SUSCEPTIBILITY OF THE UPPER FLORIDAN AQUIFER IN CAMDEN COUNTY TO SALT WATER INTRUSION

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GEORGIA GEOLOGIC SURVEY

Contract No. 701- 990099

Atlanta

2001

PROJECT REPORT 46

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EXECUTIVE SUMMARY

Susceptibility of the Upper Floridan Aquifer in Camden County to Salt Water Intrusion

The upper Floridan aquifer underlying Camden County, Georgia ***is*** susceptible to salt water contamination although no such contamination is presently known to exist. Recent TDEM survey data and deep well data from Camden, Glynn (GA), Nassau (FLA), and Duval (FLA) Counties indicate that brackish or more saline water (i.e. chloride concentrations > 5,000 mg/L) exists at the either the base of the Floridan aquifer (Fernandina permeable zone) or below the base of the aquifer. The hydrogeology of the Floridan aquifer below Camden County is quite similar to Glynn County where a chloride plume has been created and has persisted for the past five decades. The major difference between the two counties is that there has been less ground-water pumping in Camden County and there has not been as much pumping from such a limited areal extent as has occurred on the Brunswick Peninsular in Glynn County.

The most likely *potential* mechanism for salt water intrusion within the upper Floridan aquifer of Camden County is the *vertical upconing* of salt water from the lower Floridan aquifer or from some deeper saline source. The most vulnerable location is within the St. Marys-Kingsland region, particularly that area also affected by ground water withdrawal for a paper processing company. Vertical upconing is the same mechanism that has been posed by the United States Geological Survey for the chloride plume that has contaminated the upper Floridan aquifer in Brunswick, Georgia. The vertical upconing mechanism is a widely accepted "working hypothesis" and requires both:

-pressure reductions within the upper Florida aquifer (i.e. reduction of the potentiometric surface to levels that are lower than the lower Floridan aquifer) and

-vertical pathways of enhanced permeability such as faults, fractures, or paleosolution features for salt or brackish water migration

Although the potentiometric surface of the upper Floridan aquifer in Camden County has been reduced 20-30 feet from estimated "pre-development" levels, these reductions are minor compared with the >60 foot reduction at Brunswick, Georgia. Subsurface faults or other potential pathways for vertical upconing have not presently been identified in Camden County, although they may exist. The key factor in forestalling salt water intrusion in Camden County is to maintain the potentiometric surface of the upper Floridan aquifer at or near present levels, particularly within the St. Marys-Kingsland area. If additional ground water is required from the upper Floridan aquifer for population and industrial growth then ground-water pumping should be spread out over an area that is as large as possible to avoid excessive potentiometric surface declines.

A ground-water monitoring scheme is proposed for the St. Marys-Kingsland area which will serve as an "early warning system" for the upward migration of salt water into the upper Floridan aquifer system. This system should be capable of recording water levels and chloride concentrations in both the upper and lower Floridan aquifers on a continuous basis. The St. Marys-Kingsland area is the primary location in Camden County where future monitoring efforts should be taken in that this is the major population center and is also located relatively close to the pumping center associated with paper production.

<u>Background:</u>

The opinions rendered in this summary report result from a hydrogeological investigation undertaken of the four-county region comprising Glynn and Camden Counties in southeastern Georgia and Nassau and Duval Counties in northeastern Florida. This investigation was undertaken at the request of the Georgia Geologic Survey, Environmental Protection Division (GGS, EPD) as *Contract Number 701-990099*. Task #6 of this contract specified that this investigator render his opinion regarding the potential for salt water intrusion in Camden County. The analyses and opinions stated herein, although based upon data acquired from governmental sources, are those of the author and do not necessarily represent those of the Georgia Geologic Survey or any other governmental agency.

The basis for this investigation of the potential for salt water intrusion in the four-county region, including Camden County, has consisted of the following activities that were specified in the aforementioned contract:

1) review of the existing literature (see accompanying citations)

2) review and synthesis of potentiometric surface data for the Floridan aquifer maps dating from the pre-development surface (as modeled by the United States Geological Survey) to the present

3) synthesis of existing well logs, geophysical logs and other hydrogeological data

4) review of chloride concentrations and other geochemical data for the upper and lower Floridan aquifers from the 1960's to the present

5) review and synthesis of time domain electromagnetic (TDEM) survey data recently acquired as part of ongoing projects by the Georgia Geologic Survey

6) taking part in conversations regarding many aspects of the salt water intrusion problem with the following key personnel from the United States Geological Survey (USGS) and various state agencies, particularly the St. Johns River Water Management District (SJRWMD) in Palatka, Florida:

Rick Krause (retired, USGS Georgia)
John Clarke (USGS Georgia)
Mike Peck (USGS Georgia)
Fred Falls (USGS South Carolina)
Rick Spechler (USGS Florida, Altemonte Springs)
Bill Osborn (SJRWMD, Palatka)
Doug Durden (SJRWMD, Palatka)
Jeffrey Davis (SJRWMD, Palatka)
Don Boliol (SJRWMD, Palatka)
Paulette Bond (Florida Geologic Survey, Tallahassee)
William McLemore (Georgia GGS/EPD, Atlanta)
Bill Frechette (Georgia EPD, Atlanta)

Part 1: Susceptibility of Camden County to Salt Water Intrusion

The Floridan aquifer system within and underlying Camden County, Georgia *is* susceptible to the intrusion of salt water. This assessment of susceptibility is based upon the five observations, which are explained below. It must be emphasized that Camden County has not *yet* experienced a salt water intrusion problem as has the Brunswick area in northern neighboring Glynn County. The observation that Camden County is susceptible to salt water intrusion does not necessarily imply that salt water intrusion of any type will occur in the future. Proper water management techniques can successfully forestall or prevent salt water intrusion from occurring within this county as will be discussed in Part 4 of this report.

Observation 1: Source of Brackish Water

Brackish water (chloride concentrations between 4,000 - 5,000 mg/L) has either been directly encountered in deep wells or has been inferred from TDEM surveys within Camden County (Fig.1). It is fairly certain that brackish to salt water underlies most, if not all, of Camden County at or near the base of the Floridan aquifer system. This saline water is either present within the lowermost unit of the Floridan aquifer system or below the base of the aquifer. Therefore, a potential source of salt water exists and caution must be taken to prevent the upconing of this salt water to the upper Floridan aquifer in Camden County.

Elaboration: The most fundamental reason why Camden County is susceptible to salt water intrusion is that brackish water is stored within the base of the Floridan aquifer system (often termed the "Fernandina permeable zone") and below the base of the aquifer in this region. Chloride concentrations between 500-1,000 mg/L have been reported within the lower Floridan aquifer within the "Fernandina Beach (Florida) cone of depression" (Bentley and Fairchild, 1977). Recent TDEM survey data suggests that brackish water with chloride concentrations of 5,000 mg/L and greater is stored at a depth of ~2,500 feet in both eastern and western Camden County (as shown on *Hydrogeologic Cross Sections F-F'* and *G-G'*, Figs. 2,3, and 5). It is most probable that similar depths to the 5,000 mg/L isochlor will be encountered throughout Camden County, given sufficient survey coverage.

Several deep wells completed to the base of the lower Floridan aquifer (i.e. through the Fernandina permeable zone) in Duval County, Florida have produced ground water with chloride concentrations greater than 5,000 mg/L (Brown et al., 1984; Brown et al., 1985, and Spechler et al., 1994). A recently drilled well by the USGS in Brunswick, Georgia (Well 34H195) encountered ground water with a chloride concentration of 27,000 mg/L at ~2,500 feet below land surface (Falls, written communication). It is most likely that such brines are also present at depths of ~2,500 - 3,000 feet in Camden County, at the base or below the base of the Floridan aquifer system.

The presence of salt water at the base of the aquifer by no means guarantees the eventual contamination of the upper Floridan aquifer. Likely, these brines have existed within these rocks for geological periods of time. As long as hydraulic head values (i.e. water levels based upon densitycorrected water pressures) are higher in the *upper* Floridan aquifer than in the *lower* Floridan aquifer the salt water should continue to reside near the base of the aquifer within or below the Fernandina permeable zone as it has in the past. The decline of the potentiometric surface of the upper Floridan aquifer caused by the exploitation of ground water resources is the condition that can trigger the upward movement of salt water from the lower Floridan aquifer.

It must also be emphasized that relatively impermeable dolomites (and dolimitized limestones) generally corresponding to the middle Eocene-aged Avon Park Formation often separate the lower Floridan aquifer from the upper Floridan aquifer in this region. This unit, the "middle semi-confining unit" of the Floridan aquifer (Miller, 1986), should not however be considered as a totally impermeable lithological barrier in that in some locations it may be thin or absent, grade into limestone units of higher permeability, or be breached by "features of structural weakness" such as fractures, faults, or ancient solution features. This "conduit problem" will be further discussed in Part 2 of this report.

<u>Observation 2:</u> Similarity of hydrogeological conditions to Glynn County

The hydrogeological conditions underlying Camden County are very similar to those underlying Glynn County, which has experienced a notable salt water intrusion problem within the upper Floridan aquifer during the past five decades. The characteristic "t"-shaped chloride plume for the Brunswick area shown on Fig. 5 (from Peck et al., 1992) has been relatively stable for approximately 40 years with chloride concentrations exceeding 2,000 mg/L in the center of this plume.

Elaboration: The Floridan aquifer system underlying Camden County is very similar to that of Glynn County, its northern neighboring county (Miller, 1986). Both Georgia counties, as is the case for the two neighboring coastal counties in northeastern Florida, are part of the extensive Tertiary Coastal Plain sedimentary depositional system. The hydrostratigraphic column shown in Fig. 6 (from Clarke and Krause, 2000) generally applies to all four counties. The various lithological units are of slightly variable thickness and are found at somewhat different depth throughout the four-county region; however, the Floridan aquifer exists in much the same state in Camden County as it does in Glynn County (see the isopach and structural contour maps shown as Figs 7, 8, and 9). The similar hydrogeological conditions underlying Camden County and Glynn County suggest that we recognize the susceptibility of Camden County to salt water contamination as a possibility.

<u>Observation 3:</u> Duval County chloride problems

Chloride concentrations within the upper Floridan aquifer underlying Duval County, Florida have progressively increased during the past two decades (although chloride concentrations generally remain less than 10 percent of those observed in the Brunswick chloride plume). The hydrogeological conditions underlying Camden County are quite similar to those of Duval County, therefore there is cause for concern.

Elaboration: Chloride concentrations in numerous upper Floridan aquifer wells completed within the Jacksonville region in Duval County, Florida have increased by 100 percent or more since the 1980's (see Figs 10 and 11). Although the chloride concentration in these wells are typically below the drinking water standard maximum concentration level of 250 mg/L, they are above *background* levels. The exact cause of this problem is not completely understood; however, the increased chloride concentrations are likely the result of the diffusive movement of salt from the lower Floridan aquifer as a result of decades of ground-water withdrawal from the upper Floridan aquifer and accompanying pressure reduction (Spechler, personal conversation, 2000).

Observation 4: The Fernandina Beach cone of depression

The extreme southeastern portion of Camden County is marginally affected by the cone of depression from the Fernandina Beach pumping center in Nassau County, Florida. However, this cone of depression does not have appreciable effect upon most of Camden County.

Elaboration: Fernandina Beach in northeastern Nassau County, Florida is a major consumer of ground water within the four-county region. Ground water withdrawal from the upper Floridan aquifer has resulted in a potentiometric surface decline of ~90 feet below sea level (Fig. 12). This cone of depression extends many miles from Fernandina Beach and impacts the extreme southeastern portion of Camden County. However, the cone of depression does not extend to the St. Marys region and therefore will not likely result in the lateral or vertical migration of salt water into the upper Floridan aquifer in most of Camden County.

Observation 5: Population growth in Camden County

The population of Camden County is growing and ground-water utilization has been increasing, thereby posing the possibility of a declining potentiometric surface and increased susceptibility to salt water upconing in the upper Floridan aquifer.

Elaboration: The 2000 census concluded that 43,664 people reside in Camden County which represents a population increase of 44 percent since the past census for 1990. In comparison, the same census figures indicate that 67,558 people reside in Glynn County (*Atlanta Journal Constitution*, March 23, 2001). The Cities of Kingsland and St. Marys grew at rates of 124 percent and 68 percent respectively in the period between 1990 and 2000 (census figures from *Atlanta Journal Constitution*, May 20, 20001). These represent the first and third highest growth rates for all cities in Georgia during the past 10 years between census counts.

As of 1997, Camden County withdrew 40.12 million gallons of ground water per day (Mgal/d) which comprises 84 percent of their total water use. The cities of St. Marys and Kingsland combine for a total withdrawal of 2.46 Mgal/d. The paper manufacturing industry is the major user of ground water in Camden County, accounting for 77 percnet of the ground-water use (Fanning, 1999). The withdrawal of ground water by the paper industry in southeastern Camden County has resulted in a steep but areally limited cone of depression of the potentiometric surface of the upper

Floridan aquifer (Fig.12). Water levels have declined to approximately 95 feet below land surface in the vicinity of a paper company (Fig. 13). However, this cone of depression has not, as of yet, resulted in elevated chloride concentrations within the upper Floridan aquifer. One factor abetting salt water intrusion here is the relatively restricted areal extent of this cone of depression.

Most all of the ground water from Camden County comes from industrial wells (used for paper production) in the extreme southeastern portion of the county, southeast of the City of St. Marys (Fanning, 1999). The most likely location for population growth in Camden County will be the corridor between the St. Marys and Kingsland, approximately 5-10 miles west of the current pumping center. Therefore, the effects of population growth must be monitored in the future as to determine how the effects of increased ground-water withdrawal will affect water levels in the Floridan aquifer.

Camden County's ground water use is best contrasted to Glynn County, its northern neighbor and site of the most significant salt water intrusion problem in Georgia. The City of Brunswick, the major municipality in Glynn County, withdrew 5.24 Mgal/d ground water as of 1997 (Fanning, 1999); approximately twice that of St. Marys and Kingsland in Camden County. Glynn County as a whole withdrew a total 65.33 Mgal/d of ground water in 1997, most of which is used by the paper industry (Fanning, 1999). The Brunswick Peninsular is the site of most of the paper and chemical plants in Glynn County which withdrew an additional 44.12 Mgal/d in 1997 (Fanning, 1999). These data indicate that far more ground water has been withdrawn from the upper Floridan aquifer below Brunswick than within Camden County. This high withdrawal rate from a limited area (e.g. ~5 square miles) with accompanying declines in the potentiometric surface is the most important factor contributing to the salt water intrusion problem in Glynn County and serves as a model for what Camden County should strive to avoid as its population grows.

Part 2: Mechanism and Location

The most logical mechanism of *possible* salt water intrusion into the upper Floridan aquifer below Camden County is *vertical upconing*. The most logical **location** for upconing to occur will be within the southeastern portion of the county in the **St. Marys-Kingsland region** where the greatest volume of ground water is extracted from the upper Floridan aquifer. Currently, to my knowledge, there does not exist a chloride contamination problem in Camden County. It is very possible that these conditions will prevail and that no salt water intrusion will occur within the county. It must also be emphasized that the vertical upconing of salt water can be mitigated through proper monitoring and water resource planning.

Spechler (1994) identified possible mechanisms for the intrusion of salt water into the upper Floridan aquifer in northeastern Florida. This is believed to be a comprehensive set and should also be given consideration for southeastern Georgia and Camden County in particular. Several of these mechanisms have been combined in this report and are listed below with a brief comment regarding the susceptibility of Camden County to each.

Mechanism 1: Relict seawater in the upper Floridan aquifer

In this scenario sea water intruded the upper Floridan aquifer during previous stands of high sea level (i.e. during interglacial portions of the Pleistocene epoch). Most of this sea water has by now been flushed by active freshwater recharge as the previously submerged coast line emerged during the last glacial period. The "pockets of salt water" that remained, presumably in zones of low-permeability within the aquifer, have become dispersed as the result of ground-water pumping during the past century. There is currently no direct evidence that such unflushed relict seawater exists within Camden County or elsewhere in the four-county study area and therefore this possible mechanism for spreading salt water within the upper Floridan aquifer is *not* considered likely.

Mechanism 2: Lateral encroachment of modern sea water

In this scenario modern sea water can intrude the upper Floridan aquifer laterally from the coast as a result of declining fresh water head. In that Camden County is a coastal county, where ground water pumping has occurred for many decades, this hypothesis should not be summarily dismissed. However, lateral intrusion of salt water is not presently occurring within the four-county study area and will not likely occur within Camden County in the future. Spechler (1994) reported that numerous monitoring wells have been installed in coastal counties of northeastern Florida and data from these wells do not indicate lateral sea water encroachment within the upper Floridan aquifer.

Furthermore, the salt water interface inferred from core data for several JOIDES and Tenneco oil exploration wells is thousands of feet below the upper Floridan aquifer, many miles offshore as shown in Fig. 14 (Brown, 1984). The JOIDES-2 test well is located near the edge of the continental shelf, approximately 65 miles east of Fernandina Beach and fresh water was apparently present within cores representative of the upper Floridan aquifer (Fig. 14). Likewise, cores from the Tenneco exploration well indicate that the base of freshwater is ~1,100 feet below sea level 55 miles off shore (Johnston, 1983). In short, the salt water-fresh water interface would have to migrate many miles from its present seaward position before the lateral encroachment of sea water would be possible within the upper Floridan aquifer in the Camden County region. This is not considered a likely possibility in that it would require a major rise of sea level.

Mechanism 3: Upward leakage through unplugged wells

In this scenario unplugged wells provide conduits for the vertical migration of salt water if a source of salt water exists at depth. Ground water then spreads outwardly (through diffusion and dispersion) from the area of the unplugged well bore, contaminating a portion of the aquifer. This scenario would require an upward vertical gradient between the lower and upper units of the Floridan aquifer. The movement of salt water up a well bore has believed to have occurred in the Fernandina Beach area where chloride concentrations decreased from 1,600 to 50 mg/L after a lower Floridan aquifer well was plugged from a depth of 1,826 to 1,100 feet (Spechler, 1994 and Brown, 1984). This implies a chloride source at depth within the lower Floridan aquifer and that the pathway of migration was the unplugged well bore. As previously discussed, the potentiometric surface of the upper Floridan aquifer below Fernandina Beach is characterized by a large and steep cone of depression; thus conditions are optimum at this location for the upward movement of salt water through unplugged well casings.

It is not known whether any production wells presently tap moderately saline portions of the lower Floridan aquifer in Camden County. However, it is not likely that many, if any, of these wells exist and therefore this is not a very likely mechanism of salt water intrusion within Camden County. However, prudent water management principles dictate that water wells should be plugged (filled with cement) after they are no longer used in order to prevent them from becoming possible conduits for salt water contamination.

<u>Mechanism 4:</u> Upward leakage through faults, fractures, or solution cavities

The upward migration of salt or brackish water is considered to be *the most likely possible mechanism* for salt water contamination of the Floridan aquifer system to occur within Camden County. In this scenario, natural features such as faults, fractures or vertical solution cavities provide a pathway for the upward migration of salt water from the lower Floridan aquifer (most likely from the Fernandina permeable zone) to the upper Floridan aquifer. The migration can only occur if the hydraulic head in the upper Floridan aquifer is lower than hydraulic heads in the lower Floridan aquifer (after correction for salinity differences to "equivalent fresh water heads"). There also must exist a pathway for vertical salt water transport. This is the model shown on Fig. 15 (from Spechler, 1994) which has been developed by the United States Geological Survey to explain the long-acknowledged salt water intrusion problem within the upper Floridan aquifer below Brunswick, Georgia. No serious objection has been given to this model and it is presently well-accepted as "the working hypothesis" by hydrogeologists within the southeastern United States.

There is substantial evidence to indicate that the lower Floridan aquifer, particularly the Fernandina permeable zone, contains salt water. The base of the aquifer is approximately 2,400-2,700 feet below sea level in Camden County (see the structural contour map shown as Fig. 16). Relatively impermeable dolomite and dolomitized limestone beds within the Floridan aquifer [i.e. the lower and middle semi-confining units (Fig. 17 from Spechler, 1994)] are thought to provide a reasonably effective barrier for the vertical upconing of salt water to the upper Floridan aquifer. Higher hydraulic head in the upper Floridan than the lower Floridan aquifer would also provide a hydraulic barrier to upconing. However, the previously discussed chloride plume within the upper Floridan aquifer below Brunswick, Georgia suggests that pathways for the vertical migration of brackish water do exist within the Floridan aquifer in southeastern Georgia.

Numerous pathways have been proposed which potentially breach the middle semi-confining unit separating the upper and lower units of the Floridan aquifer. Two buried high-angle normal faults have been hypothesized from well data from central Duval County in Florida. These faults have been proposed as conduits for the movement of brackish water from a depth ~1,800 feet to the upper Floridan aquifer (Leve, 1983). Four major northeast-southwest trending faults have been hypothesized from structural analysis of geophysical data to occur within the Brunswick area in Glynn County, Georgia (Maslia and Prowell, 1990). These proposed faults along with an accompanying increase in fracturing may provide the conduits for the upconing of salt water responsible for the chloride plume below Brunswick (Maslia and Prowell, 1990). Recent seismic and sonic televiewer studies in northeastern Florida have emphasized paleokarst features such as solution cavities (connected by fractures), buried solution pipes and/or paleosinkholes as conduits that breach the middle semi-confining unit within the Floridan aquifer system (Phelps and Spechler, 1997 and Odum et al., 1997).

There are no buried fault-type features currently identified within the Floridan aquifer system in Camden County. Paleosolution features may likely be inferred by land based high resolution seismic studies; however, there has been no systematic seismic coverage of Camden County to this date. It is my opinion that although such studies would undoubtedly be interesting and useful, it is reasonable to make the *a priori assumption* that paleokarst features do exist within the Camden County subsurface based upon the geological similarity with northeastern Florida.

The second prerequisite for the vertical upconing of salt water from the lower Floridan aquifer is reduced hydraulic head (pressure reduction) in the upper Floridan aquifer. Such pressure reduction is a direct result of excessive pumping within a geographically limited area. Significant withdrawal of ground water from the upper Floridan aquifer in Camden County is limited to paper production within the southeastern portion of the county. As previously mentioned, there also exists a very small area within southeastern coastal Camden County that is affected by the cone of depression associated with ground water withdrawal in the Fernandina Beach (Nassau Co., Fla.) region.

Due to the historically limited population growth in Camden County, ground water levels have declined less here than in the Brunswick region of Glynn County. Ground water levels in the upper Floridan aquifer throughout most of Camden County are 30-40 feet above mean sea level (see the potentiometric surface map for 1996 shown on Fig. 12). The estimated decline in the potentiometric surface from pre-development levels for the upper Floridan aquifer in Camden County, has been 30 feet or less (Fig. 18). This stands in contrast with Glynn County where the estimated decline in the potentiometric surface from pre-development levels has been between 40-60 feet. Currently there is insufficient data to evaluate potentiometric surface differences between the upper and lower Floridan aquifer in Camden County. However, the 30-foot estimated decline in the potentiometric surface is significant in that is about equivalent to that which is estimated for Duval County (Fig. 18) where numerous wells have experienced low levels of salt water contamination during the past several decades (refer to previous section for discussion). Caution must be taken to see that the potentiometric surface of the upper Floridan aquifer does not further decline in the future. Ground water extraction from the St. Marys - Kingsland region in the southeastern portion of the county is problematic and this area should be monitored most closely. The reduction or elimination of future water level declines is the most important factor in forestalling or preventing the upconing of salt water into the upper Floridan aquifer in Camden County.

Part 3: Description of Monitoring Program

Objectives:

The major objective of this proposed salt-water intrusion monitoring system for Camden County is to provide an accurate indication of the vertical upconing of salt water into both the upper zone of the lower Floridan aquifer and the lower portion of the upper Floridan aquifer. These monitoring wells should serve as an "early warning system" for the upward movement of chloride and other solutes within the Floridan aquifer system. The system should be placed within the St. Marys-Kingsland region most affected by ground-water utilization for both municipal use and paper production. The system should be designed to quantify changes in hydraulic head (water levels), temperature, salinity, and chloride concentrations on an in situ and continuous basis. One further design option that should be considered is the possibility of recovering water samples from both aquifers. The following design considerations are of a generalized nature and more rigorous specifications would be needed for actual design of the monitoring wells.

General Design Considerations:

1) Monitoring wells should be completed at two locations in the St. Marys-Kingsland area (Fig. 19). These wells can complement the recently completed "Ball Park" monitoring well in St. Marys. Appropriate methods should be used such that drilling or other fluids are not introduced into the aquifer. At each location one well should be completed approximately 100 feet below the top of the Floridan aquifer (approximate depth = 750 feet below land surface) and another well should be completed approximately 100 feet below the top of the lower Floridan aquifer or below the base of the middle semi-confining unit (approximate depth = 1550 feet below land surface).

2) The monitoring zone of both aquifers should be approximately 25 feet long and 6 inches in diameter, completed with an appropriate stainless steel well screen coupled to a steel well casing. The casing should be grouted up to the earth's surface with cement. The upper portion of the well penetrating the surficial and Miocene aquifers should be cased with steel pipe and grouted with cement. This typically requires three steel casings of 24", 18" and 12" diameter for the lower Floridan aquifer (in these wells the upper Floridan aquifer should also be cased) and two steel casings (18" and 12" diameter) for the upper Floridan aquifer (Osborne, written communication, 2001). The annulus above the sampling interval should be grouted with cement as to insure a discrete sampling zone.

3) The monitoring zone for both wells (upper Floridan and lower Floridan aquifers) should be equipped with an in situ chloride electrode sensing device and temperature sensor (usually standard with all other devices). An accompanying salinity or total dissolved solids (TDS) sensor is an optional probe that may also be placed (but not used in lieu of a chloride-specific electrode) within the monitoring zone of both wells. All sensors should be precalibrated before being placed downhole and then periodically recalibrated. If funds are available, the chloride and salinity data

should be recorded on a continuous basis and then either relayed remotely to a personal computer terminal or recorded on site such that the data are readily retrievable from the well location. A less expensive alternative to continuous monitoring would be to monitor the aquifer on a biannual basis for chloride, salinity and TDS concentrations.

4) A pressure transducer should be placed in each well such that it is capable of resolving water level changes of ~0.1 foot. Such resolution is necessary to insure that potentially small hydraulic head differences between the lower and upper Floridan aquifer can be differentiated. The transducers should be precalibrated before being placed downhole and then periodically recalibrated. The water level data should be recorded on a continuous basis and then either relayed remotely to a personal computer terminal or recorded on site such that the data are readily retrievable from the well location.

5) All methods of data gathering should be consistent with USGS specifications such that these wells could be used as part of a USGS ground-water monitoring network. Taking this action would insure that the Camden County data can be used with other data in the official USGS data base. The USGS would likely be responsible for these monitoring activities.

6) A final optional design consideration would involve equipping the wells with a submersible pump capable of transporting small volumes of water (i.e. ~1-10 liters) to the surface through a small diameter (nominal 2" dia.) PVC sampling pipe. Retrieval of an actual water sample (if funds are available) would allow a complete chemical and isotopic analysis of the ground water to be made. This in turn might assist in better understanding the origins of ground water in each aquifer and mixing processes that might occur between the aquifers.

Part 4: General Recommendations

The susceptibility of the Floridan aquifer underlying Camden County to salt water intrusion does not imply that it must or will necessarily become contaminanted in the future. Wise water management and ground-water monitoring practices can be used to forestall the possible chloride contamination of the upper Floridan aquifer in Camden County. The following recommendations are given for future consideration:

1) Take preemptive actions to minimize the decline of the potentiometric surface within the upper Floridan aquifer. This is the ultimate means of preventing the upconing of salt water from the lower Floridan aquifer to the upper Floridan aquifer. Preemptive action schemes can take these forms:

a) limiting the volume of water pumped from the upper Floridan aquifer

b) developing water resources other than those of the Floridan aquifer (if available and practical)

c) initiating conservation methods and incentives designed to reduce water demand

d) developing a plan for decentralized ground water-pumping in Camden County (see elaboration given below)

A decentralized ground-water pumping scheme in which production wells are spaced as far apart laterally as possible might allow for the continued or even expanded utilization of ground water from the upper Floridan aquifer while minimizing potentiometric surface declines. The main drawback of this scheme is that it would involve a large capital expenditure in terms of well drilling, pipelines and pumps. However, by optimally spreading the pumping center from an area of a few square miles to possibly tens of square miles, potentiometric surface declines can likely be minimized. This in turn would favor retention of the hydraulic barrier posed by higher heads within the upper Floridan aquifer relative to the lower Floridan aquifer. Alternative pumping scenarios can be tested using numerical ground-water modeling techniques capable of simulating solute transport between the upper and lower Floridan aquifers. Engineering estimates of pipeline and related infrastructure costs can accompany ground-water pumping scenarios that have been determined favorable by ground water modeling.

2) Continued efforts should be given to using geophysical techniques to find the depth of salt water below Camden County and surrounding region. The data gathered to date have been useful in better understanding the extent of salt water in the lower Floridan aquifer; however, more data are required for a meaningful depiction of regional conditions. The safe working assumption is that the Fernandina permeable zone at the base of the lower Floridan aquifer contains brackish to salt water on a regional basis. Efforts to find locations where the lower Floridan aquifer is fresh throughout its vertical extent will be costly and are probably not justified.

3) Lower priority should be given to studies designed to find subsurface faults, fractures, solution features, or zones of enhanced permeability below Camden County. Although these studies certainly have merit, the ultimate cause of the vertical intrusion is not the "conduit"; rather it is pressure reduction within the upper Floridan aquifer. To reiterate, conduits can exist and not result in salt water intrusion if the *downward hydraulic gradient* between the upper and lower Floridan aquifers is maintained through wise water management and ground-water exploitation practices.

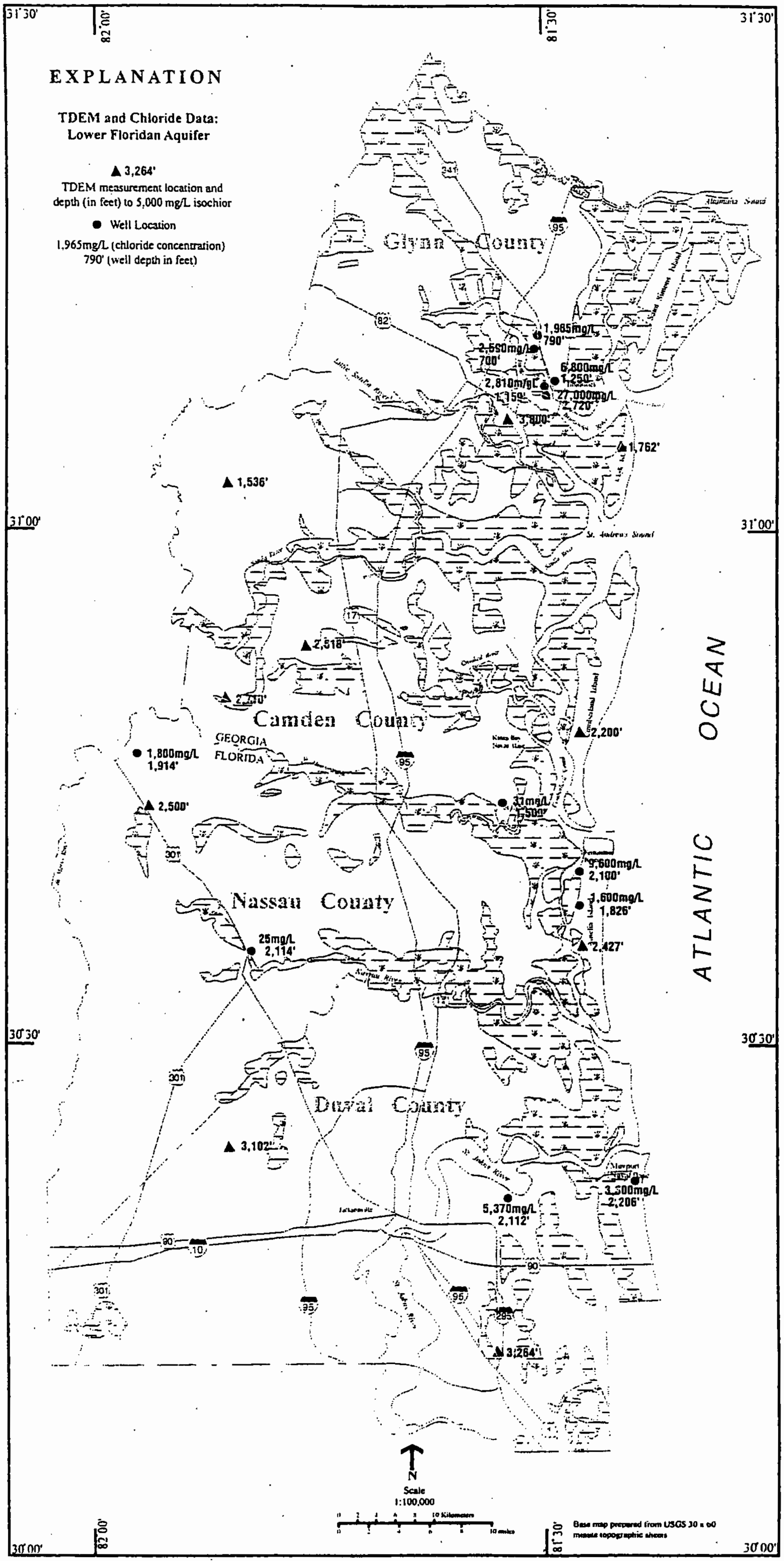


Figure 1: TDEM and chloride data for the four-county study area

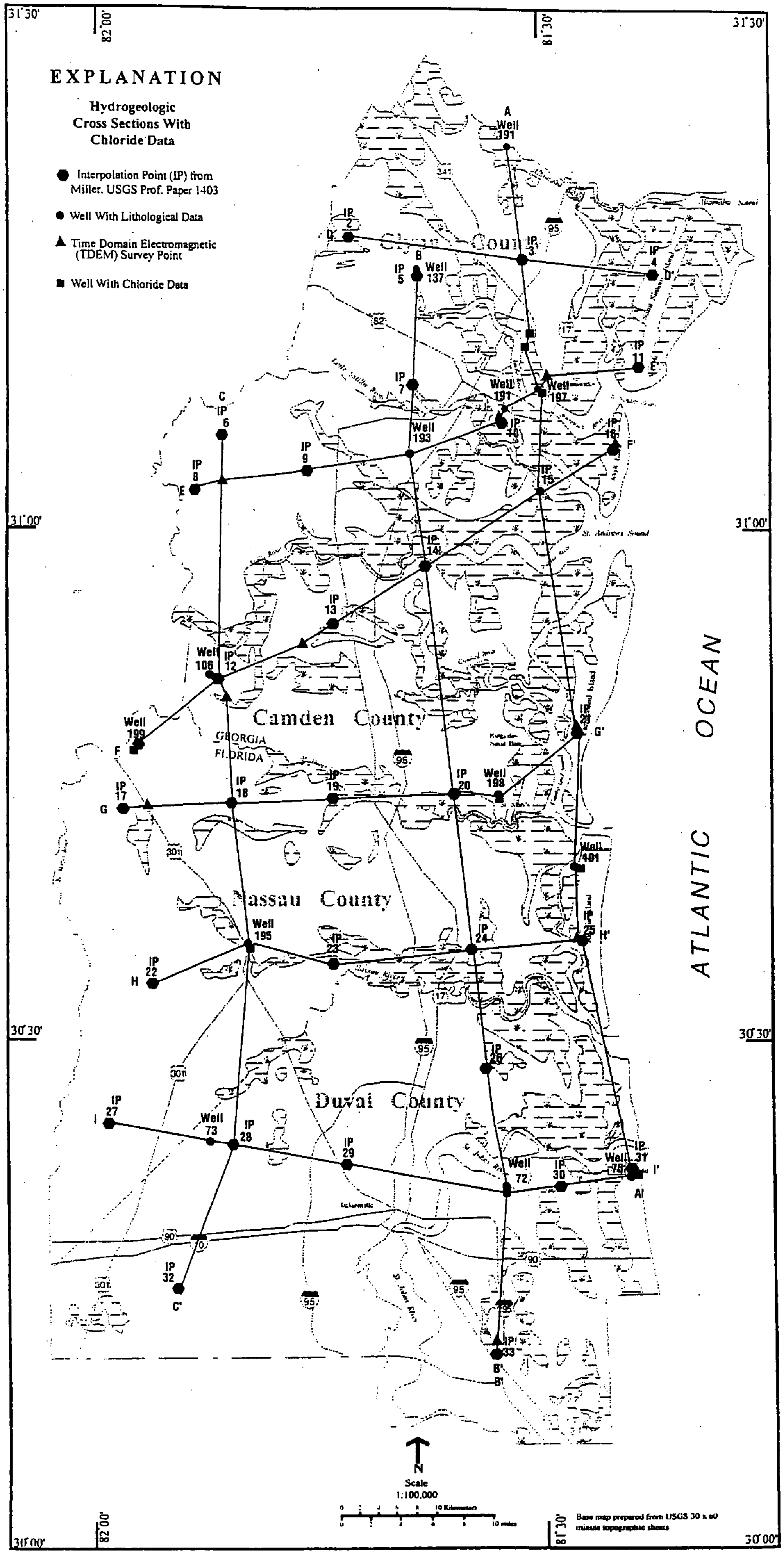
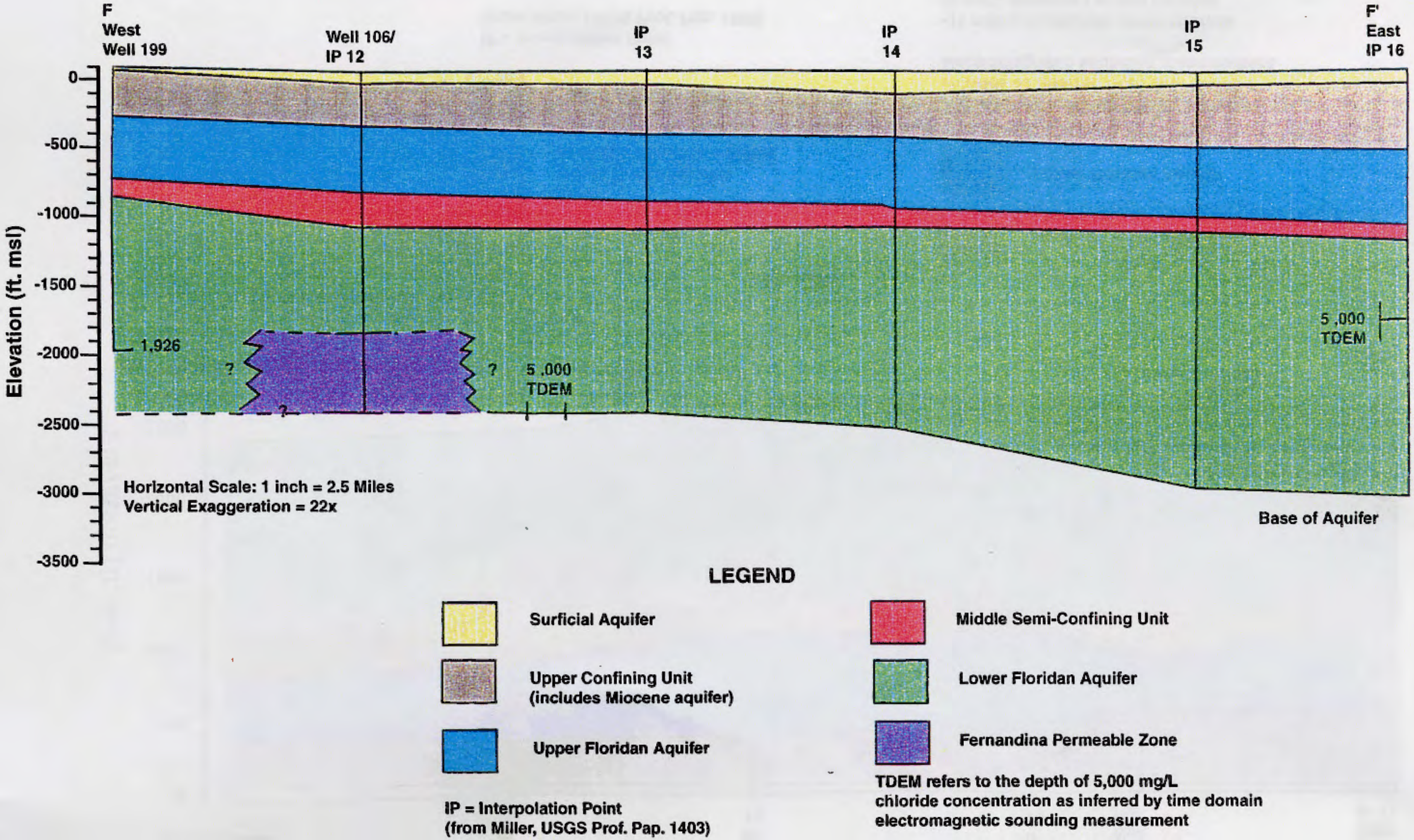
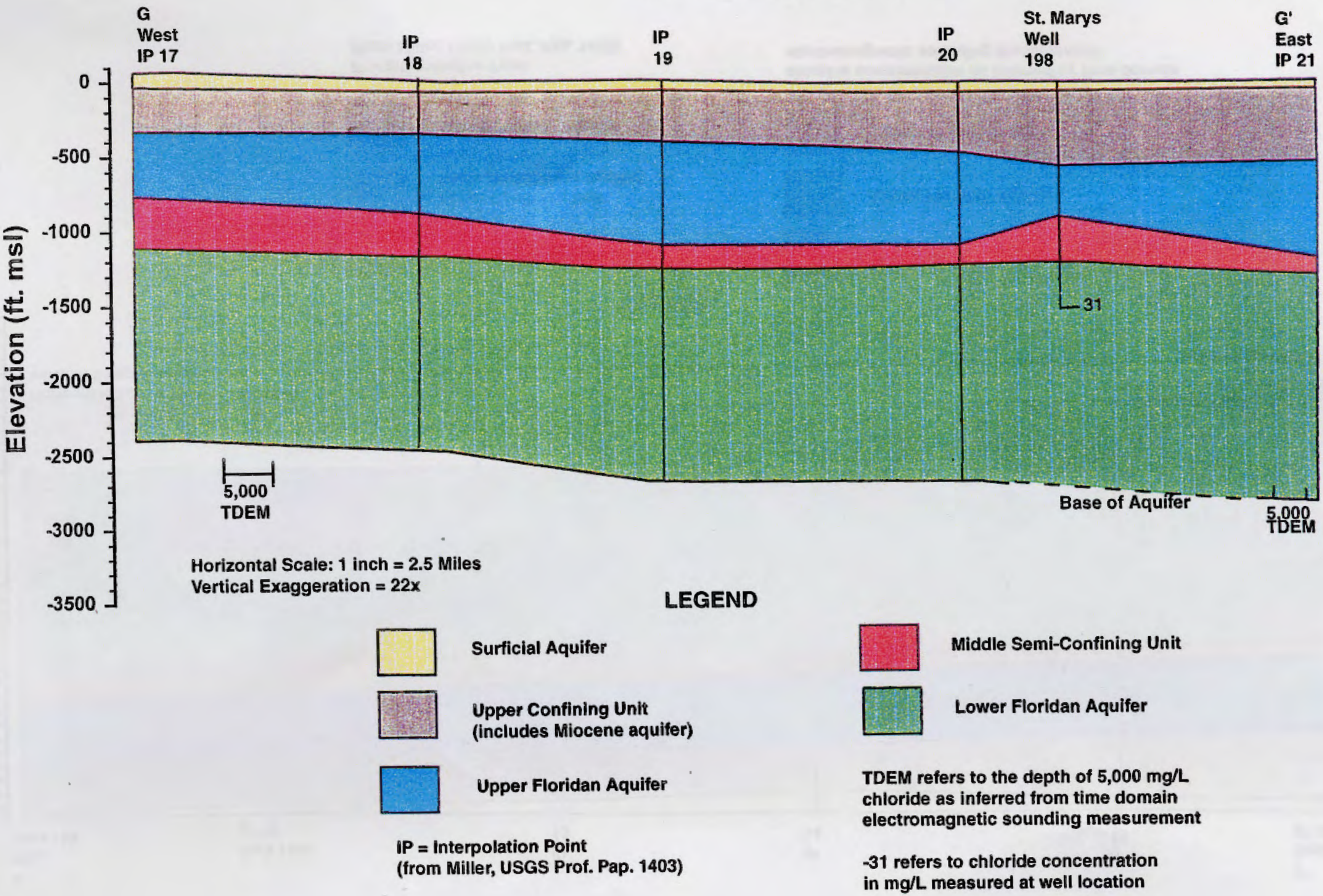


Figure 2: Base map showing cross section locations (see Figures 3 and 4)

Hydrogeologic Cross Section F-F' with Chloride Data



Hydrogeologic Cross Section G-G' with Chloride Data



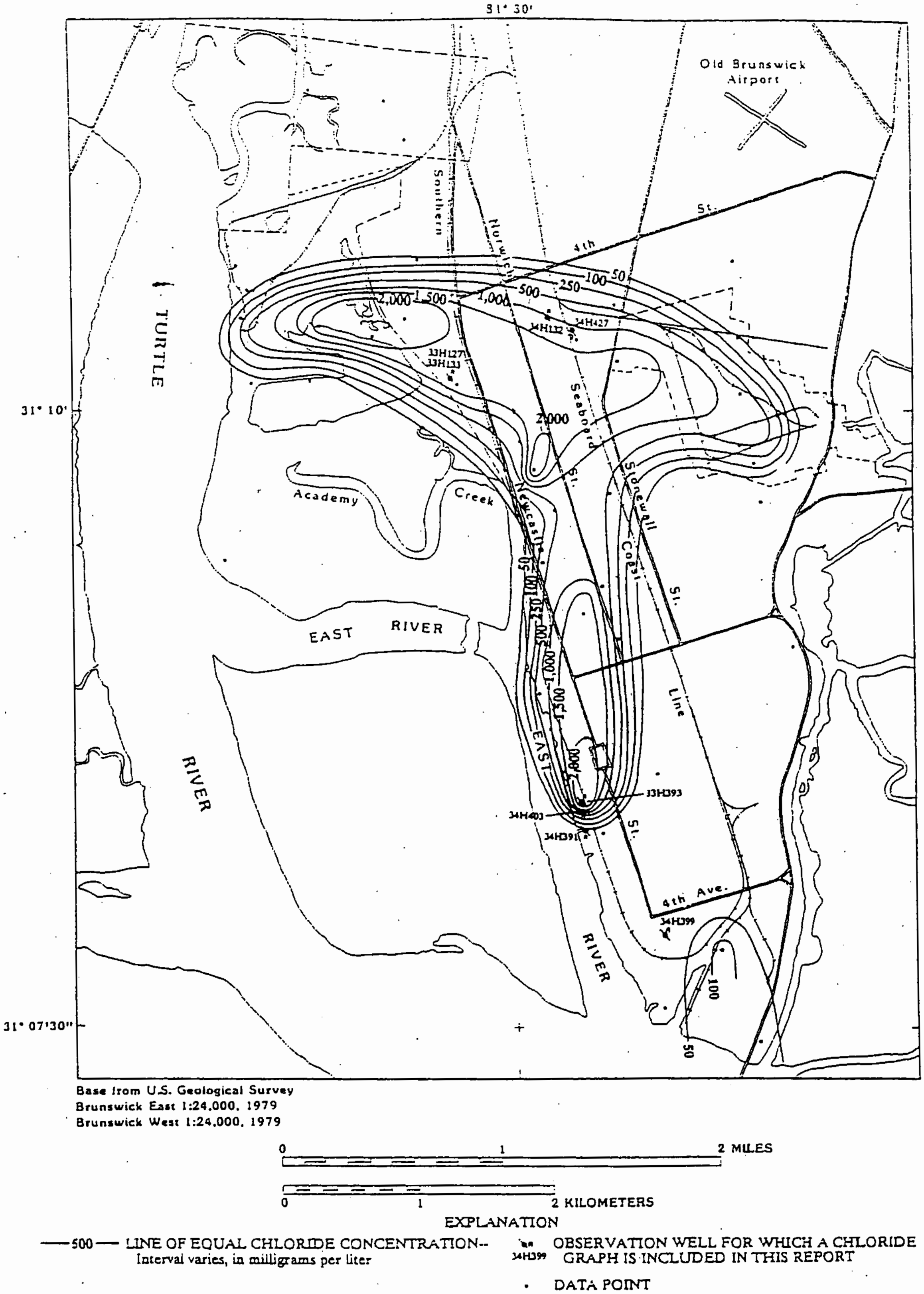


Figure 5: Chloride plume within the upper Floridan aquifer below Brunswick, Ga (after Peck et al., 1992)

GEOLOGIC UNIT			HYDROGEOLOGIC UNIT		
Series	Stage	Formation	Savannah area	Brunswick area	Model layer
Post-Miocene		Undifferentiated	Surficial aquifer	Surficial aquifer	A1
Miocene		Hawthorn Formation	Upper confining unit[1]	Upper confining unit[1]	C1
Oligocene		Suwanee Limestone	Upper Floridan aquifer	Upper Floridan aquifer	A2
Eocene	Upper	Ocala Limestone	Middle semiconfining unit	Upper Floridan aquifer	A2
Eocene	Middle	Avon Park Formation	Middle semiconfining unit	Middle semiconfining unit	C2
Eocene	Middle	Avon Park Formation	Lower confining unit	Lower Floridan aquifer: Brackish and deep freshwater zones[2]	A3
Eocene	Lower	Oldsmar Formation	Lower confining unit	Lower Floridan aquifer: Lower semi-confining unit	C3
Paleocene		Cedar Keys Formation	Lower confining unit	Lower Floridan aquifer: Fernandina permeable zone[3]	A4
Upper Cretaceous		Undifferentiated	Lower confining unit	Lower confining unit	Not simulated

[1]Includes the upper and lower Brunswick aquifers in the Brunswick area (Clarke and others, 1990)
[2]Gregg and Zimmerman (1974)
[3]Krause and Randolph (1989)

Figure 6. Generalized hydrostratigraphic column for the four-county study area (after Clarke and Krause, 2001)

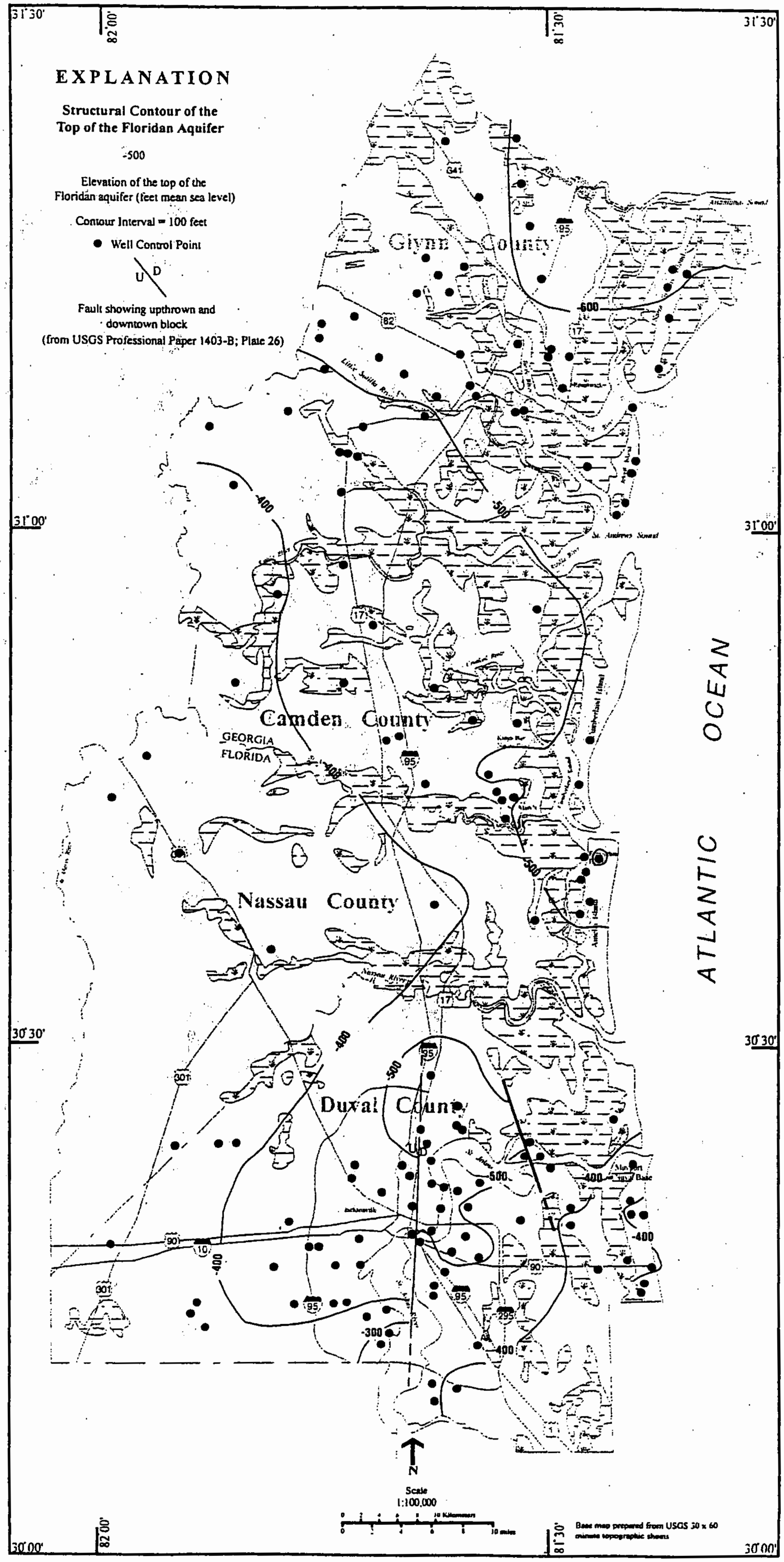


Figure 7: Structural contour of the top of the Floridan aquifer

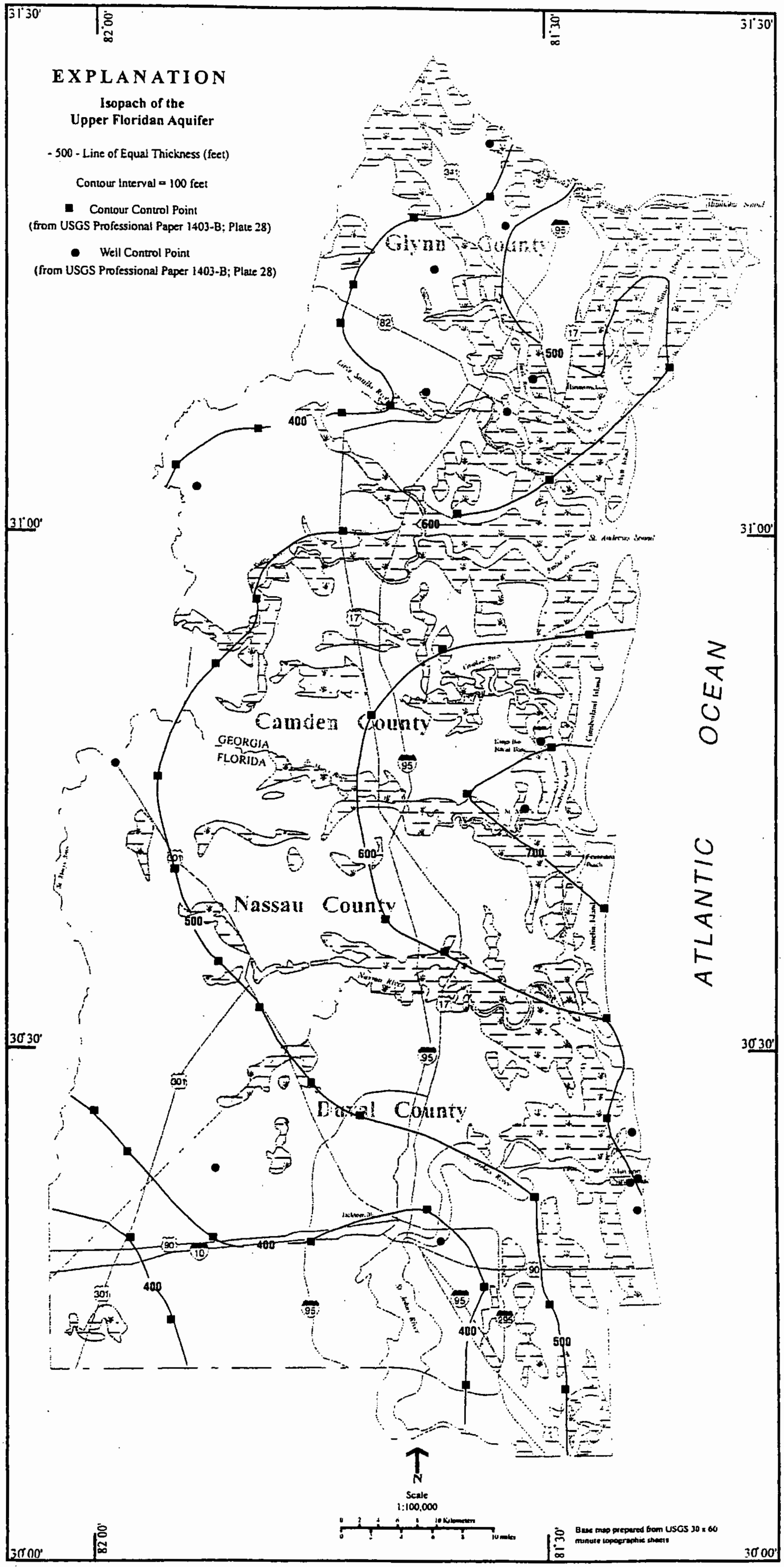


Figure 8: Isopach map of the upper Floridan aquifer

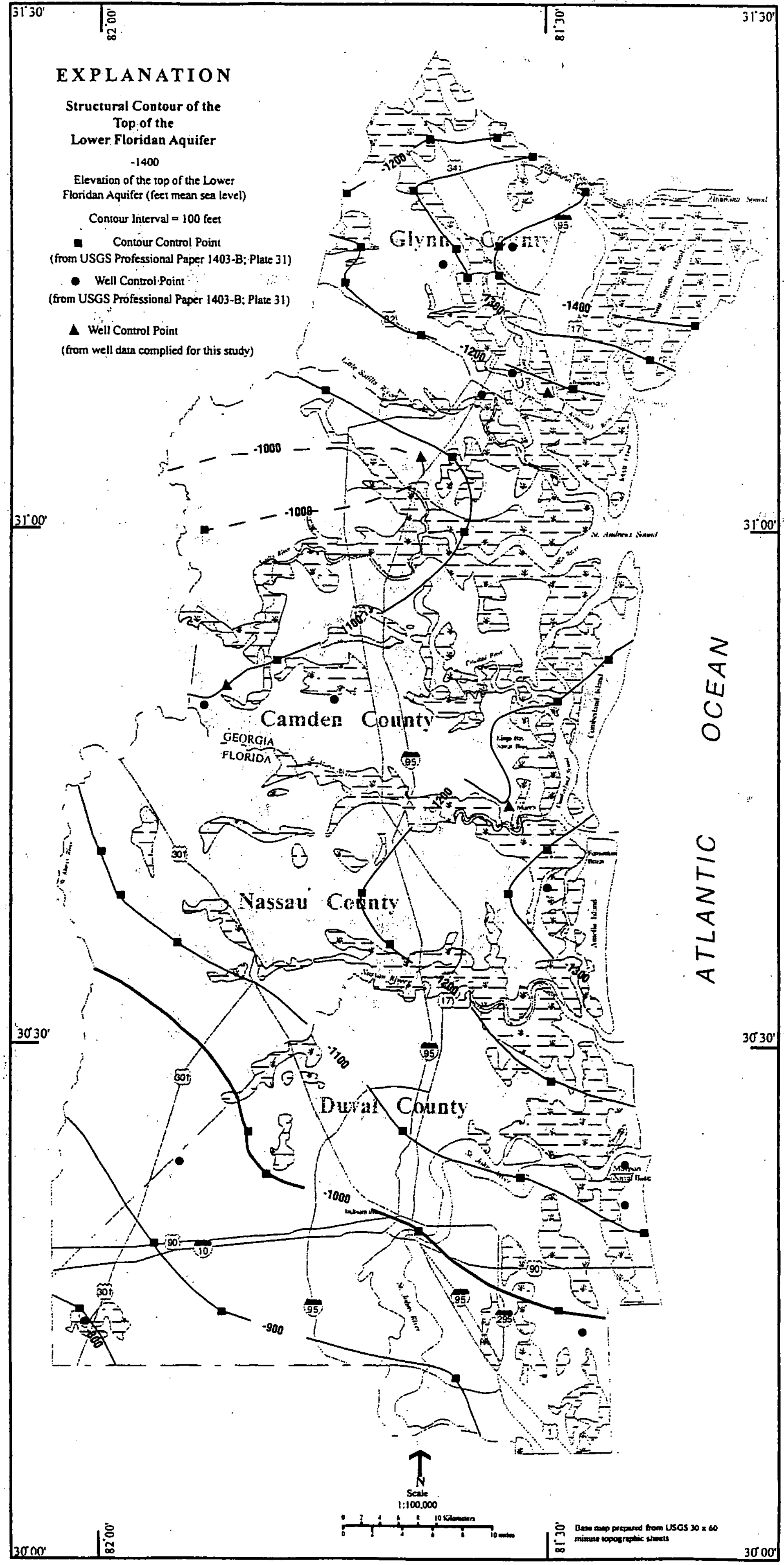


Figure 9: Structural contour map of the lower Floridan aquifer

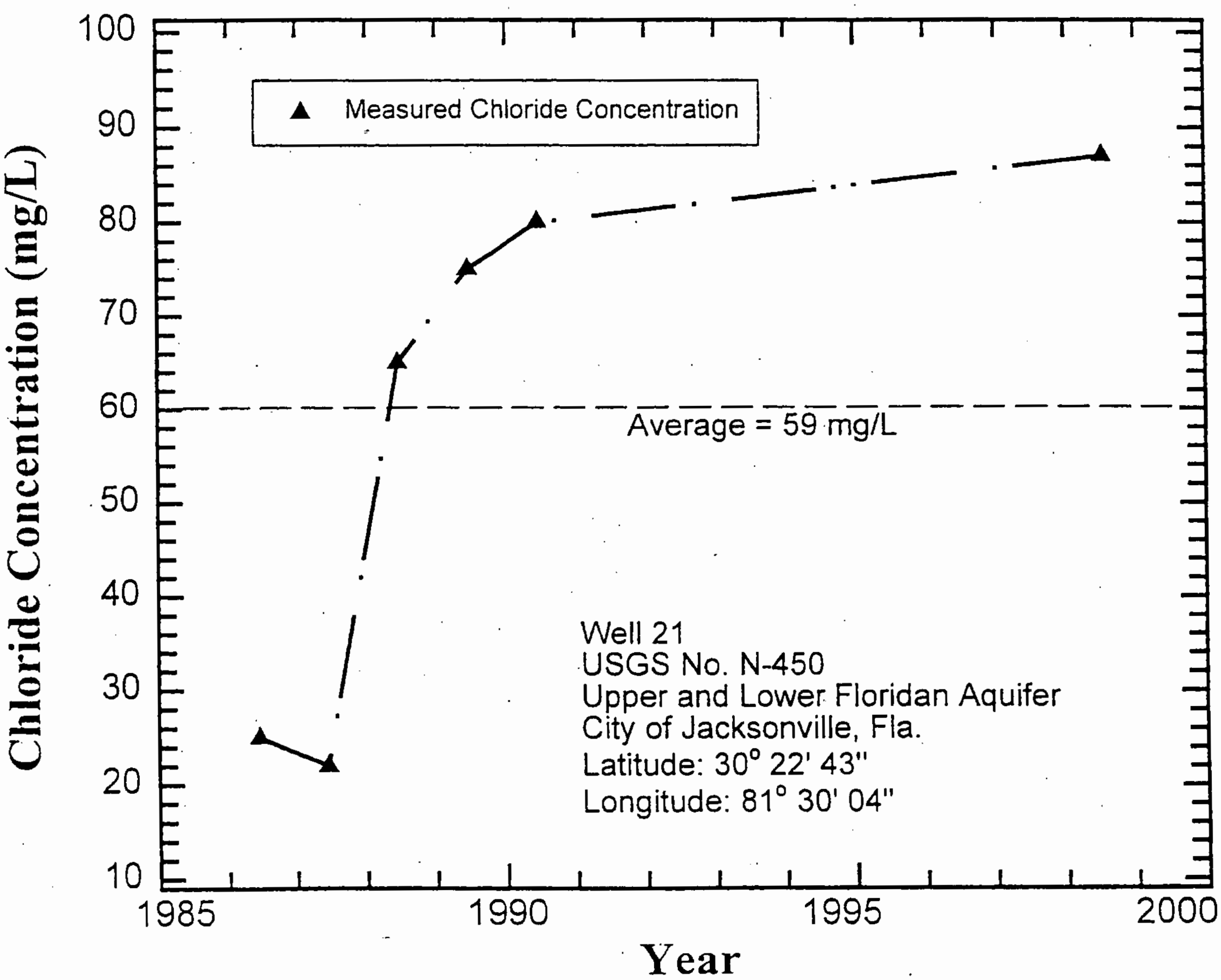


Figure 10: Chloride trends, Well 21, Duval County, Florida

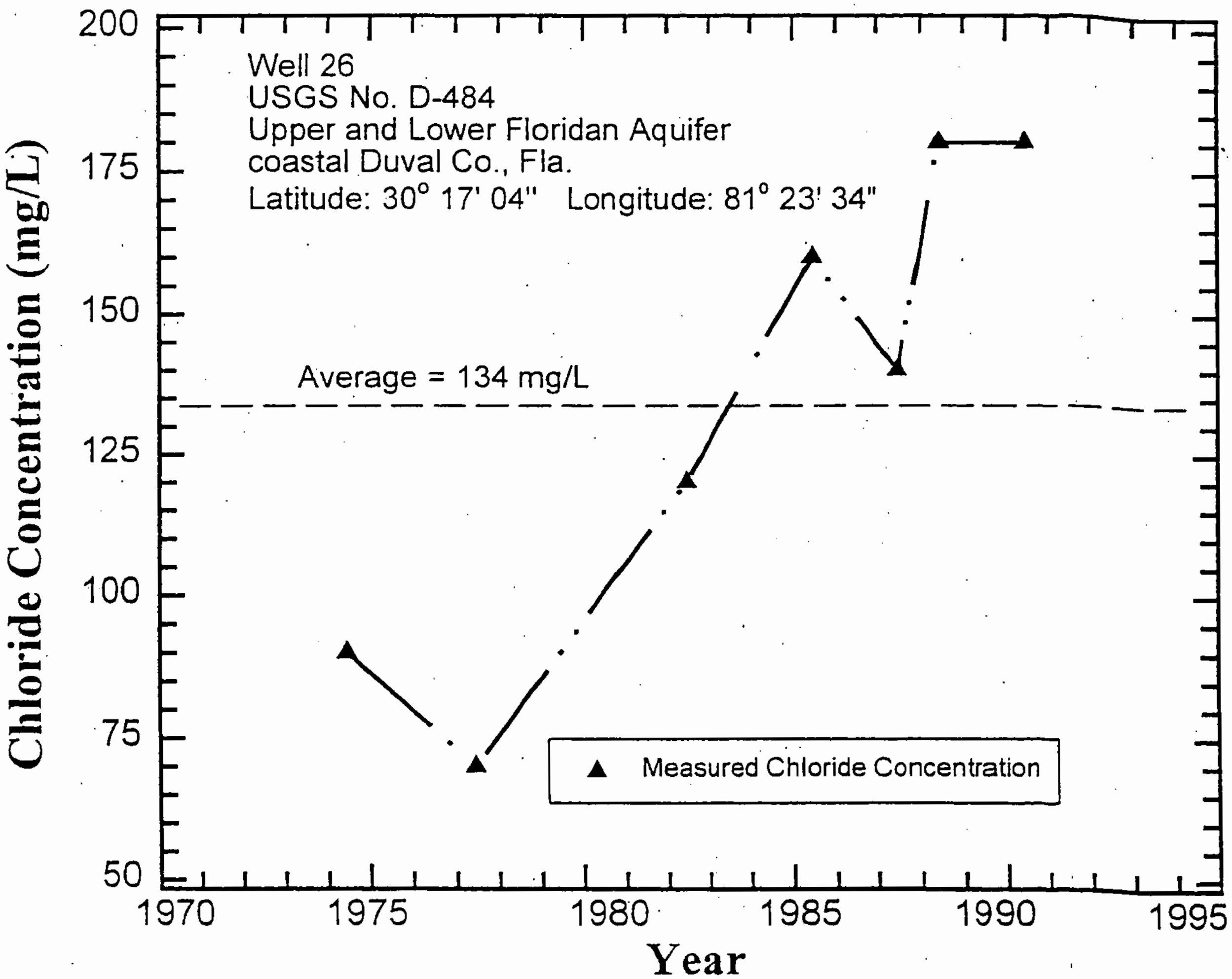


Figure 11: Chloride trends, Well 26, Duval County, Florida

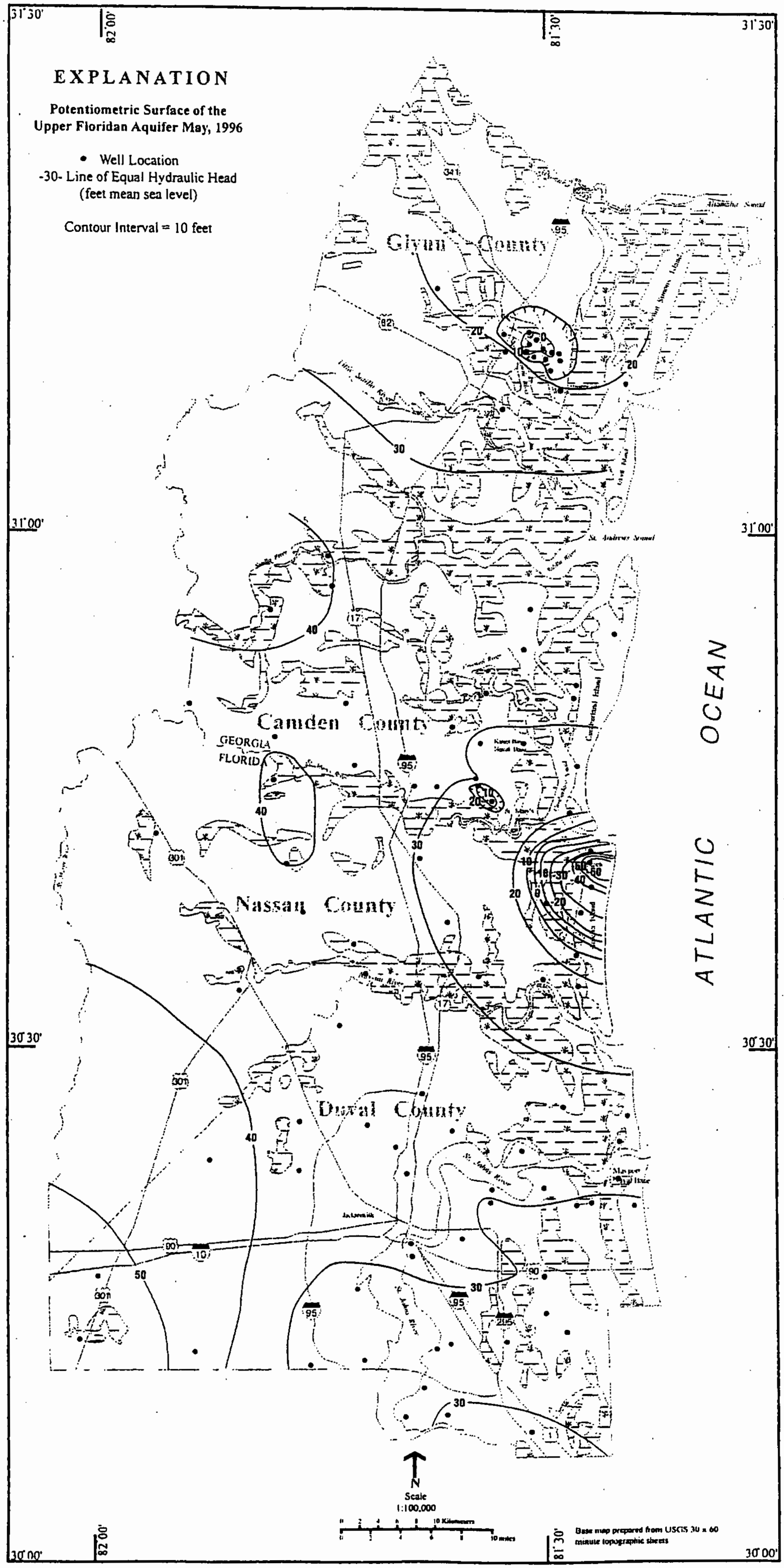


Figure 12: Potentiometric surface map of the upper Floridan aquifer, 1996

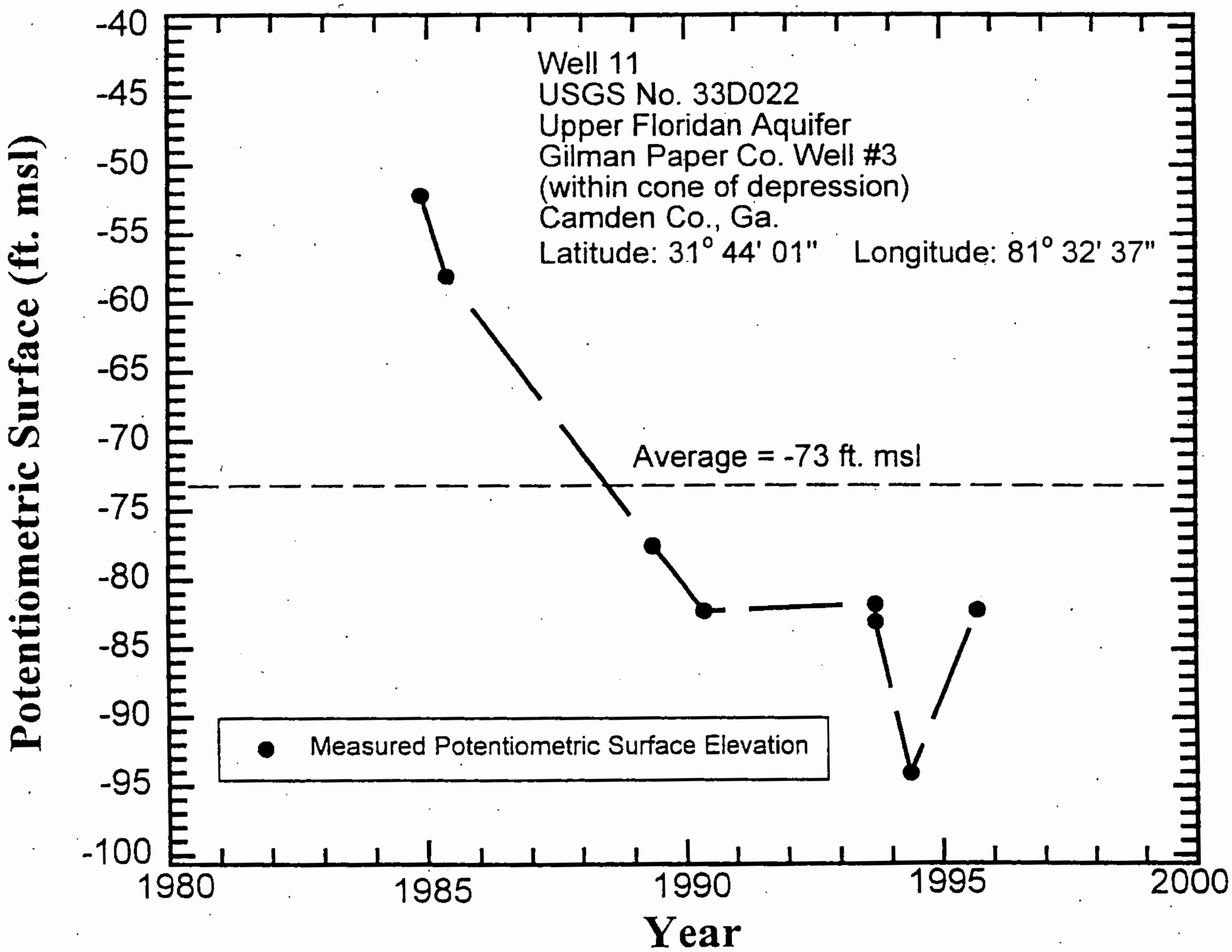


Figure 13: Potentiometric surface trends, Gilman Paper Co well, Camden Co., Georgia

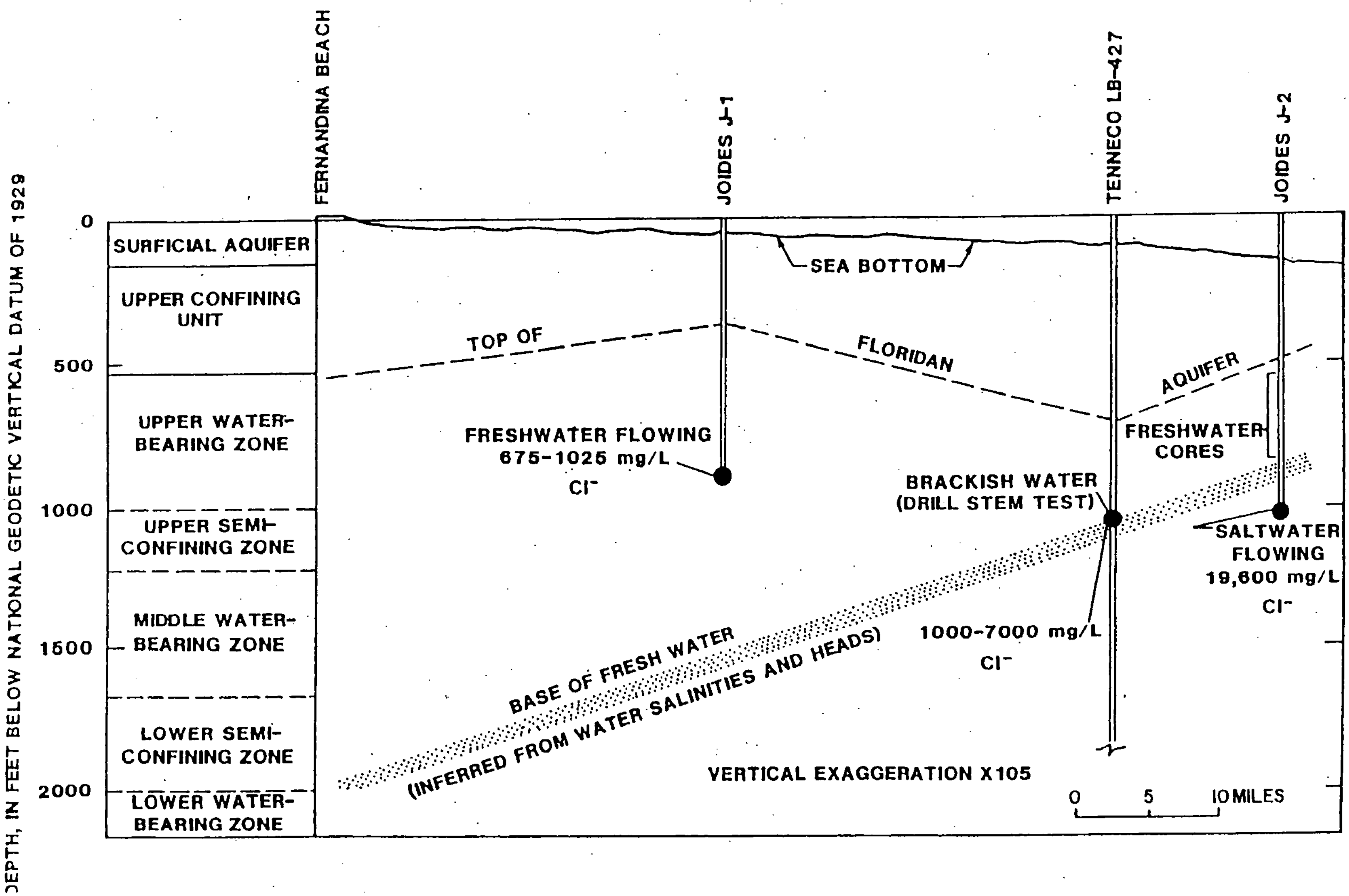


Figure 14: Inferred position of the saltwater-freshwater interface offshore Fernandina Beach, Fla.

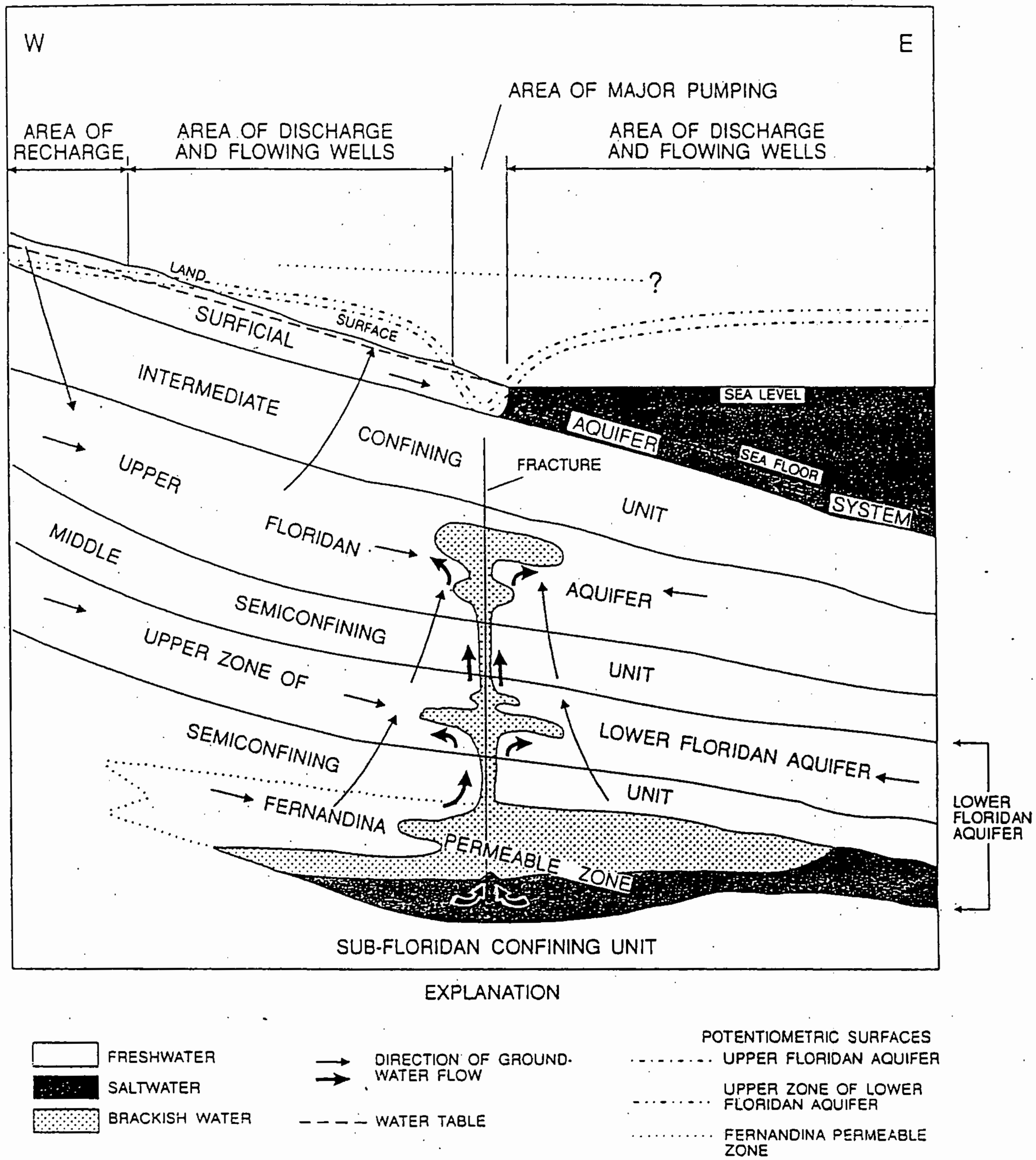


Figure 15: Model for the upwelling of brackish water in the Floridan aquifer system (from Spechler, 1994)

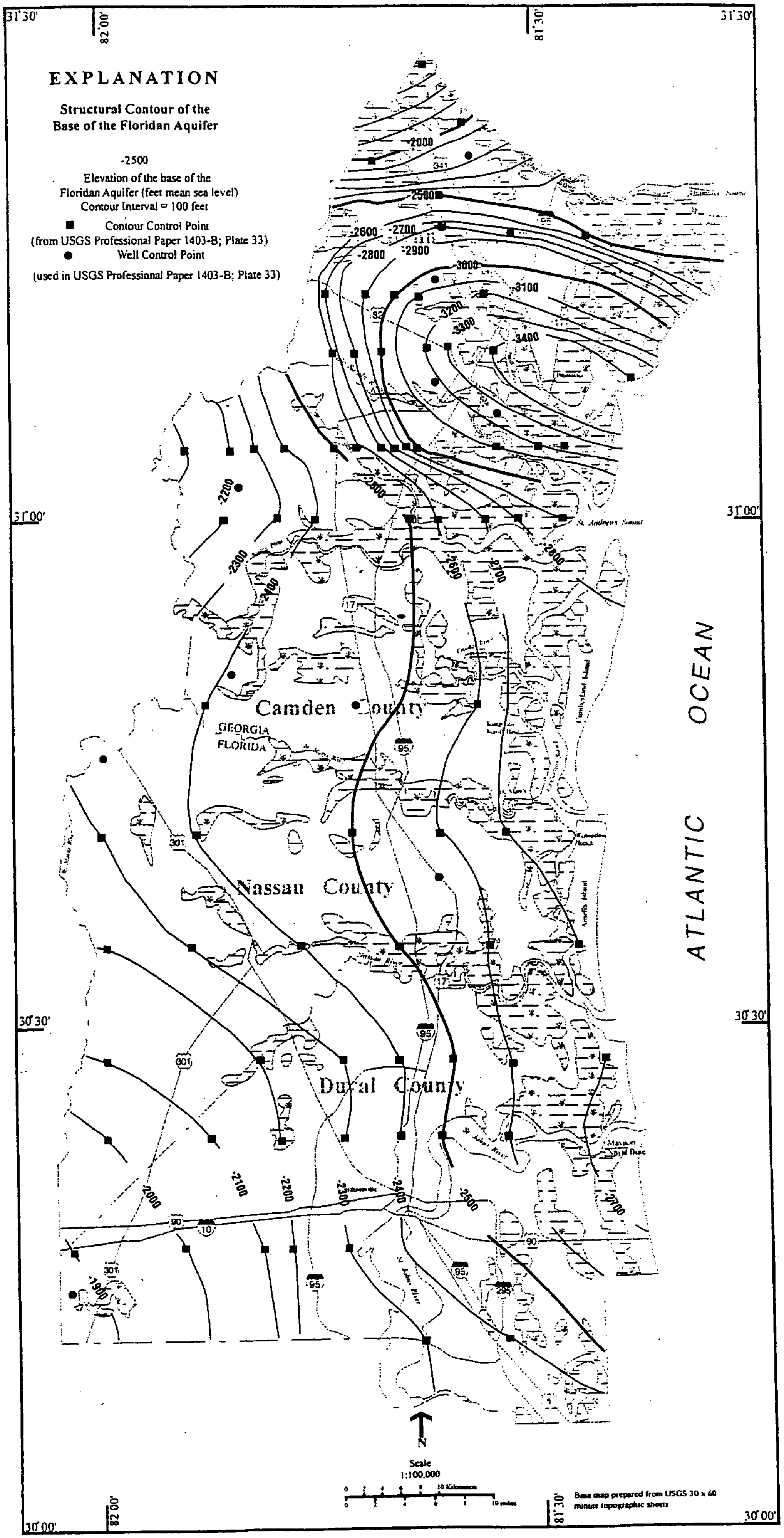


Figure 16: Structural contour map of the base of the Floridan aquifer

Series	Formation	Approximate thickness (feet)	Lithology	Hydrogeologic unit	Hydrologic properties
Holocene to Upper Miocene	Undifferentiated surficial deposits	20-120	Discontinuous sand, clay, shell beds, and limestone	Surficial aquifer system	Sand, shell, limestone, and coquina deposits provide local water supplies.
Miocene	Hawthorn Formation	100-500	Interbedded phosphatic sand, clay, limestone, and dolomite	Intermediate confining unit	Sand, shell, and carbonate deposits provide local limited water supplies. Low permeability clays serve as the principal confining beds for the Floridan aquifer system below.
Eocene	Upper: Ocala Limestone	100-350	Massive fossiliferous chalky to granular marine limestone	Floridan aquifer system: Upper Floridan aquifer	Principal source of ground water. High permeability overall. Water from some wells shows increasing salinity.
Eocene	Middle: Avon Park Formation	700-1,100	Alternating beds of massive granular and chalky limestones, and dense dolomites	Floridan aquifer system: Middle semiconfining unit	Low permeability limestone and dolomite.
				Floridan aquifer system: Lower Floridan aquifer: Upper zone	Principal source of ground water. Water from some wells shows increasing salinity.
Eocene	Lower: Oldsmar Formation	300-500		Floridan aquifer system: Lower Floridan aquifer: Semiconfining unit	Low permeability limestone and dolomite.
				Floridan aquifer system: Lower Floridan aquifer: Fernandina permeable zone	High permeability; salinity increases with depth.
Paleocene	Ceder Keys Formation	about 500	Uppermost appearance of evaporites; dense limestones	Sub-Floridan confining unit	Contains highly saline water; low permeability.

Figure 17: Generalized hydrogeology and geology of the study area (from Spechler, 1994)

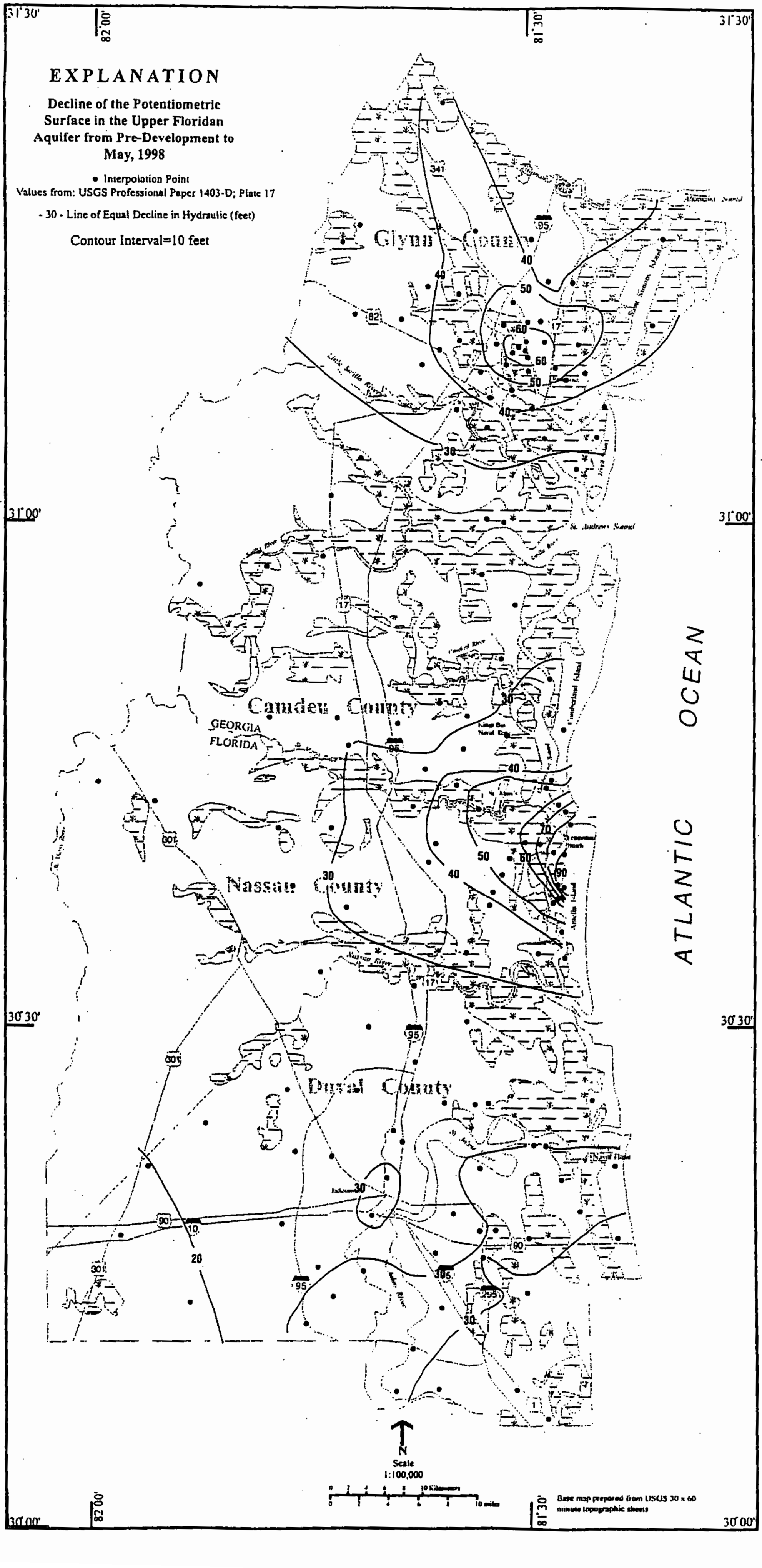


Figure 18: Estimated decline in the potentiometric surface of the upper Floridan aquifer from pre-development levels

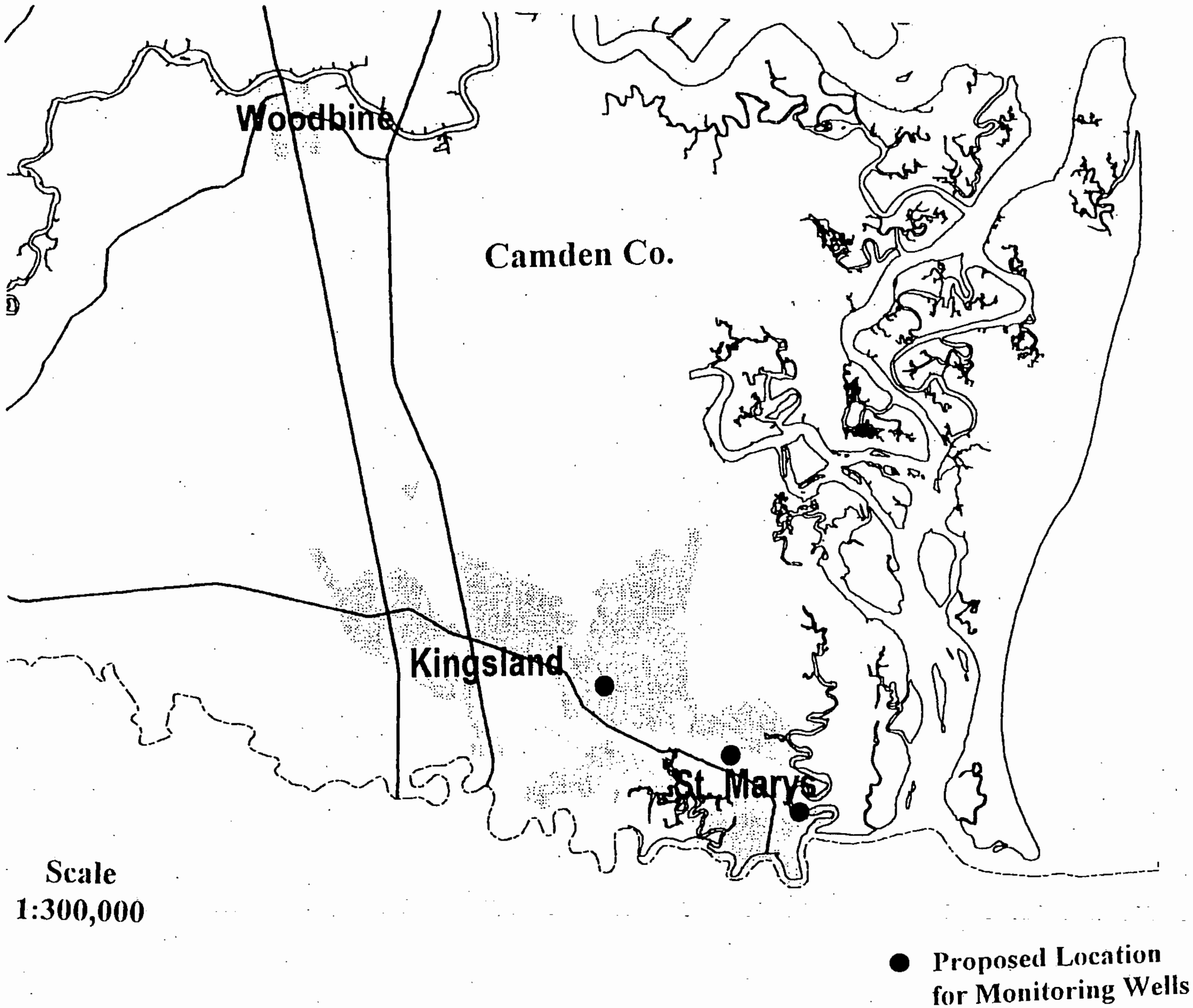


Figure 19: Map of Camden County showing proposed monitoring well locations

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