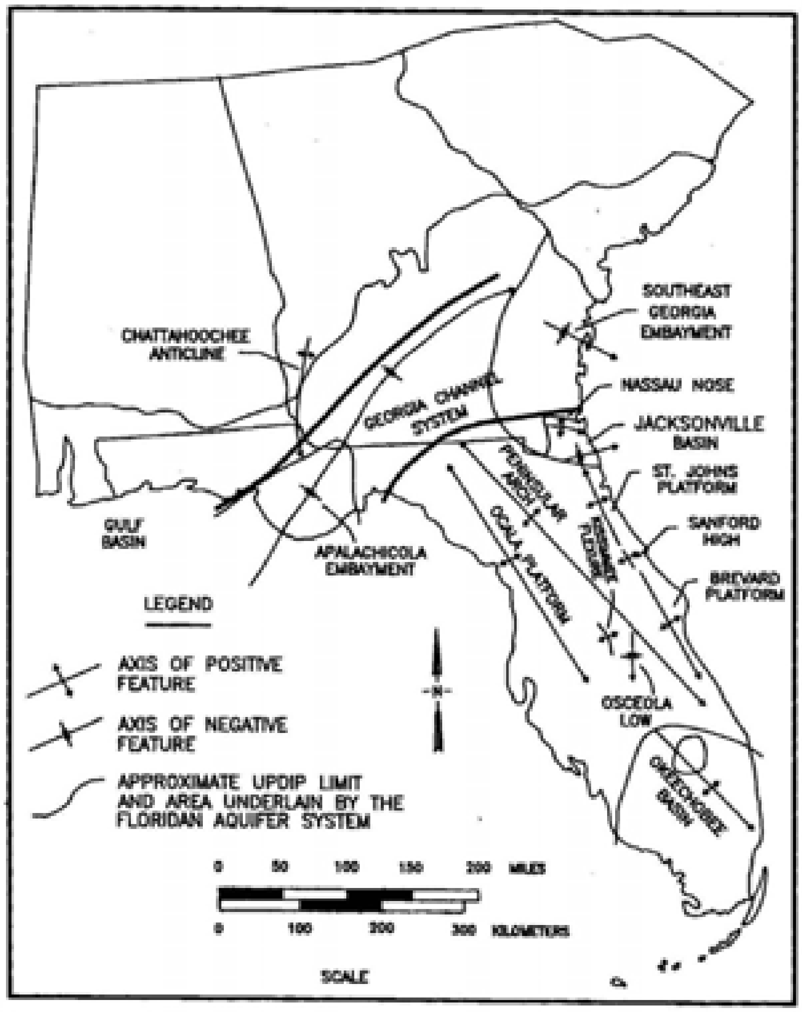
In the Lake Okeechobee vicinity, the potentiometric surface rises above the land surface, resulting in artesian conditions with wells flowing freely up to 2,000 gpm. Less permeable carbonate units, referred to as the middle confining unit, separate the system into two major aquifers called the Upper and Lower Floridan aquifers. North of Lake Okeechobee, the FAS yields freshwater, although it is more mineralized (total dissolved solids are greater than 1,000 milligrams per liter) along coastal areas and in southern Florida (Sprinkle 1989).

Depth to the top of the FAS is approximately 700 feet near Naples and 900 feet in coastal Miami-Dade County (Klein and others, 1975). The transmissivity is generally less than 250,000 square feet per day, generally decreasing to the south due to the presence of low permeability limestone. In the Upper East Coast, the Upper Floridan aquifer is used for drinking water supply. In the Lower East Coast, from Jupiter south to Miami, the Upper Floridan aquifer is sporadically used as a supply source for reverse-osmosis water treatment plants and for ASR systems.

Geologic Structure

The present day Florida Platform is generally considered to be part of a relatively stable setting on the passive margin of the North American plate (Scott, 1977). However, geologic features in Florida suggesting folding, faulting, uplift, and subsidence have been recognized in Miocene to Holocene rocks (Vernon, 1951; Chen, 1965; Meisburger and Field, 1976; Missimer and Gardner 1976; Winker and Howard 1977; Bond and others, 1981; Scott, 1983; Opdyke and others, 1984).

Scott (1997) wrote that these structural features indicated the Florida Platform has endured and responded to tectonic forces during the Miocene through the Holocene. Geologic structures observed in Florida are shown on Figure 7.



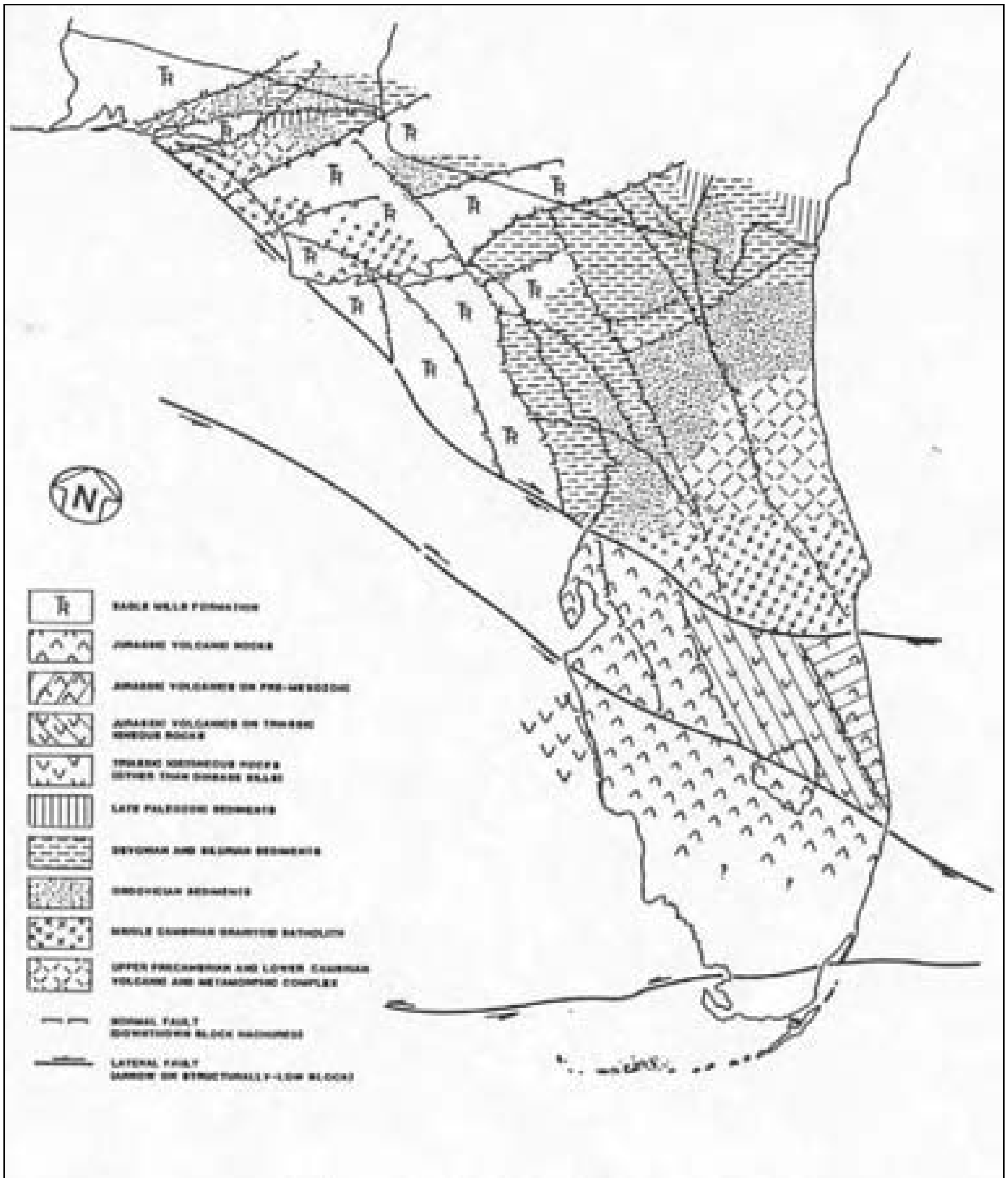
Structural features of Florida.

Figure 7. Structural features of Florida (from Smith & Lord, 1997).

The basement rocks underlying Florida also reflect a complex tectonic history. What is now Florida was once part of the Pan-African continent until the final stages of the development of the Appalachian Mountains in the mid- to late-Paleozoic (Smith, 1982). In peninsular Florida, tectonic activity during the Jurassic created relatively complex structural features in the basement rock, including a number of shear zones. Barnett (1975) suggested that right- and left-lateral shear zones across the state accounted for apparent offsets of basement rocks (Figure 8); however, Klitgord and others (1984) later proposed left-lateral movement along these shear (fracture) zones associated with tectonic plate movements.

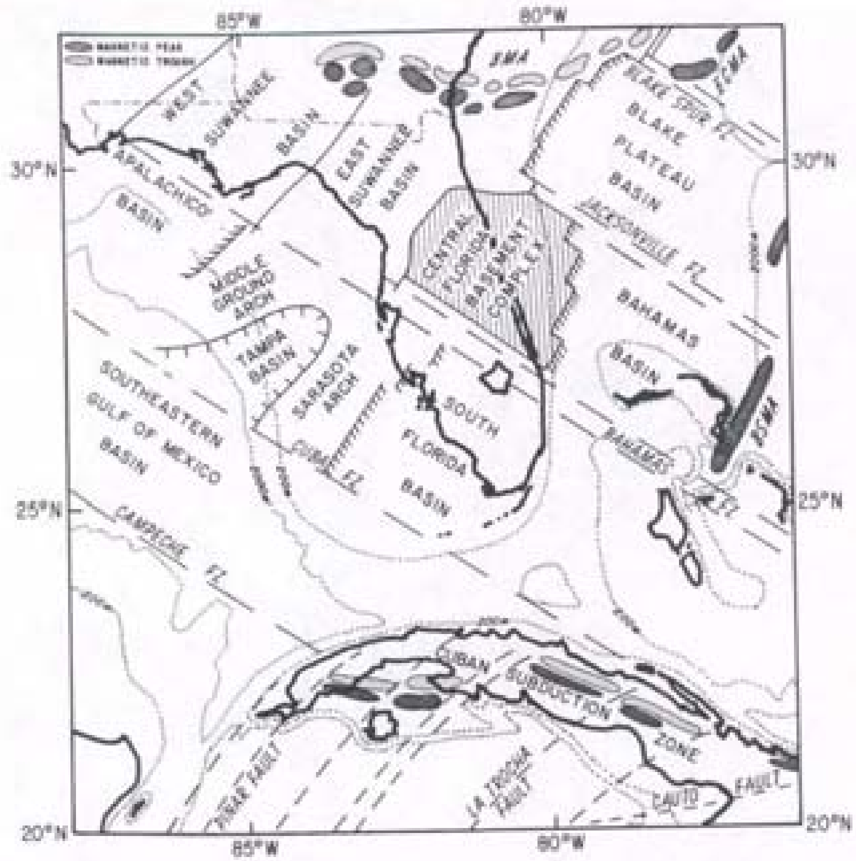
The major shear zones occur along what has been interpreted as a transform plate boundary that connected oceanic spreading ridges in the Gulf of Mexico with spreading ridges in the Atlantic

Ocean (Figure 9). This tectonic transform boundary, separating a major crustal discontinuity (Klitgord and others, 1984), has been recognized for some time and has been documented by several authors such as Walper and Rowett (1972); Beall (1973); Barnett (1975); King (1975); and Klitgord and others (1984), and is referred to as the Bahamas Fault Zone (BFZ). Christenson (1990) referred to this shear zone as the Florida Lineament, interpreted as a Triassic-Jurassic extensional rift margin and a southeastward continuation of the Gulf peripheral fault system trending southeast from Texas into Florida (Duncan and others, 1994). The BFZ trends in a northwesterly direction at approximately 300-305°.



Subcrop map of the sub-Zuni surface
(after Barnett, 1975).

Figure 8. Map by Barnett (1975) showing inferred shear zones and basement rock types (from Culbreth, 1988).



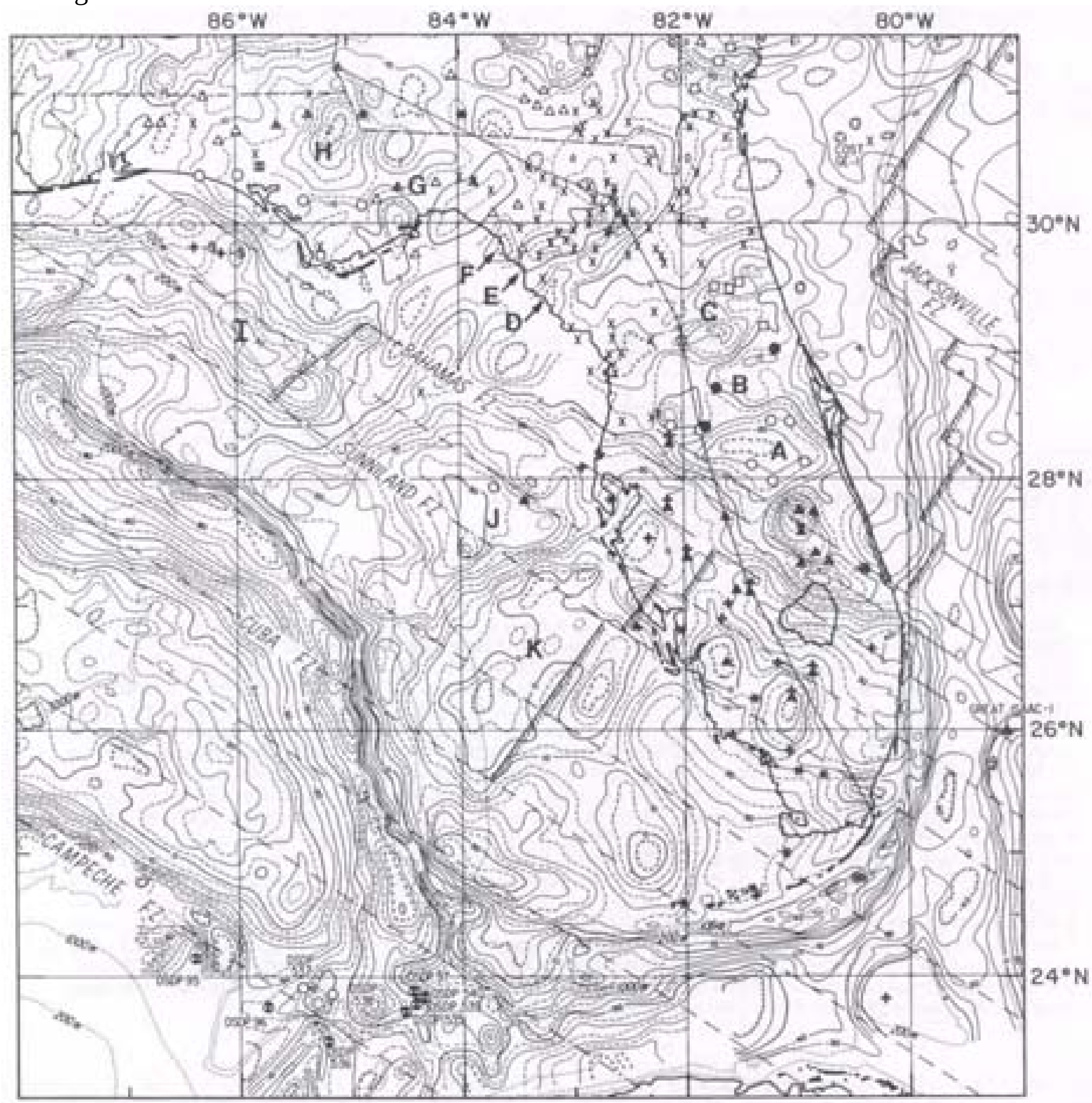
Tectonic map of the Florida-Bahamas-Cuba region. Prominent magnetic anomaly lineations are indicated: East Coast magnetic anomaly (ECMA), Brunswick magnetic anomaly (BMA), and the Blake Spur magnetic anomaly (BSMA). Basement hinge zones separate the Jurassic marginal basins from Paleozoic and older crust. Only the most important fracture zones (FZ) are shown. Bathymetric contours [from *Martin*, 1975] are in meters.

Figure 9. Tectonic map of the Florida-Bahamas-Cuba region (from Klitgord and others, 1984).

The disparity of gravity and magnetic geophysical anomaly patterns between north and south Florida has been cited as evidence for a transform plate boundary through Florida during the Jurassic (Klitgord and others, 1984). Figure 10 presents a gravity anomaly map of the Florida region with the interpreted shear and basement hinge zone locations. Additional evidence of the BFZ is given by detailed magnetic studies in Polk County (Smith and Graves, 1986), which have yielded anomalies interpreted as being consistent with a basement granitic feature truncated by a major northwest-trending fault.

Geophysical surveys east of Lake Okeechobee provide evidence of shears and basement hinge zones within the BFZ. Klitgord and others (1984) referred to the basement hinge zone as representing the block-faulted edge of the North American plate, separating the Jurassic rifted crust from Paleozoic and older crust beneath marginal basins. Barton (1984) adopted this definition and referred to these hinges as “extensional block fault zones”.

Gravity and magnetic geophysical investigations of the basement structures in St. Lucie, Martin, and Palm Beach Counties, within the BFZ, which supports the existence of a combined Jurassic transform plate boundary in south Florida (Barton, 1984). The results of the investigations show an abrupt continental margin trending to the northwest with a gradual transition, indicative of a basement hinge (extensional block fault) zone trending to the northeast. Figure 11 shows that the interpreted structure in this area coincides closely with the trends proposed by Klitgord and others (1984). The dashed feature north of the main shear zone is interpreted as another transform fault in a broad fault zone (Figure 11). The data appears to suggest that the BFZ is, indeed, a wide zone that is probably subject to significant fracturing as well as transform faulting.



Gravity anomaly contour map of the Florida region. Gravity features discussed in the text are indicated with letters. Drill hole basement rock symbols are the same as in Figure 3.

Figure 10. Gravity anomaly contour map of the Florida region with shear and basement hinge zones delineated (from Klitgord and others, 1984).

A second major shear zone in the study area is identified as the Sunniland Fracture Zone (SFZ), located parallel to and south of the BFZ (Figure 10). Several oil-producing fields have been discovered along this trend. Culbreth (1988) performed a gravity survey across a mapped lineament he described as being the Sunniland Lineament, which trends 297°. This lineament was also recognized during this study and is highlighted in Figure 24. The results of the survey was interpreted to indicate that the geologic structure responsible for the observed gravity signature was deep and may not consist of a large density contrast (Figure 11). He interpreted the vertical displacement along the basement faults to be on the order of 1640 feet (0.3 km) to 6560 feet (2 km). Depth to basement in this area is approximately 14,760 feet (4.5 km). The survey results are consistent with a strong gradient Bouguer gravity trend present in this area.

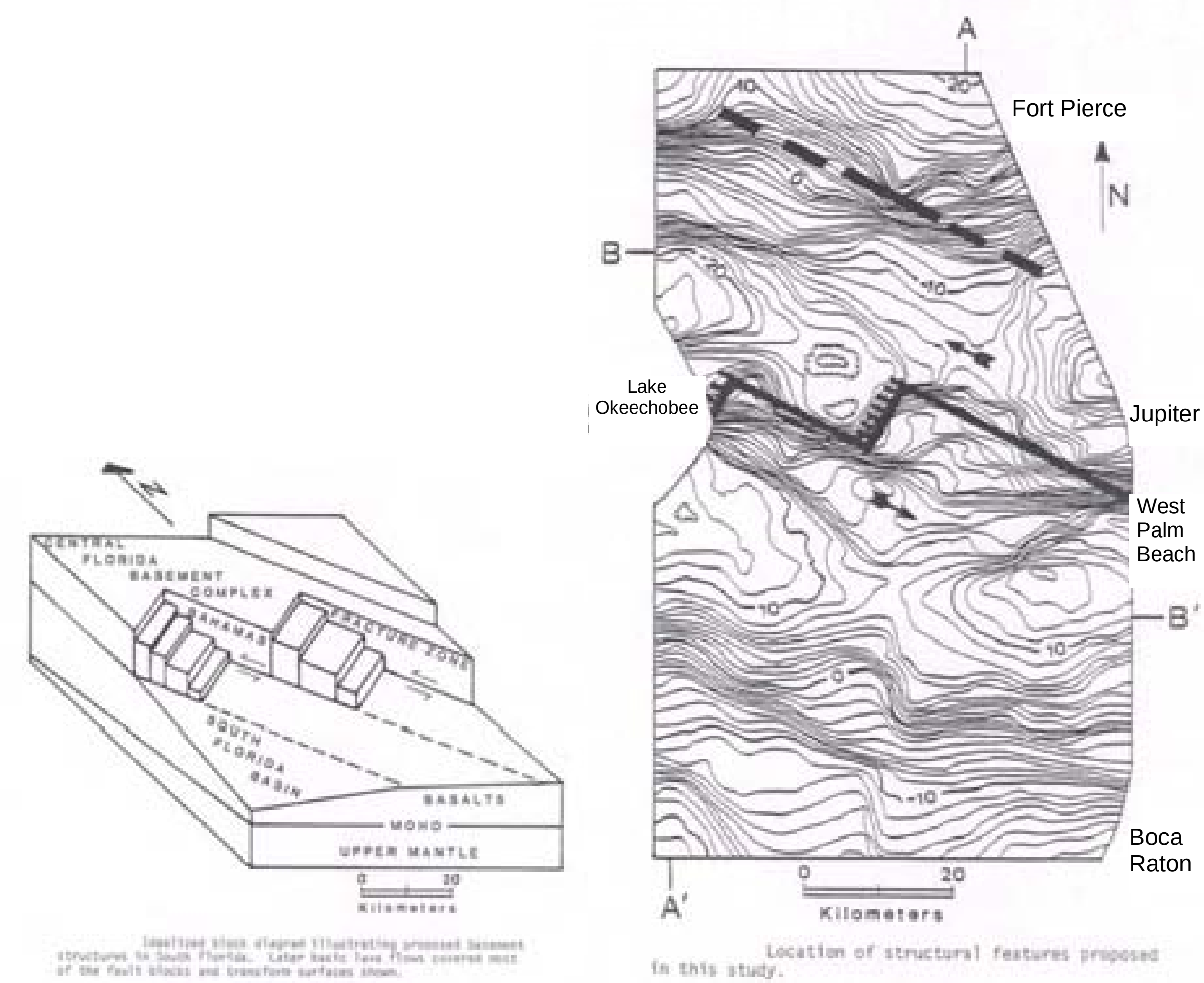


Figure 11. Idealized block diagram illustrating basement structures in south Florida and the structural features identified, shown on a gravity anomaly map (modified from Barton, 1984). The basement hinge zone is represented by the extensional fault blocks in the block diagram.

The collision of the Cuban Island arc/margin with the North American Plate during Late Cretaceous through Middle Tertiary is the most recent major tectonic event potentially affecting south Florida (Sheridan et al., 1981; Hempton, 1991). Sheridan et al., (1981) suggested that convergence-related stresses reactivated old (Jurassic) planes of crustal weakness such as the BFZ with possible left lateral shear displacement (Duncan and others, 1994). Hempton (1991) interpreted anomalous vertical seismic features in south Florida, commonly attributed to paleokarst or static problems, as true vertical faults that propagated upward from reactivated basement faults of the basement into the overlying carbonate section during this same time period (Duncan and others, 1994).

Reports of faulting or potential faulting in the younger rocks overlying the basement rocks, including the FAS and SAS, in south Florida has been reported by numerous authors including Barnett (1975), Sproul et. al. (1972), Miller (1989), Duncan and others (1994), Reese (1994), Mitchell-Tapping (1995), Winston (1995), Mitchell-Tapping et al. (1999), and Reese and Cunningham (2000). The relationship between these faults and underlying structure is uncertain at this time.

Another major structural feature of the basement in central and south Florida is the Peninsular Arch (Figure 7). The Peninsular Arch plunges southeast towards central Martin and Palm Beach Counties in the project area and has been a positive feature affecting sedimentation from the Jurassic into the early Cenozoic (Miller, 1986).

The primary Middle Cenozoic structures in the project area are the Lake Okeechobee Basin and the Brevard Platform. Riggs (1979) described the Okeechobee Basin as a Neogene depositional low with thick accumulations of Hawthorn Group sediments in the south Florida Region. Scott (1988) described the Brevard Platform is a low relief ridge that plunges gently to the south-southeast and southeast (Duncan and others, 1994).

Findings and Discussion

Mapped Lineaments

Most lineaments have been identified in the western and north central part of the study area, whereas the southeastern peninsular area has the least number identified. While this may reflect the decreased occurrence of lineament traces in the southeastern part of the study area, the primary reasons for this appears to be the degree of urbanization and other man-made activities, natural surface geomorphology and surficial deposits, and water covering much of the land surface that mask lineaments in the south and southeast.

A number of factors together caused this exercise to be tremendously challenging. First, the large project area and correspondingly large-scale image coverage made it difficult to fully evaluate any one particular area. A regional approach was utilized to identify the dominant lineaments rather than trying to identify every short lineament and fracture zone trace. The scale of the project necessitated the use of Landsat imagery as the primary source with DOQQ photos used to complement the Landsat images for the ASR pilot project site areas. Second, stereographic images were not available at the large scale necessary to perform the regional analysis. Much smaller scale aerial photographs were available. Such small scale aerial photographs are valuable for detailed site specific lineament/fracture trace analysis, but were not be very useful for this large study area, given the time and budgetary constraints. Third, the high degree of man-made surface features along with natural constraints (water, lack of topographic relief) made identification of lineaments difficult.

A total of 548 lineaments greater than one mile in length were mapped within the study area on the Landsat mosaic prepared for this study. The length of any single lineament ranged from approximately 1.1 miles (1.8 km) to 111.6 miles (179.6 km), with the majority having lengths less than ten miles. The average length the identified lineaments is 11.5 miles (18.5 km) and the median lineament length is 6.8 miles (10.9 km). Figure 12 presents a histogram of the lineament lengths versus number of lineaments; Figure 14 shows the lineaments identified in this study.

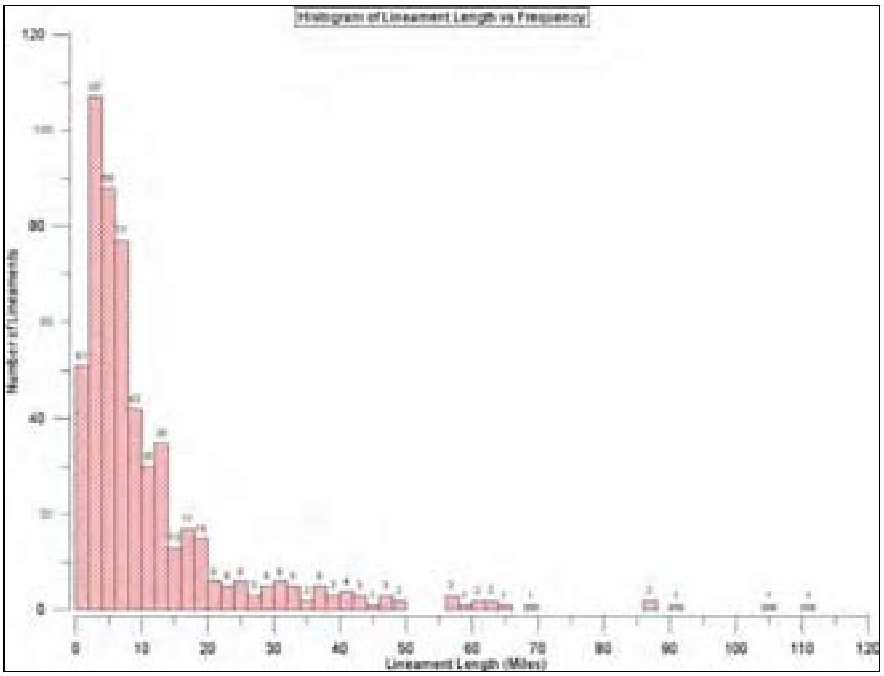


Figure 12. Graph showing lineament length versus number of lineaments.

Lineament orientations plotted a Rose diagram show the dominant orientations of the lineaments are in a northwest-southeast and northeast-southwest direction, with azimuths ranging approximately from 280°-330° and 25°-60°, respectively (Figure 13). The primary, or prominent, lineament sets, in descending order are: 305°-310°, 300°-305°, 310°-315°, 35°-40°, 40°-45°, and 45°-50°. There are also several minor (less prominent) lineament sets with azimuths in a more northerly and easterly direction. Figure 13 presents a rose diagram showing the lineament orientation distribution and a graph showing lineament length versus azimuth.

The ranking of the lineaments using the guidelines discussed above show that 198 lineaments have a “High” confidence level; 141 have a “Medium” confidence level, and 209 have a “Low” confidence level. Sinkholes and solution depressions were the most common feature recognized on the lineaments. The number of each criterion factor present in the identified lineaments were: Stream segment alignment – 190; Ponds and lakes – 62; Sinkholes and solution depressions – 388; Vegetation/soil tonal changes - 307; Drainage patterns and topographic relief – 350.

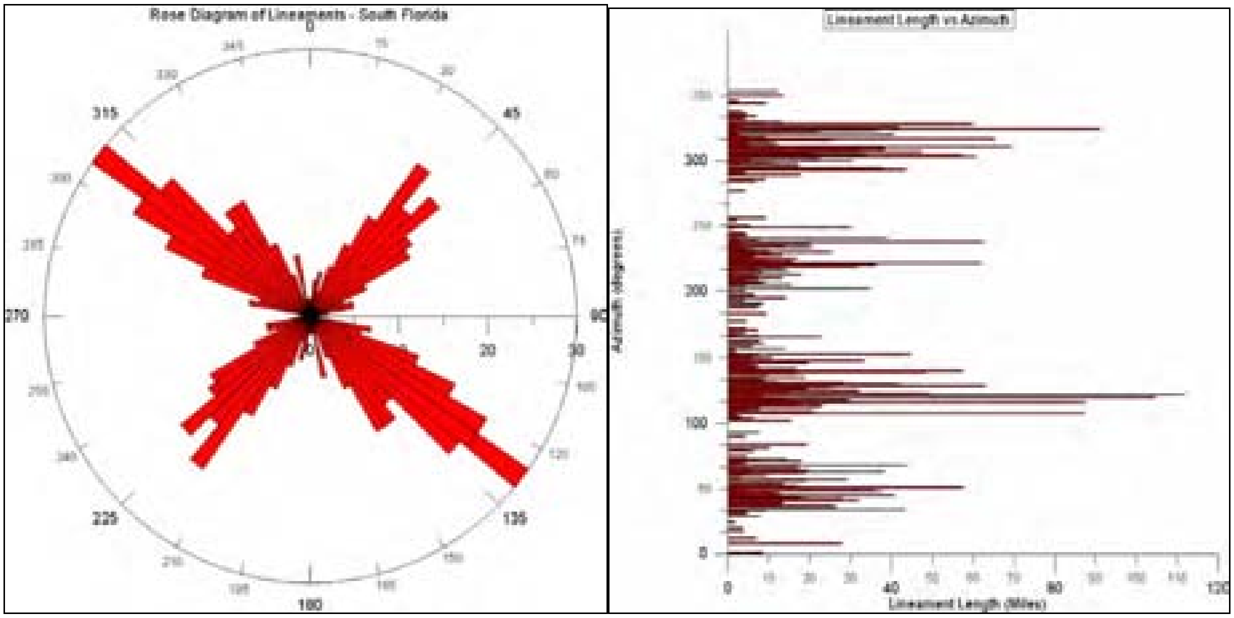


Figure 13. Rose diagram and graph showing lineament length versus azimuth of lineaments identified in south Florida.

There was good repeatability with the previous studies in the region, with 90 lineaments identified in this study matching parts of, or entire, lineament traces identified by Culbreth (1988). Figure 15 shows the matching lineaments. Several fracture traces identified by Watkins and Ruth (1983) at the Southwest Regional Airport site in Lee County also correspond to lineaments identified in this study. Other traces fall near these lineaments.

Various configurations of the mapped lineaments were prepared to remove 'clutter' so that groupings and trends may be more readily observed. Mapping lineaments greater than 25 miles (40.2 km) provides a clearer view of the major lineaments and trends. Sixty-three lineaments 25 miles or longer in length have been mapped and are shown on Figure 16. The majority of these longer lineaments are northwest trending.

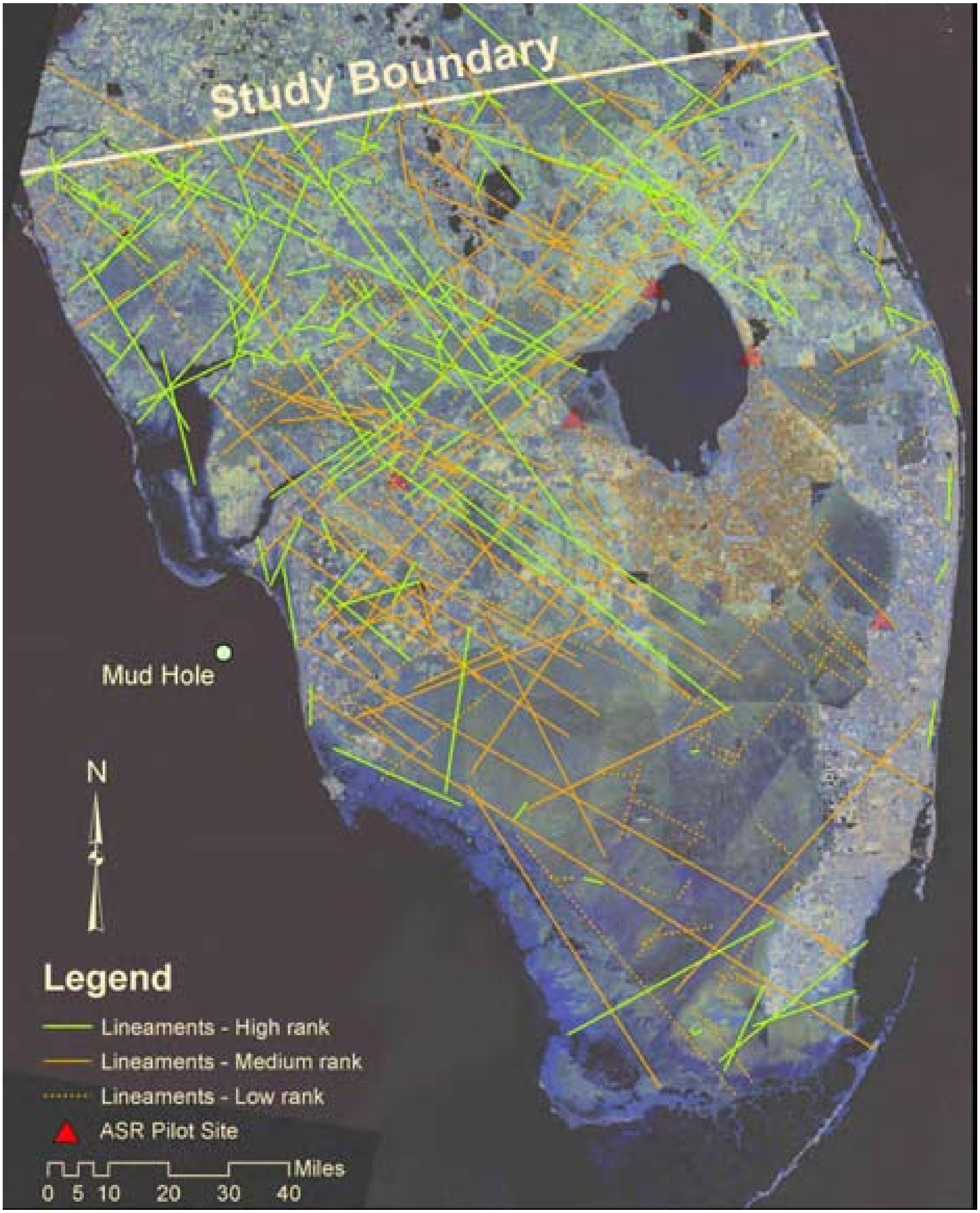


Figure 14. Site map showing lineaments identified in south Florida on Landsat mosaic.

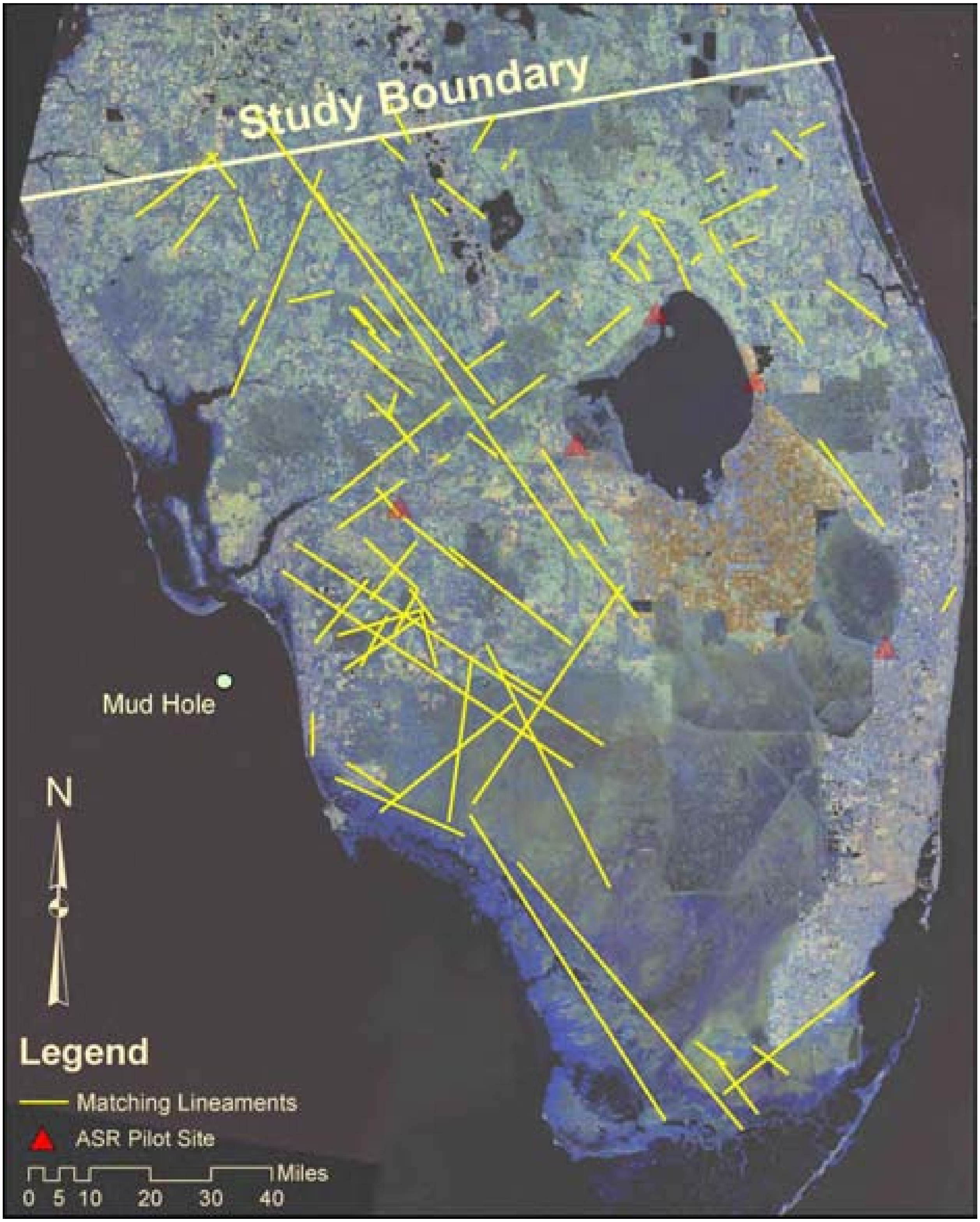


Figure 15. Lineaments matching previous work by Culbreth (1988).

Maps showing the northeast and northwest trending lineaments separately provide some of the clearest groupings of lineaments. The northwest trending lineaments are spread out more evenly across the study area, but do appear to be more concentrated in the vicinity of, and southwest of Lake Okeechobee (Figure 17). Whether this is because of the inability to identify lineaments in the southern part of the study area because of water, urban growth, etc. or because of geologic features is uncertain. The northeast trending lineaments show a distinct concentration from the study area from the Fort Myers, along the northern Caloosatchee River corridor and across the northwest side of lake Okeechobee (Figure 18).

Several lineaments were identified on the DOQQ photo mosaics, many of which were along lineaments identified on the Landsat images. Figures 19 through 23 show the lineaments observed on the DOQQ photos in each of the five ASR pilot sites. The orientations of the lineaments identified on the DOQQ mosaics are consistent with the regional trends. However, the Caloosahatchee River ASR pilot site had the most lineaments falling along lineaments observed on the Landsat mosaic. The Hillsboro ASR pilot site had the nearest lineament to the site identified on the DOQQ mosaics. Table 2 below shows the nearest lineament to each ASR pilot site identified on Landsat and DOQQ imagery.

Table 2
Distance from Nearest Lineament to ASR Pilot Project Site

ASR Pilot Site	Nearest Lineament on Landsat image (miles)	Nearest Lineament on DOQQ photo (miles)	Nearest lineament on DOQQ along lineament identified on Landsat?
Kissimmee River	0.6 northwest	1.4 miles north-northwest	Yes
Port Mayaca	5.6 northeast	3.2 south-southeast	No
Caloosahatchee River	0.35 northwest	1.0 north-northeast	Yes
Hillsboro	1.0 northeast	0.3 southwest	No
Moore Haven	2.7 northeast	2.2 southeast	Yes

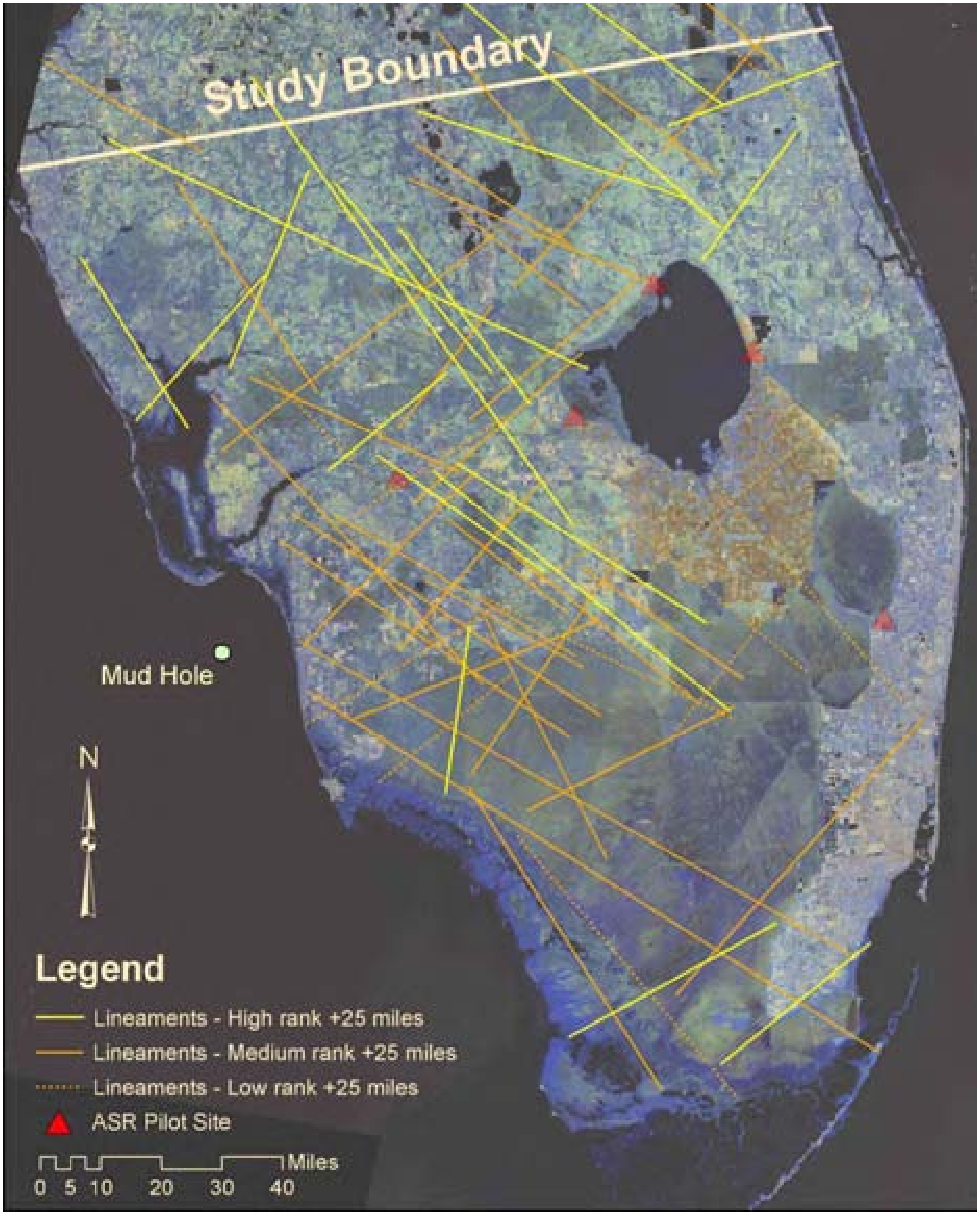


Figure 16. Site map showing lineaments longer than 25 miles.

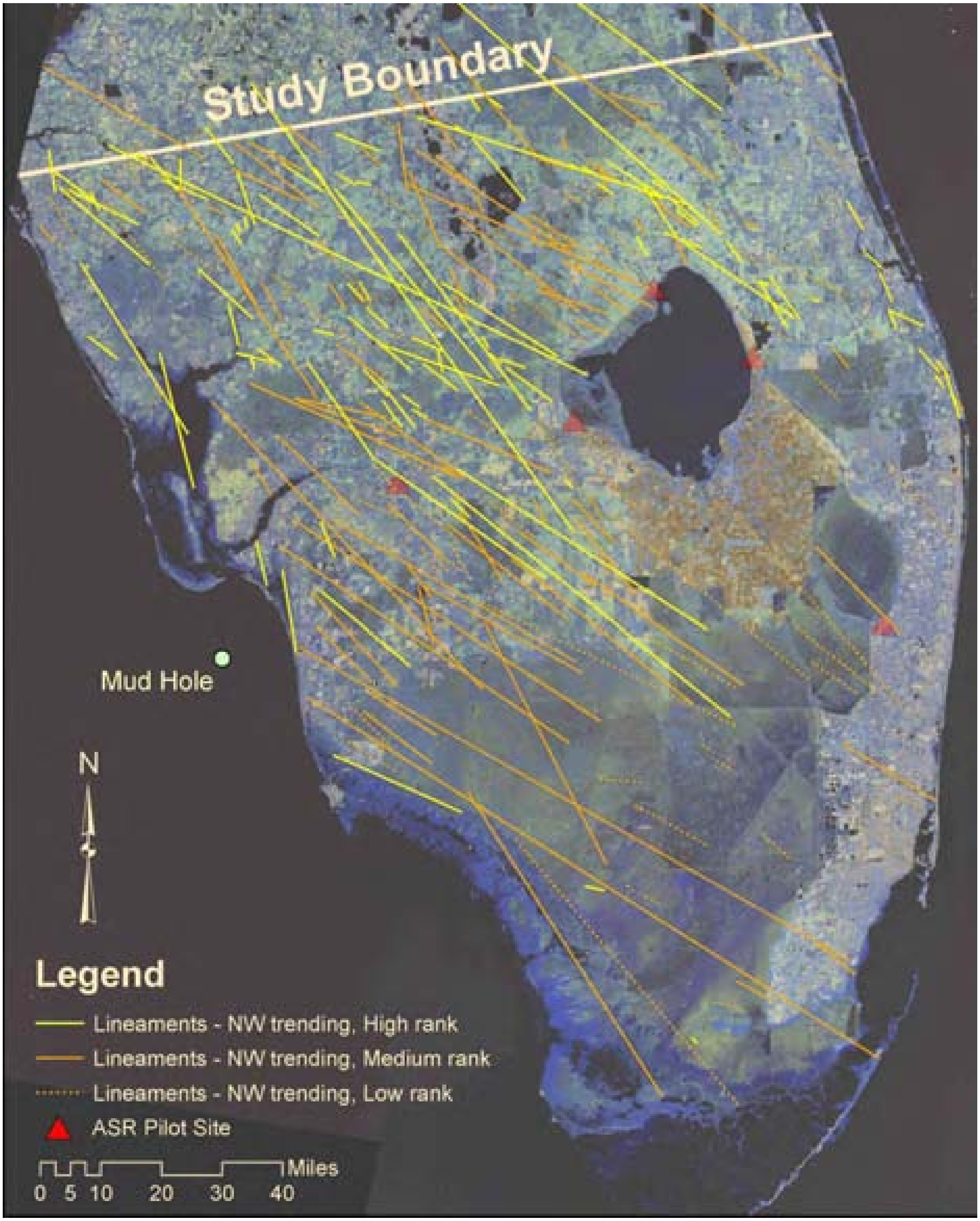


Figure 17. Map showing northwest trending lineaments

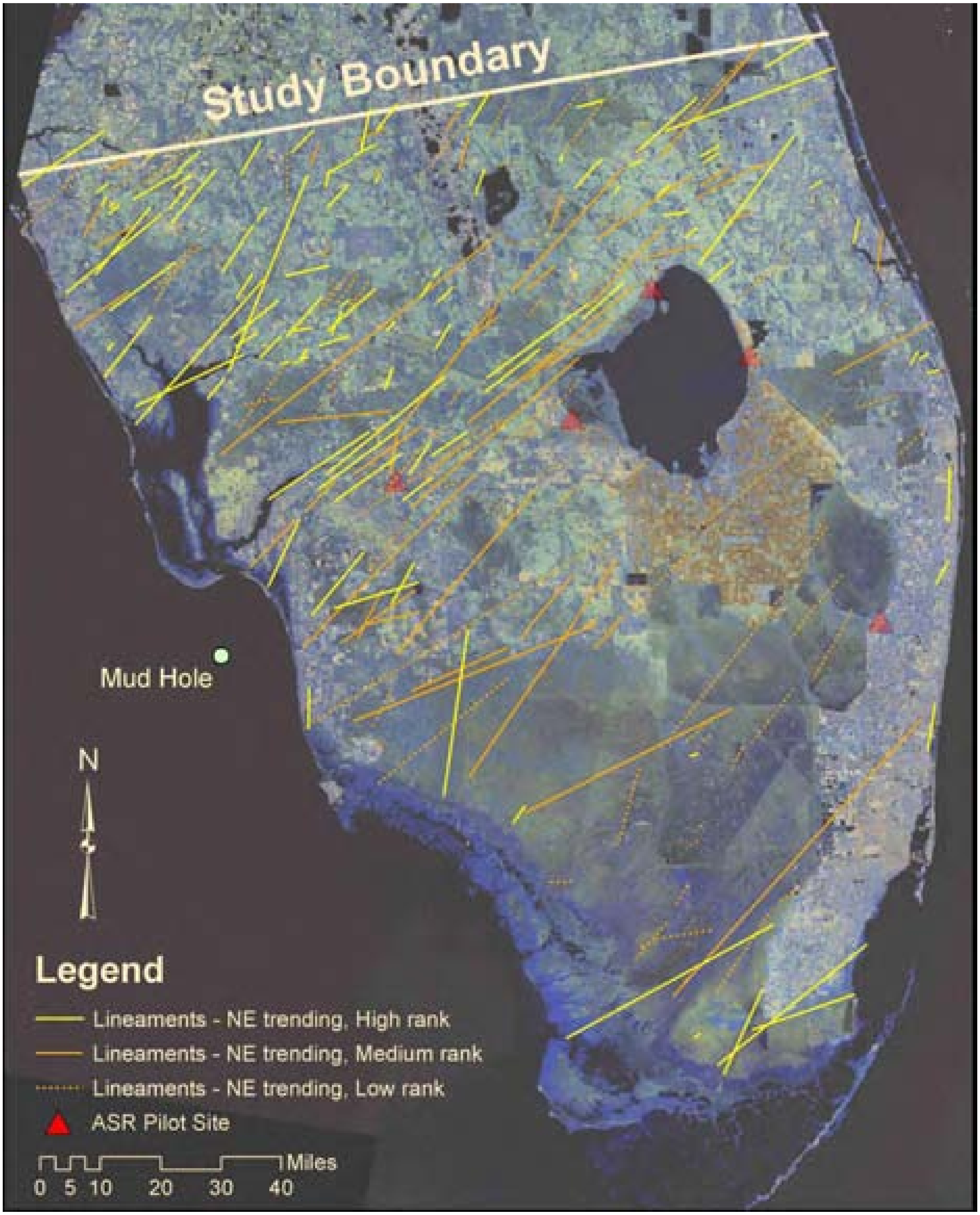


Figure 18. Map showing northeast trending lineaments.

Figure 19. Lineaments identified on DOQQ mosiac in vicinity of Kissimmee River ASR pilot site.

Figure 20. Lineaments identified on DOQQ mosaic in vicinity of Port Mayaca ASR pilot site.

Figure 21. Lineaments identified on DOQQ mosaic in vicinity of Caloosahatchee River ASR pilot site.

Figure 22. Lineaments identified on DOQQ mosaic in vicinity of Hillsboro ASR pilot site.

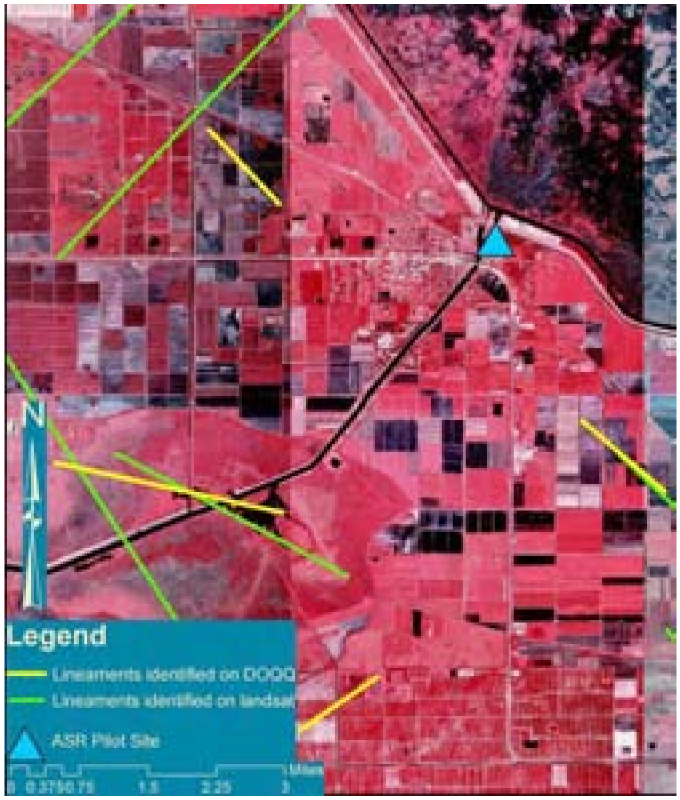


Figure 23. Lineaments identified on DOQQ mosaic in vicinity of Moore Haven ASR pilot site.

Discussion

Relationship of Lineaments to Basement Structure

The mapped lineaments coincide fairly well with published basement fracture/shear and basement hinge zone structural features. Several factors could contribute to the variations between lineaments and structures. Because structural features were mapped using geophysics and limited well data, actual locations may vary from their mapped positions. Additionally, dominant structural features (fracture/shear and basement hinge zones) can be expected to be thousands of feet wide. Variations in exact location are exacerbated by the wide fracture zones characteristic of carbonate terrains, and the possibility that fractures, dipping even a few degrees off vertical, will have a surface offset from the subsurface features. These factors notwithstanding, mapped surface lineaments trending along, or near major basement fracture/basement hinge zones makes a compelling argument of reflecting basement structure.

One significant observation is that the major lineaments identified in this study essentially match major shear zones identified by Barnett (1975), and generally follow the same trends as the major deep-seated fracture zones and basement hinge zones mapped by Klitgord, et al. (1984). The number of northwest-trending lineaments increases in the immediate vicinity of the mapped shear and basement hinge zones. Additional shorter lineaments fall along the wide BFZ alignment (Figures 10 and 14), albeit with offset azimuth orientations. These, if related to the shear zones, could reflect en-echelon fractures in and along the zones. An example of possible en echelon factures along a lineament observed on large-scale imagery is seen on Figure 22, where shorter lineaments (or fractures) were identified along the longer lineament.

Klitgord and others (1984) mapped basement hinge zones northwest of Lake Okeechobee and near the eastern shore off Stuart, Florida. However, no basement hinge zones were mapped along the BLZ in the Lake Okeechobee area (Figure 10).   An increase in the number of mapped northeast trending lineaments identified for this study was observed in the Caloosahatchee River vicinity and immediately north of Lake Okeechobee (Figure 18). Although the orientations of these lineaments are approximately 10°-20° more towards the east than the basement hinge zones mapped by Kiltgord and others (1984). the concentration of surface lineaments along this trend may reflect a basement hinge zone or some other structure not previously identified in this area.

Further evidence of a potential basement hinge zone in the Lake Okeechobee area is Barton’s (1984) geophysical investigation of the basement structure (see discussion in the Geologic Structure section), in which northwest trending shears connected by basement hinges in one area and a separate shear have been identified in a broad fault zone (Figure 11). Many normal faults with varying strikes can be expected to occur in basement hinge zones. The surface lineaments identified along this zone may be surface reflections of these features.

Identified lineaments generally overlay a some mapped faults in the northeast portion of the study area. Figure 24 (after Reese, 2004), shows a lineament directly overlaying a portion of the northwest trending fault near the coast, identified by Lichtler (1960). Other lineaments are near this mapped fault and another mapped fault identified by Winston (1995), located just south of the fault mapped by Lichtler. Four lineaments have also been identified along the northwest trending faults mapped by Barnett (1975).

Potential Relationship to Hydrostratigraphy

Fractures or faults extending from deep-seated geologic structures through the overlying rocks to the ground surface could have profound ramifications on the local and regional hydrostratigraphic conditions of overlying aquifer systems and confining units, such as the FAS and Hawthorn group in south Florida.

While there is currently not an abundance of data confirming upward leakance into or out of the FAS in south Florida, there is plenty of indirect, or circumstantial, evidence suggesting that transmission of water through “confining” layers occurs through fractures as well as by diffuse leakance. Sproul (1977) reported that in southern Florida producing wells, groundwater temperature measurements reveal anomalous relationships between temperature and depth that can be attributed to upwelling of warmer water along fracture systems (Smith, D.L. & Lord, K.M, 1997).

On a regional scale, the chloride concentration of the upper FAS (Figure 25) increases dramatically south of a northeast trend line generally corresponding to the mapped northern boundary of the Okeechobee Basin (Figure 7) and the approximate locations of concentrated northeast trending lineaments, which may be reflective of a geologic structure at depth (Figure 18). The increase in chloride in the upper FAS may be a result, at least in part, of upward leakance through lower semi-confining and confining units, as well as naturally high chloride content in the connate water and lateral infiltration of sea water from the Atlantic Ocean and Gulf of Mexico into the FAS. Alternatively, the high salinity south of this northeast trend may be due to residual sea water or connate water because of poor flushing by groundwater flow originating in the central Florida area.

Figure 24. Lineaments imposed on mapped faults in northeast portion of study area (fault map modified from Reese, 2004).

The recently completed test well at the Kissimmee River ASR pilot site just northwest of Lake Okeechobee shows highly fractured sections in the upper FAS, that may be associated with a basement hinge zone at depth.

Figure 25. Map showing chloride concentrations in the Upper FAS in Florida (from Berndt, Mahon, & Schmidt, 1998).

Diffuse upward leakance and partially cased artesian wells are two possible pathways of saltwater intrusion from underlying aquifers in southwest Florida (Schmerge, 2001). Further investigation should help ascertain if flow is increased along fracture zones or lineaments.

Another example of possible leakance is the injection of industrial liquid wastes (chiefly acetic acid) into brackish zones of the Upper Floridan aquifer, which occurred in the 1960s and 1970s at a furfural plant in Palm Beach County (Meyer, 1989). Miller cited several authors who documented that the injected hot acid waste migrated from the lower part of the FAS aquifer to appear in a shallower monitored zone.

Potential faults have also been mapped in the FAS and shallower aquifers, which are reflected by anomalous contours on potentiometric, isopach, and structure maps. Most documentation of potential geologic structures have been reported in southwest Florida, possibly because of increased evidence of such features in the subsurface. Surface lineaments have been recognized along several of these possible faults.

Watkins and Ruth (1983) summarized the lower Hawthorn Group geology of the Lee County area, as originally reported by Sproul et al. (1972), as being a heavily faulted zone, with faults having a northwest-southeast trend. Evidence of faulting extending above and below the Hawthorn Group in southwest Florida is supported by Osmond and Cowart (1977), who demonstrated upwelling of deeper waters in southwestern Florida through interpretation of uranium-series isotopic anomalies (Smith, D.L. & Lord, K.M, 1997). The northwest-trending lineaments probably represent the surface expressions of the better-developed faults.

The Mud Hole Spring, located south of Sanibel Island (Figures 14 and 16), is thought to be fault-related to the basement Sunniland Fracture Zone, with the source water migrating through faults extending from the basement and mixing with cooler FAS water as it moves upward (Mitchell-Tapping and others, 1999). The water issuing from the spring has a temperature of 35.3°C, compared to the average 21°C of the surrounding seawater, whereas the upper Floridan aquifer ranges from 26.6°C to 29.4°C. A temperature profile from a nearby oil-exploration well indicates that this temperature exists at a depth of approximately 980 feet bls, which is in the Boulder Zone of the Oldsmar Formation. Sodium, silica, and sulphate chloride levels are all higher than the open ocean and a nearby injection well completed in the Boulder Zone (Mitchell-Tapping and others, 1999). This work has not been widely accepted; however, it is interesting to note that a significant northwest trending lineament and a shorter northeast trending lineament, if projected into the sea, would intersect near the Mud Hole Spring.

Northeast Study Area

The presence of surface lineaments coinciding with mapped faults in the northeast study area discussed above is just one of several examples of potential relationships of surface lineaments to underlying geologic conditions. A structure contour map of the altitude of the top of the basal Hawthorn/Suwannee unit shows general northwest-trending ridge and swales with a weakly defined northeast-trending component (Reese, 2004). A northwest-trending trough roughly coincides in position and trend with the basement fault mapped by Barnett (1975) (Reese, 2004), as well as with several lineaments (Figure 26). This trough is in the immediate vicinity of two lineaments identified along this fault.

Lineaments are also present in and near a northwest-trending trough located closer to Lake Okeechobee. A portion of a relatively long high rank lineament coincides with a northeast-trending ridge in the north central map area, and above the aforementioned northwest-trending trough.

A map of the altitude of the top of the Ocala Formation (Reese, 2004) also shows northwest-trending ridge and swale topography, and a similar northwest-trending trough seen in the structure contour map of the top of the basal Hawthorn/Suwannee unit (Figure 27). There is much more apparent correlation between the contours and the northwest-trending lineaments than with the northeast-trending lineaments.

From a hydrogeologic perspective, contour maps of the chloride concentrations in the Upper Floridan aquifer and distribution of water temperature in the Upper Floridan aquifer (Reese, 2004) are particularly interesting. The map (Figure 28) showing the chloride concentrations in the Upper Floridan Aquifer in this area (Reese, 2004) also shows chloride concentrations to generally increase to the south and southeast. However, there is a northwest trend to the contours, with higher concentrations reaching higher to the north along the fault mapped by Barnet (1975), and an area with higher concentrations at the north edge of Lake Ok. Northwest-trending lineaments coincide or are in the immediate vicinity of other locations where the higher chloride concentrations extend to the northwest.

The distribution of temperature map shows the highest temperatures along the aforementioned fault mapped by Barnett (1975), at the north edge of Lake Okeechobee, and in two areas near the coast in the northeast portion of the study area (Figure 29). The map also shows wells that have had increasing chloride concentrations over time. As with many of the examples cited above, these temperature highs tend to appear along or near mapped lineaments.

Southwest Study Area

Examples of potential correlation of surface lineaments with subsurface features in the southwest study area focus on the FAS.

Reese (2000) shows a projection of the inferred North Port fault (Winston, 1996) trending northwest through Collier and Lee Counties on a map of the altitude of the top of the basal Hawthorn unit of the Hawthorn Group in southwest Florida (Figure 30). This fault parallels several ridges and troughs having the same orientation across the region. A large northwest trending lineament has been identified along the same alignment of the mapped fault; a few others are oriented en echelon to the trace (Figures 14 and 17). Several shorter lineaments are mapped in the immediate vicinity of the mapped northwest-trending ridges and troughs, as are two northeast trending lineaments, which seem to correspond to northeast-trending troughs in the study area.

Similarly, Reese's altitude map of the basal contact of the Hawthorn Group of the same study area shows definite northwest trending ridges and troughs across the study area, with troughs parallel to mapped lineaments (Figure 30). The isopach map of the basal Hawthorn unit shows relatively narrow thinning of the basal Hawthorn group along the projected North Port fault (Figure 31).

The approximate axis of the top of a dolomite-evaporite unit in the FAS middle confining unit in this area (Figure 33) also follows in the immediate vicinity of the projected North Port fault Reese (2000). This suggests that the diagenetic process is responsible for the formation of dolomite in the higher sections of host rock. This process may have occurred at least in part as a result of the upward flow of water along the fault and associated fractures. There are also two long lineaments generally paralleling a northeast trending ridge extending from the Naples area to the edge of the mapped area in central Hendry County (Figure 18).

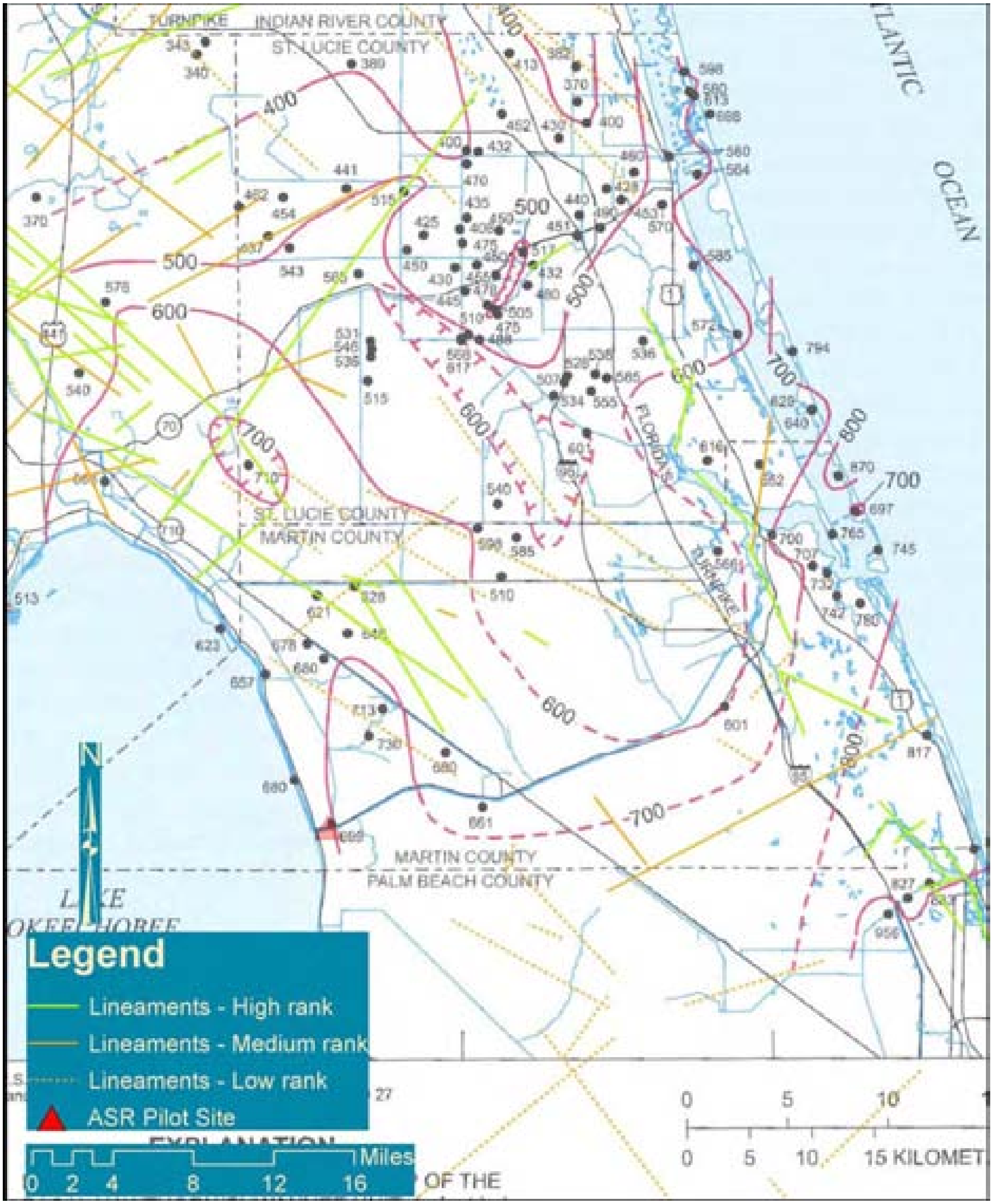


Figure 26. Surface lineaments superimposed on a map of the altitude of the top of the basal Hawthorn/Suwannee unit (modified from Reese, 2004). Contours are lines of equal altitude in feet below National Geodetic Vertical Datum of 1929.

Figure 27. Surface lineaments superimposed on a map of the altitude of the top of the Ocala Limestone (modified from Reese, 2004). Contours are lines of equal altitude in feet below National Geodetic Vertical Datum of 1929.

Figure 28. Surface lineaments superimposed on a map showing the distribution of chloride concentration in the Upper Floridan aquifer (modified from Reese, 2004). Contours are lines of equal concentration in milligrams per liter.

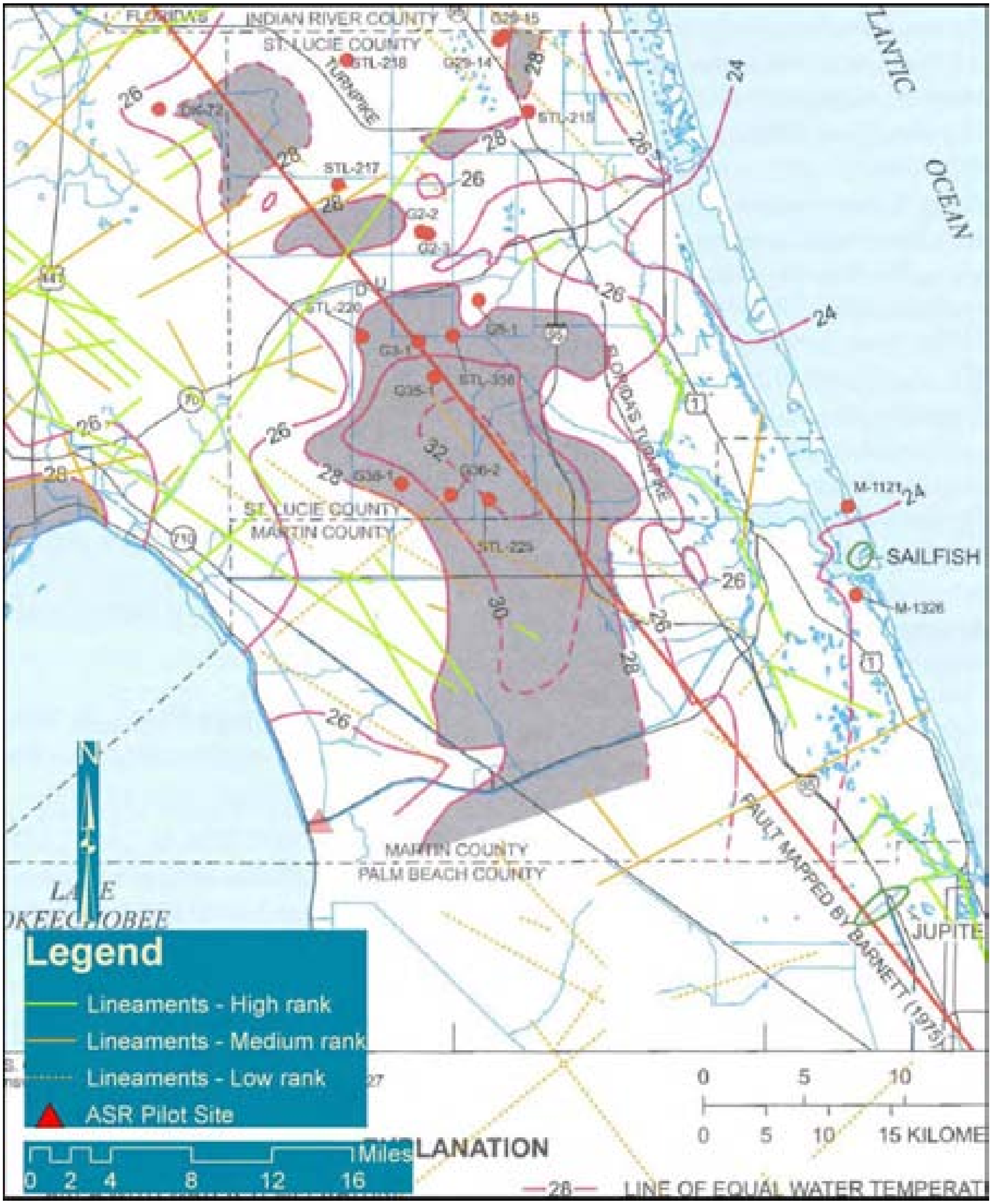


Figure 29. Surface lineaments superimposed on a map showing the location of monitoring wells and well fields with increasing salinity over time and distribution of temperature in the Upper Floridan aquifer (modified after Reese, 2004). Contours are lines of equal water temperature in degrees Celcius. Shaded areas have water temperature greater than 28 debrees celcius. Green circled areas are well field locations.

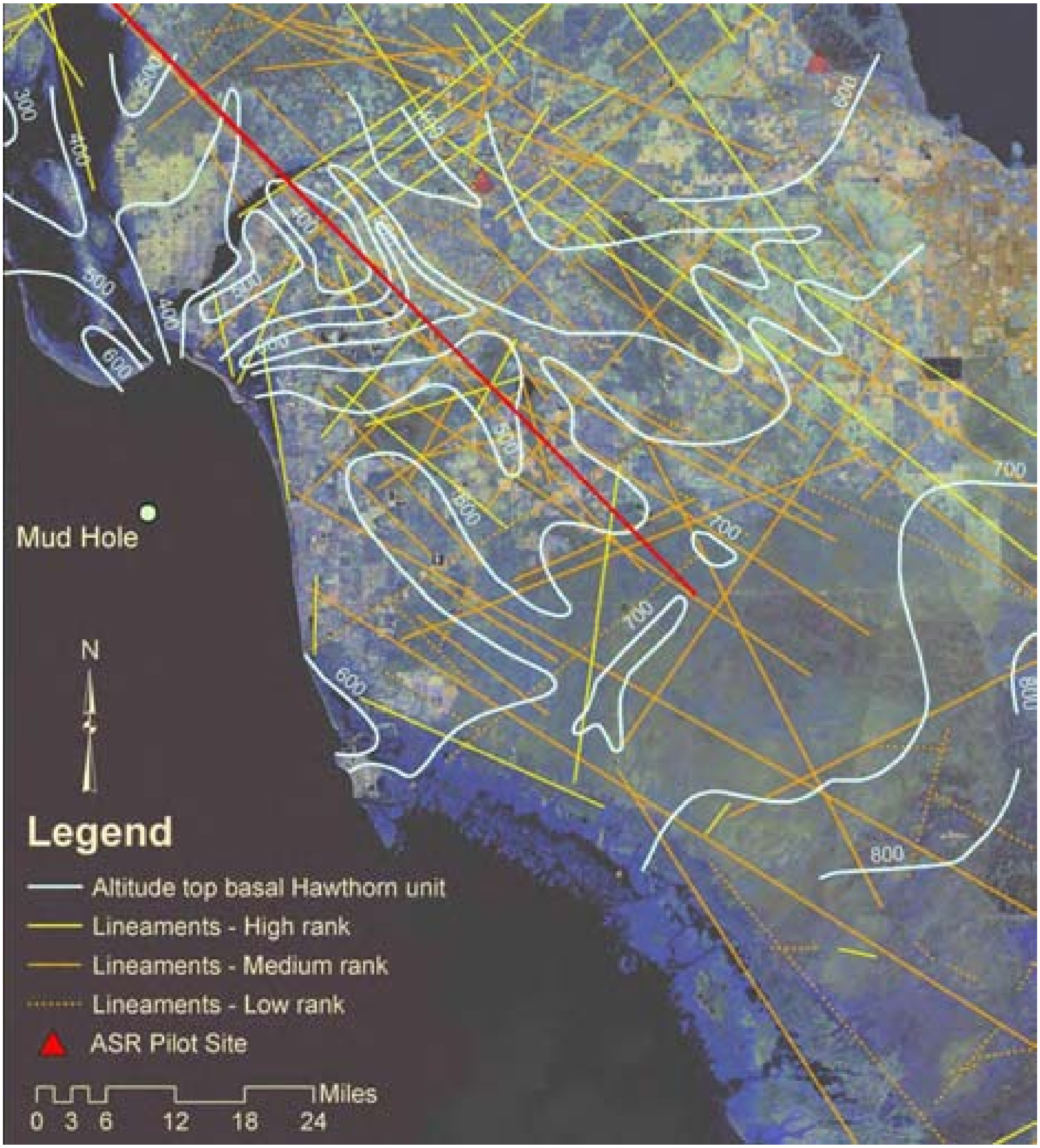


Figure 30. Altitude map of top of basal Hawthorn Unit (Reese, 2000). Inferred North Point Fault is shown in red.

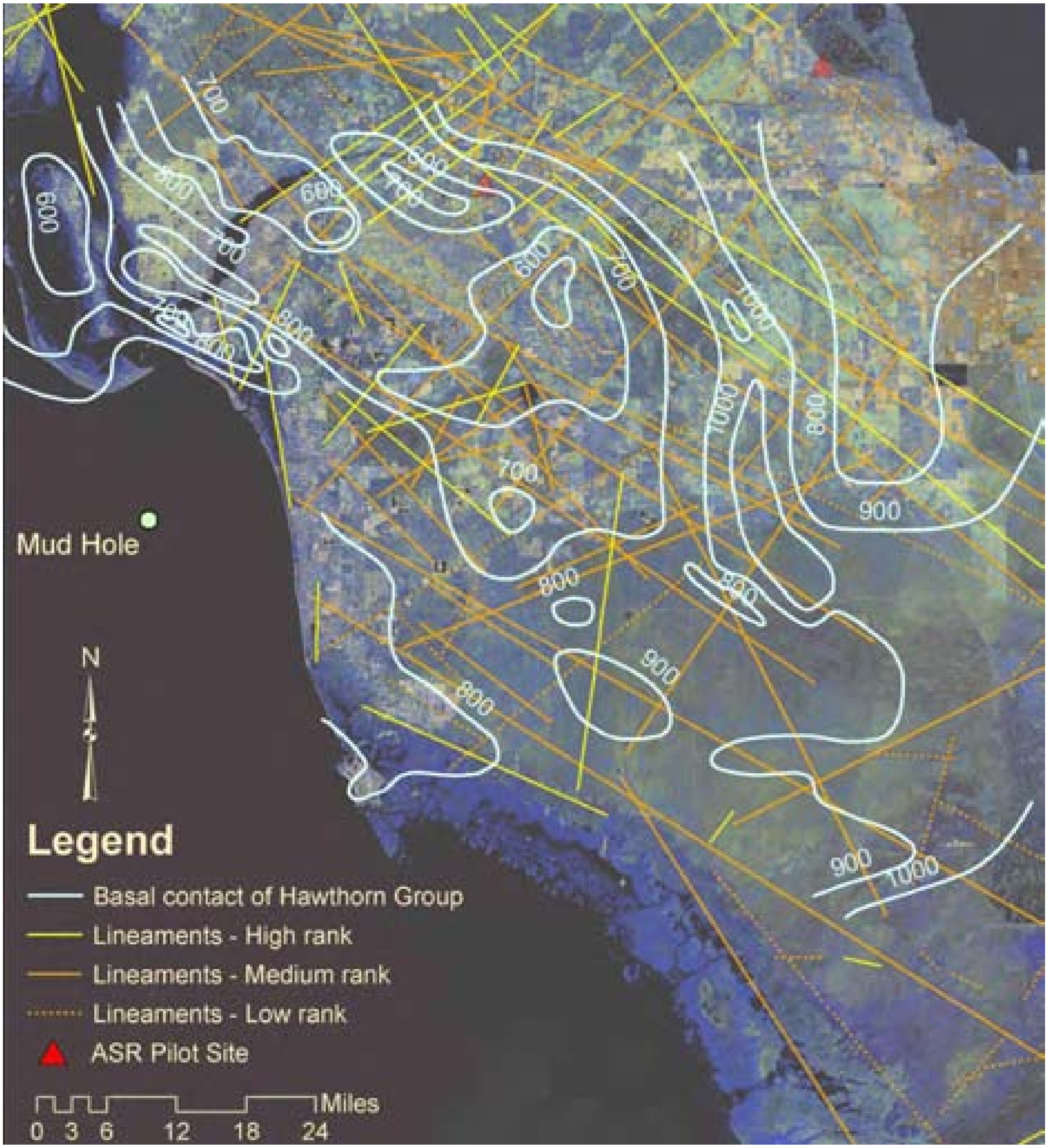


Figure 31. Altitude map of the basal contact of Hawthorn Group (Reese, 2000).

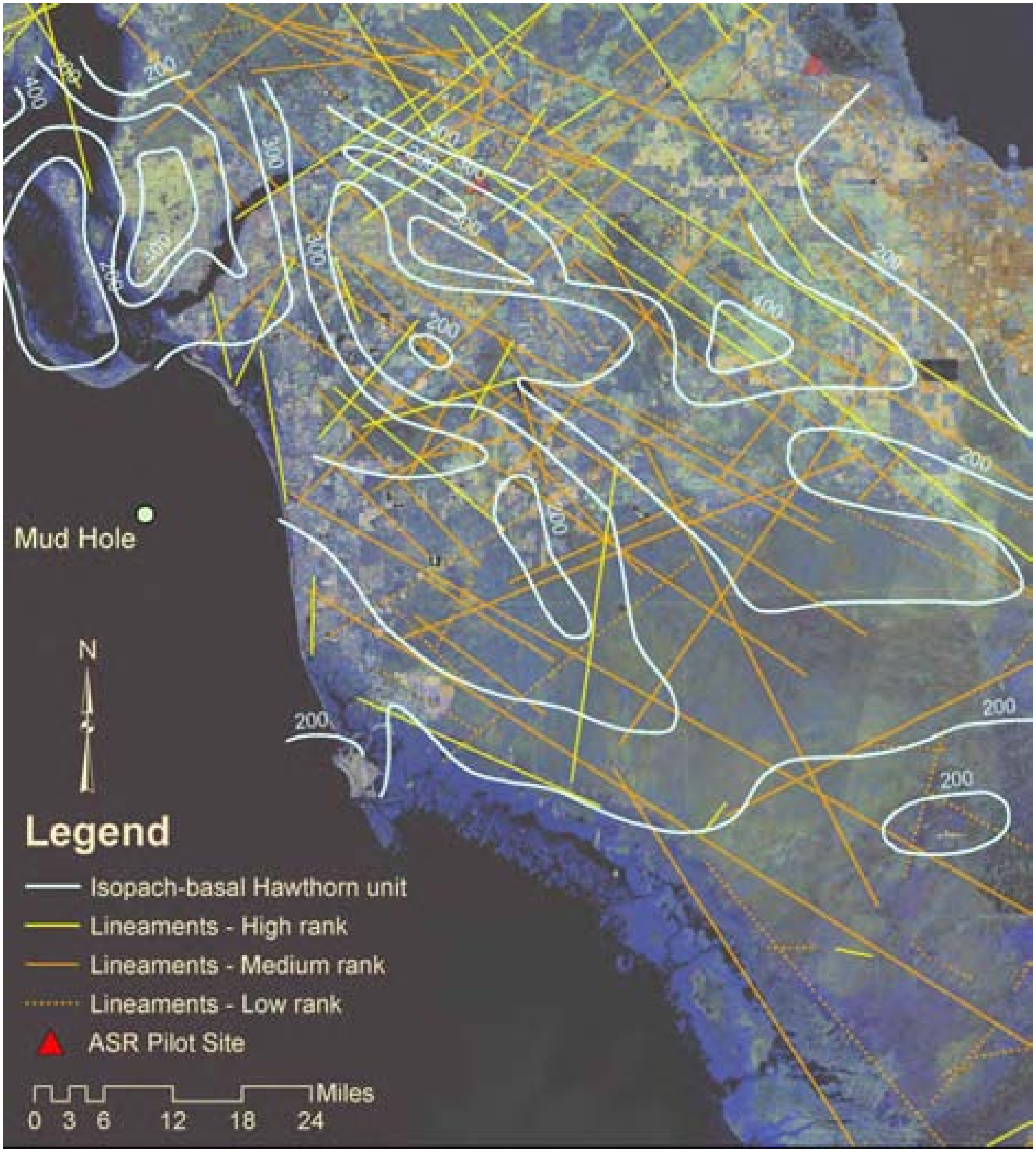


Figure 32. Isopach map of the basal Hawthorn unit (Reese, 2000).

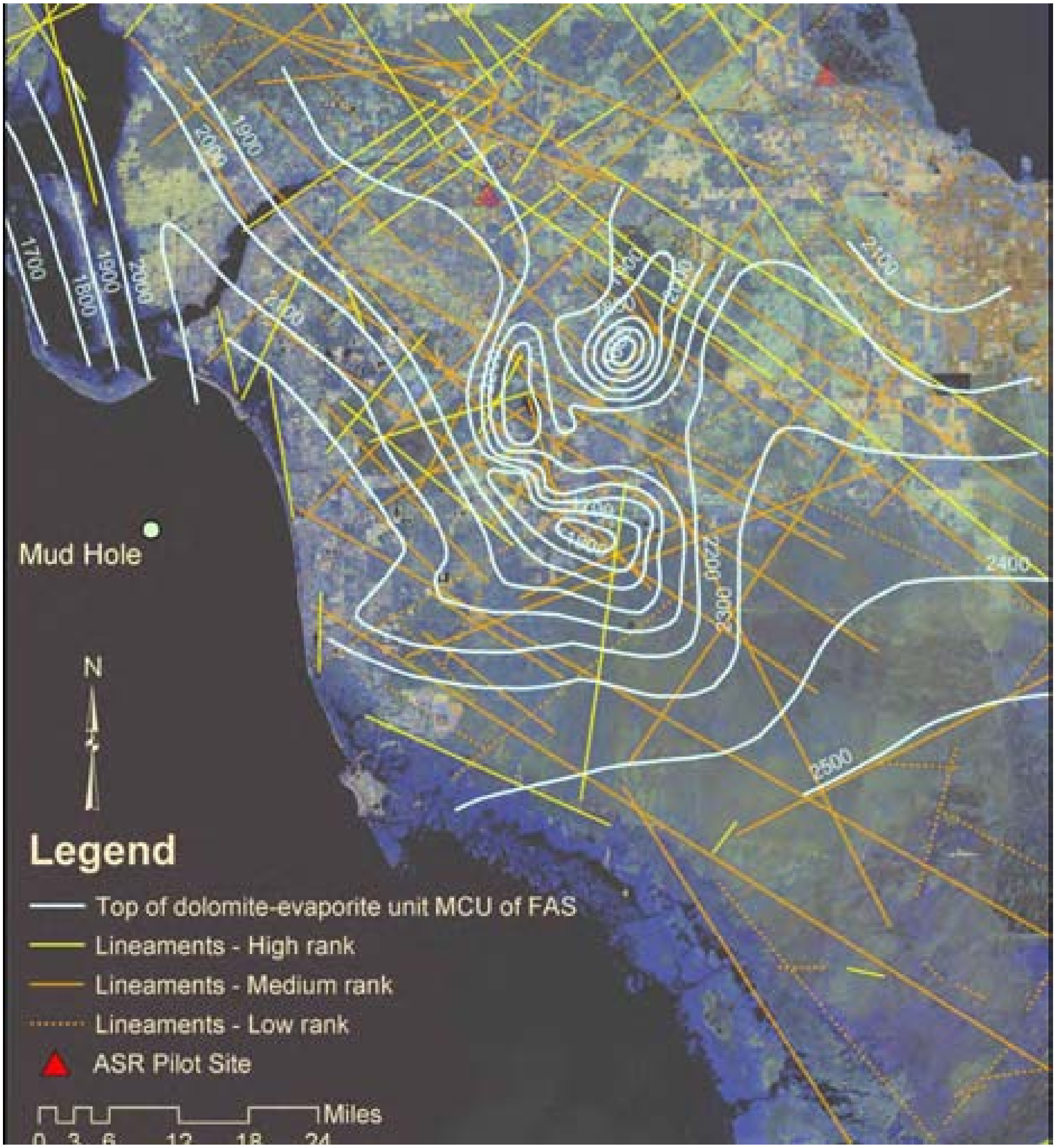


Figure 33. Altitude map of the top of the dolomite-evaporite unit in the FAS middle confining unit (Reese, 2000).

Another example of a possible connection between surface lineaments and subsurface features can be seen in the upper portion of the Hawthorn Group and overlying SAS in south central Florida. A lineament has been identified near the location of an inferred fault mapped along the Tamiami Trail (Figure 34) (Reese and Cunningham, 2000). The cross section shows an abrupt offset in the stratigraphy, that may have some effect on the groundwater flow system, at least locally. Based on the length of the surface lineament at this location, this fault probably extends well into the Hawthorn Group and possibly through the FAS. This fault lies close to and roughly parallel with the North Port fault (Winston, 1996).

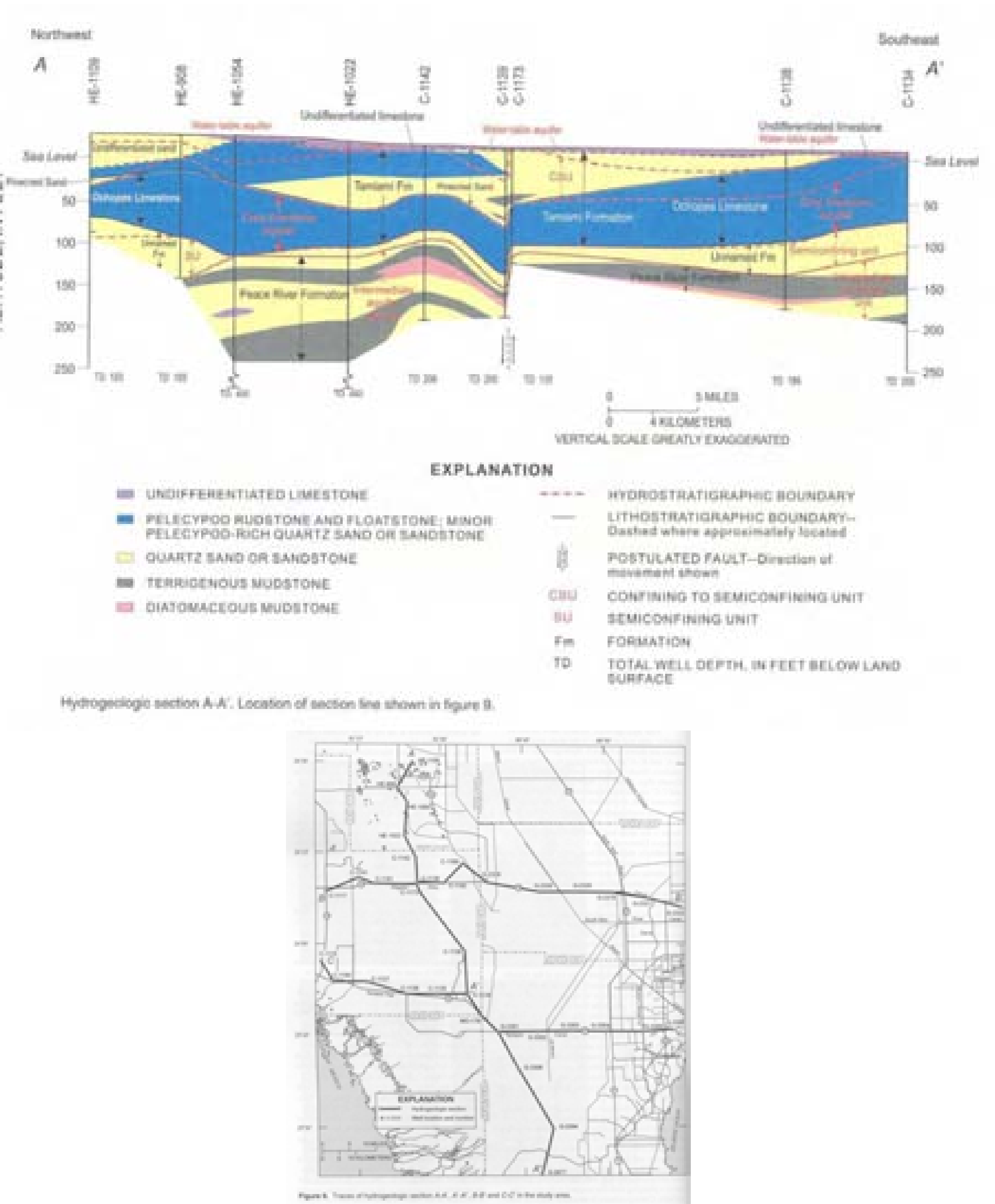
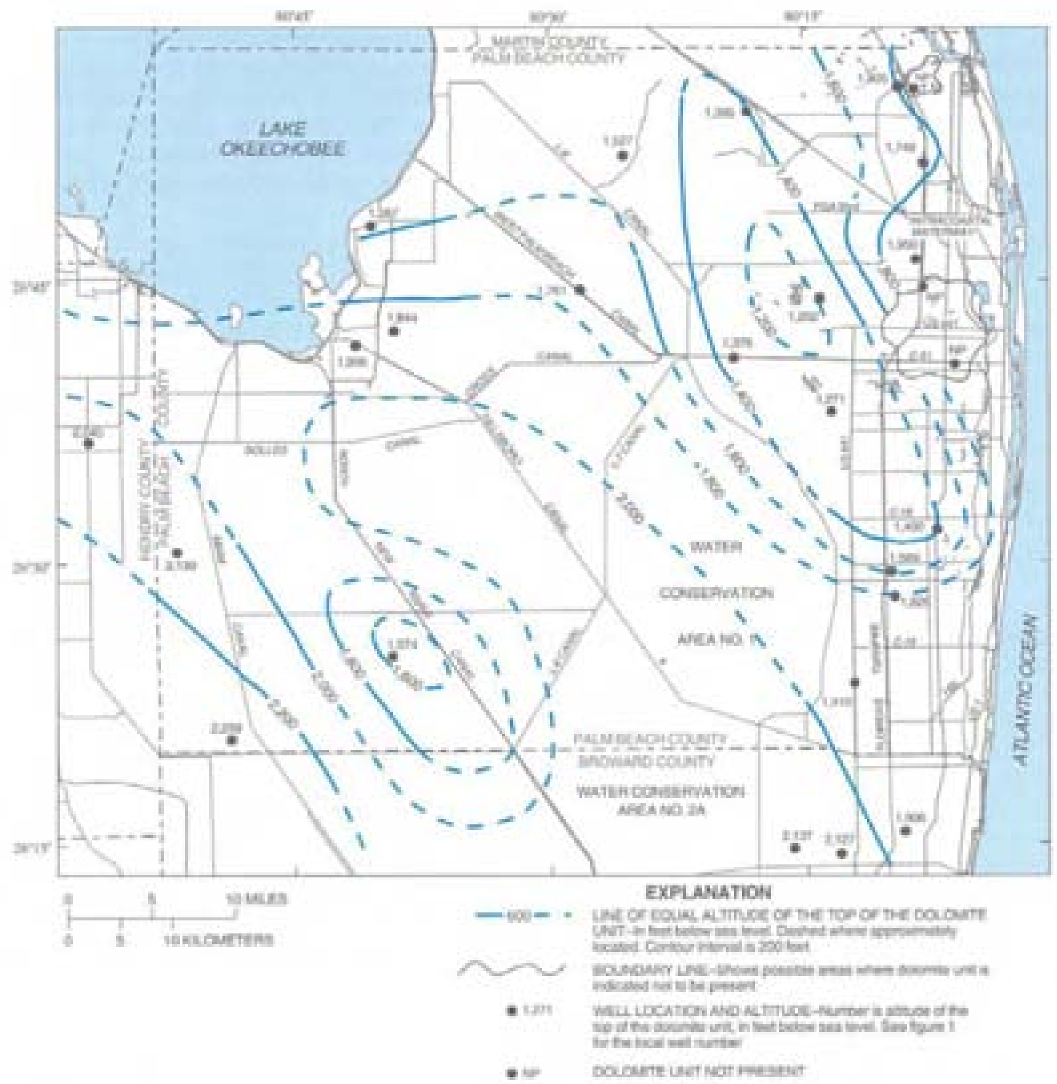


Figure 34. Hydrogeologic cross section showing inferred fault and location map (Reese and Cunningham, 2000).

Southeast Study Area

An example of a potential relationship between surface lineaments and subsurface geology is the southeastern portion of the study area (Palm Beach and northern Broward Counties) (Figure 35, Reese and Memberg, 2000), is shown by a structure contour map of the top of the Eocene group dolomite unit in the FAS. This map shows troughs that generally aligning with mapped lineaments. The contours are based on sparse lithologic log data; however, they appear to coincide with both the mapped lineaments (Figure 17) and generally trend along the BFZ structural feature (Figures 8, 9, 10). The hydrogeology of there FAS could be impacted and exhibit preferential flow (ie., higher transmissivities) in the northwest direction. This would further complicate the hydrogeology of the FAS.



Altitude of the top of the Eocene group dolomite unit in the Floridan aquifer system in Palm Beach and northern Broward Counties.

Figure 35. Altitude map of the top of the Eocene group dolomite unit (Reese and Memberg, 2000).

Summary and Conclusions

The purpose of this investigation was to identify surface lineaments in south Florida, show possible relationships between the lineaments and known geologic structure, and to help define structural features that may impact hydraulic parameters of the FAS and confining units.

A total of 548 lineaments have been mapped in the study area. Of these, 63 are equal to or greater than 25 miles in length. Many lineaments observed on DOQQ photo mosaics at each of the ASR pilot project sites were along the lineaments identified on the Landsat images, thus adding confidence to the presence of the lineament. Further confidence is gained by the repeatability of lineaments identified by other authors.

The examples cited in this report illustrate that regional geologic structure and hydrogeologic character often parallel surface lineament trends. While a considerable number of the mapped lineaments may be dismissed after further investigation, the data suggest that many lineaments are indicative of geologic structures, typically fractures (or faults in some cases) extending from basement structures up into the overlying rock, and are reflected on the ground surface.

One of the most noteworthy findings of this investigation is the concentration of northeast trending lineaments along the northern Caloosahatchee River corridor and the northwest side of Lake Okeechobee. These lineaments seem to correlate to a possible basement hinge zone at depth and, hydrogeologically, to a significant increase in chloride concentrations in the upper part of the FAS. A recently completed test well at the Kissimmee River ASR pilot site at the mouth of the Kissimmee River also shows highly fractured sections in the upper FAS that are not as highly fractured in other FAS wells outside of this area.

Other noteworthy findings are: 1) Lineaments coinciding with a mapped fault and in areas of higher chloride concentrations and higher Upper Floridan aquifer groundwater temperatures in the northeast study area; and 2) The northwest-trending lineaments in the southwest portion of the study area, which appear to correlate with reports of upward leakage through semi-confining and confining units, and inferred faulting and structure in the FAS, Hawthorn Group, and SAS.

Further investigation, is necessary to verify the presence of the lineaments identified during this study, and their relationship to geologic and hydrogeologic features. Investigative results will likely show many of these lineaments do not have any relationship to the subsurface conditions. Others will be shown to be the surface manifestation of fractures and/or faults extending far up into the sedimentary section, or to have an effect on the local and regional hydrogeology. Some of the types of investigation that could be initiated are:

- High-resolution seismic reflection geophysical surveys. Two-dimensional surveys across the study area will provide valuable data to further evaluate the possible existence of fracture zones and other structural features. Specific areas of interest can be further defined with 3-dimensional seismic surveys.

- Hydrogeologic investigations. Investigations such as aquifer performance and leakance tests with multiple monitoring zones in the aquifers and confining units will help to validate potential impacts of fractures on the hydrogeologic system. Tracer tests or tomography could also be employed at specific locations to evaluate the presence of fractures and groundwater movement.

- Detailed geologic structural and stratigraphic analyses. Detailed geologic analyses incorporating available geophysical, hydrogeologic, and geochemical data will provide further analyses of variances in hydraulic characteristics and water quality of the FAS.

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