THE MIOCENE AQUITARD AND THE FLORIDAN AQUIFER OF THE GEORGIA / SOUTH CAROLINA COAST: GEOPHYSICAL MAPPING OF POTENTIAL SEAWATER INTRUSION SITES

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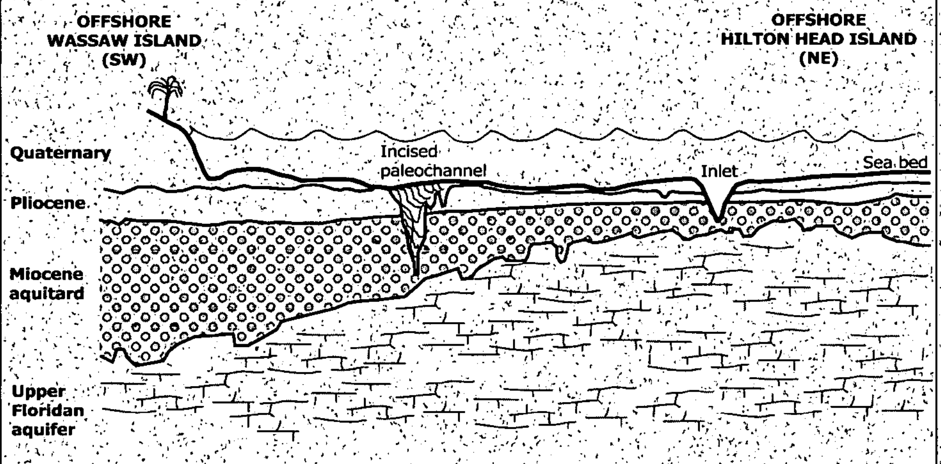

Schematic Seismic Stratigraphic Framework

GEORGIA DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION
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EXECUTIVE SUMMARY

This report provides the Georgia Department of Natural Resources, Environmental Protection Division (EPD) with geophysically derived information pertinent to identifying areas where the Upper Floridan aquifer (UFA) is susceptible to seawater intrusion in coastal Georgia and South Carolina. The report is a contract deliverable for Contract 10-21-6-15-120-317 between EPD and the Georgia Southern University Applied Coastal Research Laboratory. The study area covers about 1400 square miles of nearshore and estuarine areas between Wassaw Sound, GA, and Port Royal Sound, SC and lies within the eastern portion of the Savannah cone of depression on the UFA.

The principal objective of the study is to identify coastal areas where the Miocene confining unit overlying the UFA is thin or absent. The Miocene is generally thinnest in areas where the UFA occurs at shallow depth and where either (1) modern tidal creeks (or dredged channels) cut into or through the Miocene or (2) paleochannels incised during lowstands of sea level cut into or through the Miocene. The primary means of identifying these areas involved applying principles of seismic sequence stratigraphy to seismic reflection data.

1215 miles of sub-bottom, single-channel, seismic reflection data form the primary basis upon which this report is based. Eight hundred miles of archive data collected between 1970 and 1997 were augmented with 415 miles of new data collected during 1999-2001. Available borehole lithology-log and gamma-log data were used to ground-truth the seismic-stratigraphic interpretations and to provide additional control in areas where seismic coverage was limited.

South of the Savannah River and within the Savannah cone of depression, the UFA is deep enough, the Miocene aquitard thick enough, and the tidal creeks and paleochannels shallow enough that the probability of occurrence of areas of thin or absent aquitard is very low. A similar stratigraphic scenario exists seaward of a coast-parallel line located about 20 miles off the Georgia/South Carolina coast, an area which lies outside of the cone of depression. The probability of seawater intrusion due to aquitard thinning or breaching in both areas is inferred to be very low.

The principal area of thinned or absent Miocene strata occurs beneath the intracoastal and inner shelf region of South Carolina. The 20-foot Miocene isopach contour defines four relatively large thin-Miocene swaths with a total area of approximately 195 square miles. Three of these swaths occur with the Savannah cone of depression on the UFA. Eleven no-Miocene sites (Areas of Concern) occur within these swaths and collectively comprise an estimated area of about 7 square miles. Ten of the eleven no-Miocene sites are within the cone of depression; at each site, 10 to 55 feet of post-Miocene non-confining material overlie the aquifer. The eleventh and most extensive no-Miocene site, located along the axis of the Beaufort River, lies just outside the 0-foot contour on the cone of depression and is likely a discharge rather than a recharge area most of the time. At this site, 0 to 10 feet of non-confining material overlie the aquifer.

A qualitative ranking scheme allows each no-Miocene AOC to be ranked in order of highest (I) to lowest (XI) susceptibility to seawater intrusion. The rankings and locations of the AOCs are as follows:

(I) AOC 1-Cooper River at Calibogue Sound
(II) AOC 6-Broad River near US Hwy 170 bridge
(III) AOC 3-Colleton River at Victoria Bluff
(IV) AOC 2-May River at Bull Creek
(V) AOC 7A-Beaufort Arch offshore Hilton Head
(VI) AOC 7B-Beaufort Arch offshore Hilton Head
(VII) AOC 7D-Beaufort Arch offshore Hilton Head
(VIII) AOC 7C-Beaufort Arch offshore Hilton Head
(IX) AOC 4-Port Royal Sound at Hilton Head
(X) AOC 5-Broad River north of Daws Island
(XI) AOC 8-Beaufort River north of Parris Island

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PART 1: STUDY DESCRIPTION

INTRODUCTION

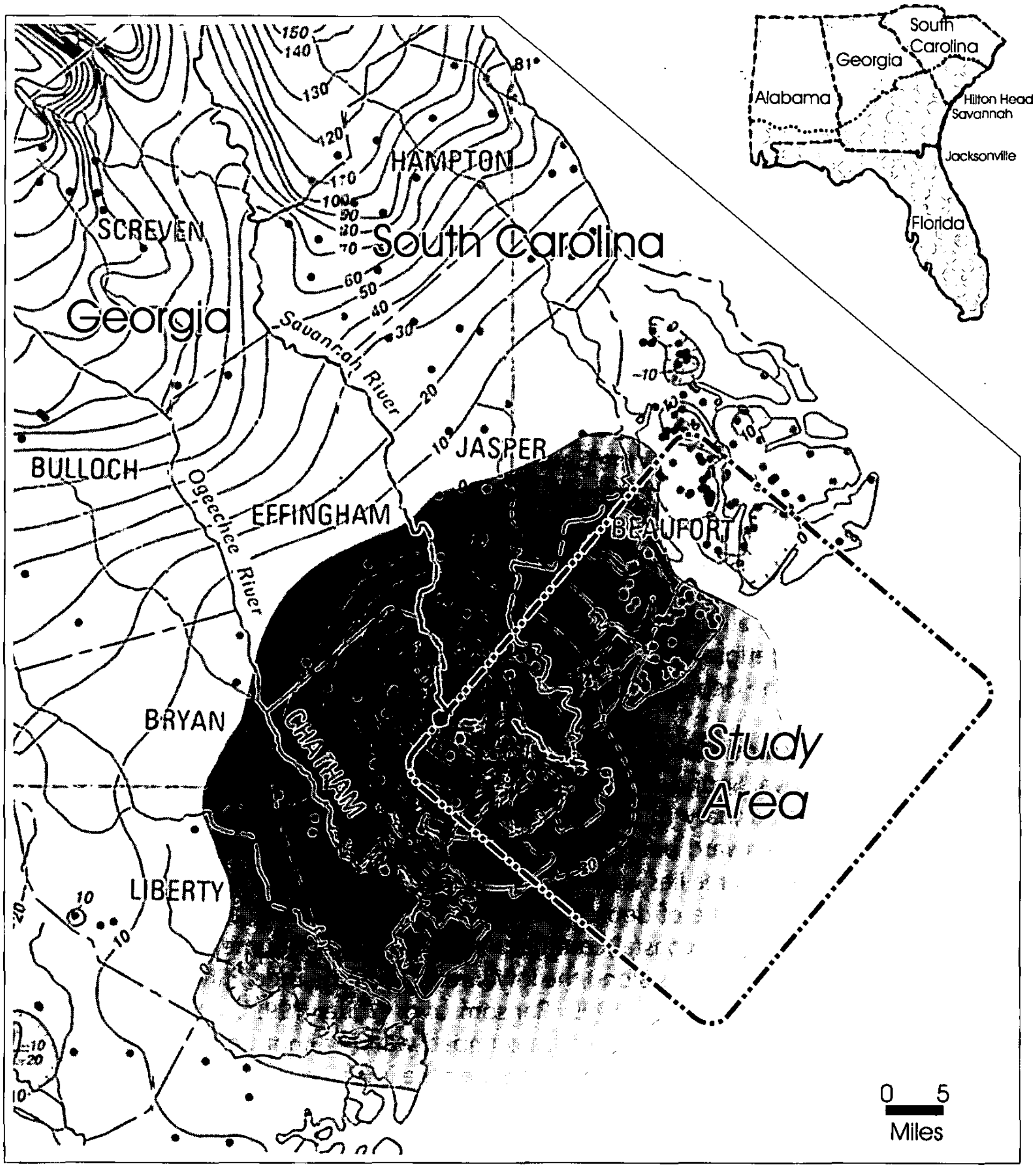
The purpose of this report is to provide the Georgia Department of Natural Resources, Environmental Protection Division (DNR-EPD) with geophysically derived information pertinent to identifying the susceptibility of the Upper Floridan aquifer (UFA) to seawater intrusion in coastal Georgia (GA) and South Carolina (SC). The report is a deliverable for Contract 10-21-6-15-120-317 between EPD and the Georgia Southern University (GSU) Applied Coastal Research Laboratory (ACRL). This two-year research study to identify areas where the Miocene aquitard (confining unit) is breached, thin, or missing was funded through EPD's Sound Science Initiative.

This report is a follow-up to a Phase I report (Foyle et al., 1999) which summarized pre-existing archive geophysical data and information for the Georgia/South Carolina coast. That report contained maps and sections showing (1) the topography on the top of the UFA, (2) the thickness of the Miocene aquitard, (3) areas where the aquitard is sufficiently thin or absent for there to be a potential threat of seawater intrusion into the aquifer, and (4) areas that needed additional geophysical investigation. This report builds upon, and supercedes, the findings of the Phase I report as it incorporates a large amount of new geophysical data collected during 1999 and 2000. The new data highlight, with greater resolution, the stratigraphic framework of the UFA, the Miocene aquitard, and the overlying post-Miocene strata on the Georgia/South Carolina coast and inner shelf.

The study area covers about 1400 square miles of nearshore and estuarine areas between Wassaw Sound, GA, and Port Royal Sound, SC (Fig. 1-1), a coastline length of approximately 37 miles. The approximate onshore boundary to the study is US Highway 17/170 linking Savannah, GA, and Beaufort, SC, while the seaward boundary is a coast-parallel line located approximately 30 miles offshore. Most of the study area lies within the eastern portion of the Savannah cone of depression on the UFA (Fig. 1-1). The cone of depression has a radius of as much as 30 miles, is centered on Savannah, and underlies eight coastal counties. The 0-foot potentiometric contour defining the northeastern edge of the cone runs along the lower reaches of the Broad River and the north end of Hilton Head Island, SC (Peck et al., 1999; Ransom and White, 1999). The cone of depression developed, and continues to persist, because pumped water cannot be replaced quickly enough through natural inflow from other parts of the aquifer; the inverted apex of the cone now lies about 100 feet below sea level (Krause and Randolph, 1989; Peck et al., 1999).

BACKGROUND

Previous studies by the U.S. Geological Survey (USGS) show that most of the groundwater used for public water supply and industrial needs in coastal Georgia and adjacent southern South Carolina is supplied from the UFA (Krause and Randolph, 1989; Garza and Krause, 1996). The UFA consists of limestone that originally accumulated in warm subtropical to tropical seas more than 25 million years ago and now underlies the lower coastal plain and continental shelf of South Carolina, Georgia, Florida, and Alabama. Since deposition, the UFA has been periodically eroded and weathered during



Base map from Peck et al., 1999

Figure 1-1 Map showing location of the study area on the Georgia/South Carolina inner shelf and coastal zone. Base map is derived from Peck et al. (1999) and shows the May 1998 potentiometric contours on the UFA. Gray-shaded area shows the Savannah cone of depression where the potentiometric surface lies below mean sea level; the location of the seaward edge of the cone is approximate. Potentiometric contours are in feet below Mean Sea Level (MSL).

times of lowered sea level and buried by younger sediments during times of higher sea level. In coastal Georgia and South Carolina, the UFA lies between 19 and 280 feet below sea level and ranges from 50 to 200 feet in thickness (Hughes et al., 1989; Clarke et al., 1990; Foyle et al., 1999). Seismic data indicate that the top surface of the aquifer is a buried karst topography with significant relief (10s of feet) over short distances (hundreds of feet).

The Miocene aquitard overlying the UFA consists mostly of sands, silts, and clays that were deposited 5 to 25 million years ago. While porous and permeable, transmissivities of the aquitard are significantly lower than those of the aquifer and the unit essentially behaves as a "cap rock" for the UFA. As highlighted in Part 3 of this report, the aquitard can be as much as 160 feet thick, but in localized areas it can be thin or absent due to two natural processes. Firstly, in coastal creeks and sounds, tidal currents are of sufficient strength to erode the channel bottoms and cut into or through the aquitard and expose the UFA to an increased susceptibility to seawater intrusion. Some of these tidal-scour holes are as much as 70 feet deep and are potential intrusion sites, especially in the Beaufort River where the aquifer is shallow and lies on the edge of the Savannah cone of depression. Secondly, several times over the past 2 million years, sea level was as much as 300 feet lower than it is today. During these times of lowered sea level, the most recent of which occurred about 18,000 years ago, the Savannah paleoriver and other coastal streams flowed across the exposed continental shelf to a paleoshoreline located 60 to 80 miles seaward of where it is today. At certain points along its route, the Savannah paleoriver channel cut down into, and locally through, the aquitard. While the paleochannels have since been filled with gravels, sands and silts, these younger sediments are not as efficient an aquitard as the Miocene strata. These paleochannels are also potential seawater intrusion sites, especially seaward of Hilton Head Island where the aquifer is relatively shallow and lies within the Savannah cone of depression. In addition to these natural processes, human impacts may also be a factor. Hughes et al. (1989) suggested that breaches in the Miocene aquitard may have been caused by 19th century phosphate mining in the Coosaw River area north of Beaufort, as well as by harbor dredging in the 1950s at Port Royal (Siple, 1960; Hayes, 1989). In the lower Savannah River, the Miocene aquitard locally crops out on the river bed within the dredged harbor channel (U.S. Army Corps of Engineers, 1998).

Recent data from the USGS show that the UFA provides approximately 350 million gallons/day of water to coastal Georgia, a volume that has increased steadily since water was first pumped from the aquifer at Savannah about 115 years ago (Krause and Randolph, 1989; Fanning, 1999). Chatham County alone consumes about 76 million gallons/day (Fanning, 1999). When groundwater is pumped out of the UFA in the coastal area, the potentiometric surface drops below sea level and there is the potential for seawater to move into (recharge) the aquifer and towards the pumping sites to replace the water being withdrawn. Certain conditions favor seawater intrusion. The two primary requirements are (1) the local absence or near-absence of a "cap rock" or aquitard, and (2) a negative pressure gradient between the ocean and the aquifer, such as occurs within the Savannah cone of depression. Both of these conditions occur on the Georgia/South Carolina coast. To address this concern, the EPD funded this two-year geophysical investigation to identify sites where seawater intrusion may be occurring. Several other groups are being funded to address different aspects of EPD's Interim Strategy (1997-2005) for managing saltwater intrusion in the UFA of southeastern Georgia. The collective results will form the scientific basis upon which EPD can formulate and adopt a comprehensive groundwater-management strategy.

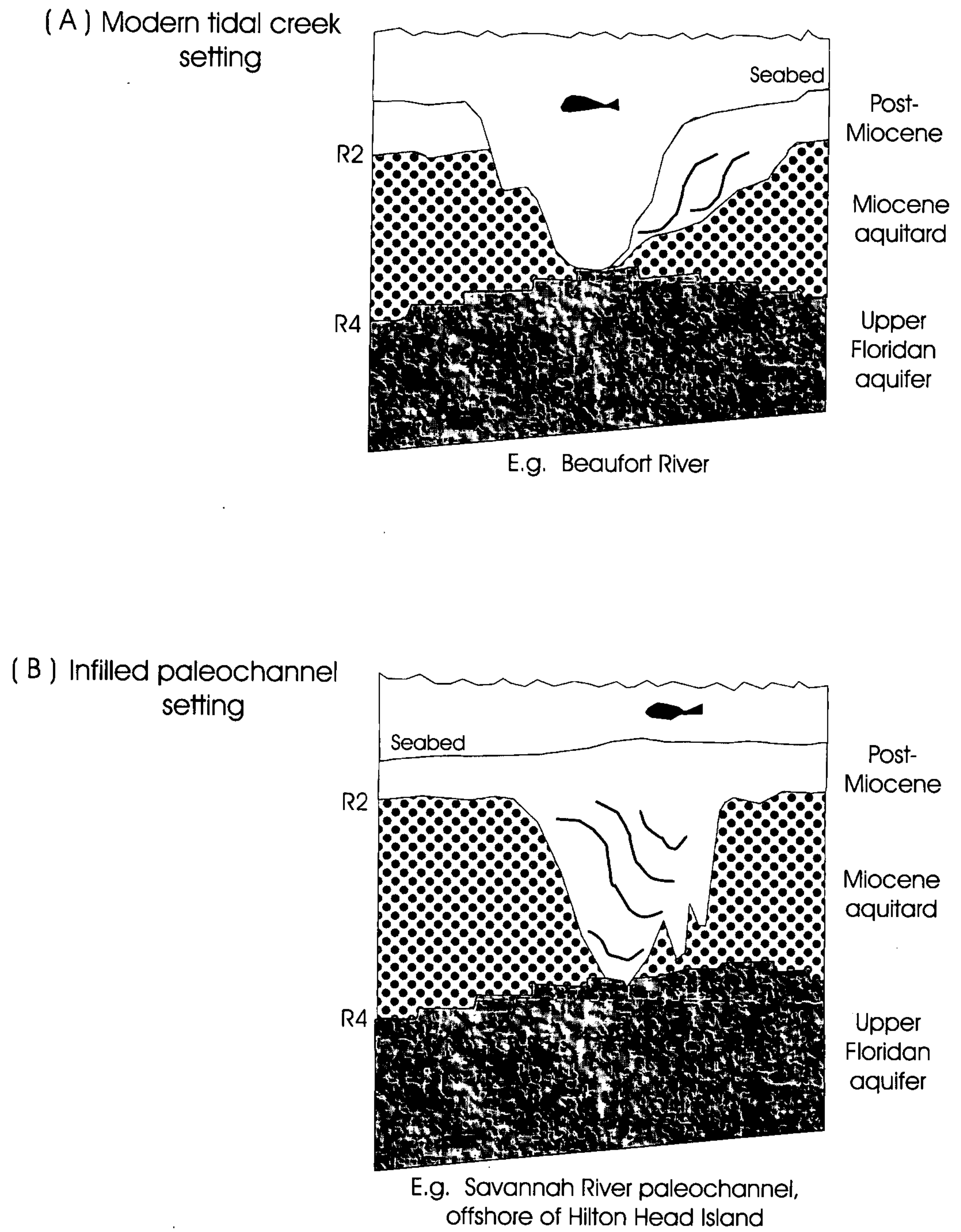


Figure 1-2 Schematic illustration of specific scenarios (a, b) for the development of areas where the Miocene aquitard is thin or absent on the Georgia/South Carolina coast. Note that the Miocene aquitard may be absent while the UFA is still separated from the seabed by a relatively thick post-Miocene section (b). R1 through R5 denote seismic reflectors associated with unconformities that were identified in this study.

STUDY OBJECTIVE

The principal objective of the study is to identify coastal areas where the Miocene confining unit overlying the UFA is thin or absent. When this phenomenon occurs in areas where the overlying water column is saline (i.e. in estuaries and beneath the inner shelf) and where the potentiometric head on the UFA is negative (i.e. within the cone of depression), there will be an enhanced susceptibility to seawater intrusion into the aquifer. Seawater intrusion into the UFA will allow seawater to mix with fresh groundwater which may ultimately lead to contamination of drinking water wells and degradation of water quality on the Georgia/South Carolina coast.

As shown schematically in Fig. 1-2, the Miocene confining unit will generally be thinnest in areas where the underlying UFA occurs at relatively shallow depth; in these areas the Miocene section onlaps topographic highs on the aquifer and is necessarily thin. However, the Miocene has the greatest probability of being thinnest where either (1) modern tidal creeks (or dredged channels) cut down into or through the Miocene (Fig. 1-2a) or (2) paleochannels incised during glacioeustatic lowstands of sea level cut down into or through the Miocene (Fig. 1-2b). The objective of this study, therefore, is to locate those areas where these scenarios occur. The primary means of identifying these areas involves the use of marine seismic reflection profiling and seismic sequence stratigraphy.

REVIEW OF PHASE I RESULTS

Approximately 650 miles of archive seismic reflection data, supporting geologic data, and wireline log data were compiled and interpreted during Phase I (Foyle et al., 1999). Five Areas of Concern (AOCs 1-5) were identified where the Miocene aquitard was breached, thin or absent. These AOCs were therefore designated as sites of potential seawater intrusion as well as sites that warranted further investigation to better define the extent of the potential breach sites (Foyle et al., 2000). At the conclusion of Phase I, it was determined that:

1. South of the Savannah River, and within the cone of depression on the UFA, the UFA is deep enough, the Miocene aquitard thick enough, and the tidal and paleochannels shallow enough that the probability of occurrence of areas of thin or absent aquitard was very low. Hence, the probability of seawater intrusion was inferred to be very low, and resurveying south of the Savannah River was deemed unnecessary.

2. Seaward of a coast-parallel line located about 20 miles off the Georgia/South Carolina coast, a similar stratigraphic scenario to (1) existed. Because this area is, in addition, outside of the cone of depression on the UFA, the probability of seawater intrusion due to aquitard thinning or breaching was inferred to be very low. Hence, resurveying in this inner shelf region (including the Tybee Trough) was deemed unnecessary.

3. The most important areas for detailed investigations were identified to be associated with AOCs 1-4 and adjacent areas on the South Carolina inner shelf and intracoastal zone that lie within or close to the cone of depression on the UFA. This covers the area offshore of Hilton Head and Daufuskie Islands and the intracoastal zone between Port Royal Sound and Savannah.

1. Outside of the Savannah cone of depression, the UFA is exposed at the seabed, or is only thinly covered by post-Miocene strata, along much of the lower Beaufort River east of Parris and Port Royal Islands (AOC 5 in Foyle et al., 1999). However, the potentiometric head on the UFA in this area lies between 0 and +5 feet MSL (Ransom and White, 1999). This means that the aquifer would likely be threatened by seawater intrusion for relatively short time periods during spring high tides, and less frequently by extreme tides during northeasterly storm events and hurricanes. For this reason, and in order to obtain good quality baseline stratigraphic data in case of possible future expansion of the cone of depression, it was determined that this area should be resurveyed.

GEOLOGIC FRAMEWORK

The stratigraphic and hydrogeologic units pertinent to this study are shown in Table 1-1 and briefly described below. Hydrogeologically, the section is divisible into three general units: the post-Miocene, the Miocene aquitard, and the UFA. Detailed discussions of the continually-evolving stratigraphic terminology, as well as the hydrogeology, of the Georgia/South Carolina area can be found in Siple (1969), Counts and Donsky (1963), McCollum and Counts (1964), McCollum and Herrick (1964), Furlow (1969), Hayes (1979), Hassen (1985), Miller (1985), Huddlestun (1988, 1993), Hughes et al. (1989), Krause and Randolph (1989), and Clarke et al. (1990).

Table 1-1 Hydrogeologic and stratigraphic units of the study area on the Georgia/South Carolina inner shelf and coastal zone

Post-Miocene	
Holocene	= Satilla Formation
Pleistocene	= Satilla Formation
upper Pliocene	= Raysor Formation or equivalent (Duplin)
lower Pliocene	= Wabasso Beds
Miocene Aquitard	
upper Miocene	= Coosawhatchee Formation (Miocene-A)
middle Miocene	= Marks Head Formation (Miocene-B)
lower Miocene	= Tampa Limestone or equivalent (Miocene-C)
Upper Floridan Aquifer	
Oligocene	= Suwanee Limestone or equivalent (upper Cooper / Lazaretto Creek)
upper Eocene	= Ocala Limestone

The study area lies within the regional Southeast Georgia Embayment, a broad structural depression and Meso-Cenozoic depocenter bounded to the north and south by the Cape Fear and Ocala Arches, respectively (Huddlestun, 1988). Hayes (1979) and Hughes et al. (1989) identified a southward plunging anticline extending from the Beaufort area towards Savannah that was evident on top-of-Eocene and top-of-Miocene structural contour maps. Siple (1969) originally designated this feature as the Burton High in the Parris Island area; it has also been referred to as the Beaufort Arch (Colquhoun et al., 1969; Huddlestun, 1988) which Woolsey (1976) traced along the Georgia shelf as far south as Cumberland Island. Furlow (1969) identified a local structural high on top-of-Eocene and Oligocene maps for the Tybee Island area and designated it the Tybee High. Seismic data from this study support the interpretation that the Burton and Tybee Highs are part of the larger Beaufort Arch that extends from Beaufort south-southeastward across Hilton Head and onto the inner shelf; seismic data indicate that the feature is both a structural high and an erosional remnant. Uplift affecting the UFA occurred in the SC/GA area during the late Oligocene to early Miocene (prior to deposition of Miocene-C) and again during the middle Miocene (prior to deposition of Miocene-A) (Furlow, 1969; Hughes et al. 1989). The topographically highest parts of the UFA in Beaufort County, SC, contain sinkholes (Hughes et al., 1989) that are believed to have been caused by aquifer dissolution associated with groundwater flow. Seismic data from this study suggest that buried sinkholes are developed further south along the axis of the Beaufort Arch beneath the Colleton River.

As discussed later in this report, this study utilizes a sequence stratigraphic approach to analyzing seismic records and wireline logs. The post-Miocene, Miocene aquitard, and UFA are separated from each other by subaerial erosion surfaces that formed during major falls in sea level. The Miocene aquitard is discussed in terms of its component A, B, and C units as used by Clarke et al. (1990) and shown in Table 1-1. In sequence stratigraphic terms, each of the hiatus-bounded A, B, and C units of the Miocene is inferred to be a partially preserved parasequence (Swift et al., 1991) that, when preserved in its entirety, consists of a shoaling upward succession of carbonates (at the base), clays, silts, and sands (at the top). Each of the Miocene units accumulated during a relative sea-level stillstand or regression when basin-margin clastic sediments prograded basinward over a shelf carbonate system. This inference is supported by seismic records which show basinward prograding clinoforms in the mid to upper parts of the Miocene A and B units. Throughout the study area, the Miocene-C unit is either very thin and not resolvable seismically, or has been removed by the erosional surface at the base of Miocene-B or Miocene-A. Clarke et al. (1990) indicate that Miocene-B and Miocene-C have minimal thickness over the Beaufort Arch. Existing literature and borehole data indicate that the Miocene-C unit is well developed in areas south of Chatham County (Huddlestun, 1988; Clarke et al., 1990).

The three principal hydrogeologic units pertaining to coastal groundwater resources in the study area are as follows:

(1) The Post-Miocene (Pliocene-Holocene) Unit consists of lower Pliocene to Holocene clastic deposits that can be as much as 130 feet in thickness. Holocene deposits are characterized by sand, clay and lesser amounts of gravel; Pleistocene deposits by arkosic sand and gravel containing discontinuous clay beds; and Pliocene deposits by phosphatic, micaceous and clayey sand. Pliocene strata are believed to be very thin to absent in coastal Georgia and southern South Carolina (Counts and Donsky, 1963; Herrick, 1965; Furlow, 1969; Clarke et al., 1990) but are well developed offshore and to the south (Woolsey, 1977; Kellam, 1981; Huddlestun, 1988; Henry and Kellam, 1988; Manheim, 1992; Foyle et al., 1999). However, interpreted Pliocene strata are identified in this study in an elongate embayment extending from the Savannah River northward to areas behind Hilton Head

Island and southward to areas landward of the Tybee Island shoreface. The embayment is generally bounded to the east by the flanks of the Beaufort Arch and to the west by a line extending NNW from Skidaway Island, GA, to Brighton Beach, SC; the Pliocene strata are interpreted to have been deposited in a deltaic depositional environment.

Onshore, the Pliocene-Holocene units contain a surficial aquifer that is primarily used for small-scale irrigation and rural domestic water supply (Garza and Krause, 1996). As a whole, the Pliocene-Holocene units are characterized by numerous infilled paleochannels that have incised as deep as -190 feet MSL and can extend into and through the Miocene aquitard. In areas where the Miocene deposits are absent or thin, these paleochannels may provide permeable pathways for seawater intrusion into the UFA. This is particularly the case on the inner shelf where the paleochannel fills are likely to be sand dominated as they have already passed through an active paleosurf zone during Quaternary marine transgressions; in the intracoastal area, infilling and infilled tidal channels have not yet passed through the late Holocene surf zone and would have a higher probability of being silt and mud dominated.

(2) The Miocene Aquitard (Confining Unit) is composed primarily of middle and upper Miocene clastic deposits. The dominant lithologies are low-permeability clays, silts, clayey silts and sandy or silty clays. The Miocene acts as the confining unit or "cap rock" for the UFA in the study region. Thin carbonate layers are generally present near the bases of Miocene units A and B. The Miocene deposits range in thickness from 0 feet (at localized sites of potential seawater intrusion) to over 160 feet (southwest of Savannah and in areas at least 20 miles seaward of Hilton Head and Tybee Islands). The top of the aquitard occurs at depths of -10 to -150 feet MSL (Furlow, 1969; Hughes et al., 1989; Clarke et al., 1990).

(3) The UFA is composed primarily of Oligocene and upper Eocene limestone that was deposited in carbonate bank environments. Within the upper Eocene Ocala Limestone, there is a gradual lithofacies transition from limestones to sands, silts, and clays in updip (onshore) areas. The Oligocene limestone unconformably overlies the Ocala and generally thins in a northward and westward direction. It has a maximum thickness of 110 feet southwest of Savannah (Furlow, 1969) and is absent (or extremely thin) due to erosion on the Beaufort Arch in areas north and northwest of Hilton Head Island. The top of the UFA ranges in depth from -20 feet MSL in the Beaufort area to -280 feet MSL in areas at least 30 miles offshore of Hilton Head and Tybee Islands. In a localized area about 5 miles offshore of Hilton Head, the aquifer is as shallow as -47 feet MSL.

RELATED PREVIOUS WORK

Much of the previous work on the Cenozoic section in coastal Georgia and southern South Carolina was conducted during a period when the stratigraphic framework was still being established. This affected the results of several research publications relevant to this report (Furlow, 1969; Hayes, 1979; Hughes et al., 1989; Clarke et al., 1990; and US Army Corps of Engineers, 1998). Differences concerning (1) the thickness of the onshore Miocene section and (2) depths to the top of the UFA are discussed below.

(1) The thickness of the Miocene onshore section can be derived from maps generated by Furlow (1969) that show depths to the top of the Oligocene and to the top of the Miocene in coastal

Chatham County, GA. Furlow included the Duplin Marl in the Miocene although it has since been assigned to the Pliocene (R. Weems and L. Edwards, pers. comm., 2000). Mapping the difference in elevation between these maps yields an over-estimate of the thickness of the Miocene section (Tampa Limestone equivalent, Hawthorne Formation and Duplin Marl) for land areas in coastal Chatham County; this derivative map is shown below in Fig. 1-3. Hughes et al. (1989) produced a map showing the thickness of the Hawthorne Formation for land areas in coastal Jasper and Beaufort Counties, SC; this map is shown in Fig. 1-4. Because Fig. 1-3 is a partial Pliocene-Miocene isopach and Fig. 1-4 is a Miocene isopach, the maps do not match at the Georgia/South Carolina border, and Fig. 1-3 actually shows an over-estimate for the Miocene. Nevertheless, both maps provide useful information on Miocene thickness in land areas that could not be surveyed during this study. They also provided input to the Miocene isopach map prepared for this study which was derived from geophysical data collected in navigable waterways.

(2) The top of the UFA has been mapped in southern South Carolina by Hayes (1979). Hughes et al. (1989) produced a similar map, based on an updated dataset. Both workers used a pronounced gamma-log peak on wireline records to pick the top of the UFA (Principal Artesian Aquifer). In coastal Georgia, Furlow (1969) produced a map showing elevations of the top of the Oligocene. Clarke et al. (1990) produced a map showing depths to the gamma-C marker horizon which is synonymous with the base of the Miocene section and the top of the Oligocene (UFA in coastal Georgia). These Georgia maps agree closely with each other and with the top-of-Floridan identified by the US Army Corps of Engineers (1998) in the Savannah River area, but do not agree with either the Hayes (1979) map or the Hughes et al. (1989) map at the Georgia/South Carolina border.

The discrepancy between the Georgia and South Carolina maps appears to be due to the lack of borehole data south of the north end of Daufuskie Island SC in the Hayes (1979) and Hughes et al. (1989) reports; this would have resulted in less accurate contouring in this area. Additionally, Hayes indicated that the Principal Artesian Aquifer (i.e., UFA) consisted of the middle Eocene Santee Limestone and the lower part of the upper Eocene Cooper Formation (Marl). Oligocene strata were thus not recognized as being part of the aquifer. In areas where the Oligocene is absent north and northwest of Hilton Head Island, this assumption is not problematic and the Hayes map agrees closely with the top-of-aquifer map prepared for this report. However, in areas south of the May River behind Hilton Head Island, where this study indicates a progressive thickening of the Oligocene section, the depth to the top of the UFA shown by Hayes (1979) and Hughes et al. (1989) would be greater than that indicated by this study and the work of Furlow (1960) and Clarke et al. (1990). This may be the reason why the maps by Hayes and Hughes et al. appear to correlate with the contour map of the gamma-D marker (top Eocene/base Oligocene, i.e. intra-UFA) rather than with the gamma-C marker (top of the UFA) in Clarke et al. (1990). In general, the top-of-aquifer map of this study (Fig. 3-1) agrees closely with those of Furlow (1969), Clark et al. (1990), and the US Army Corps of Engineers (1998) in coastal Georgia, and with those of Hayes (1979) and Hughes et al. (1989) in South Carolina north of the Oligocene pinchout line.

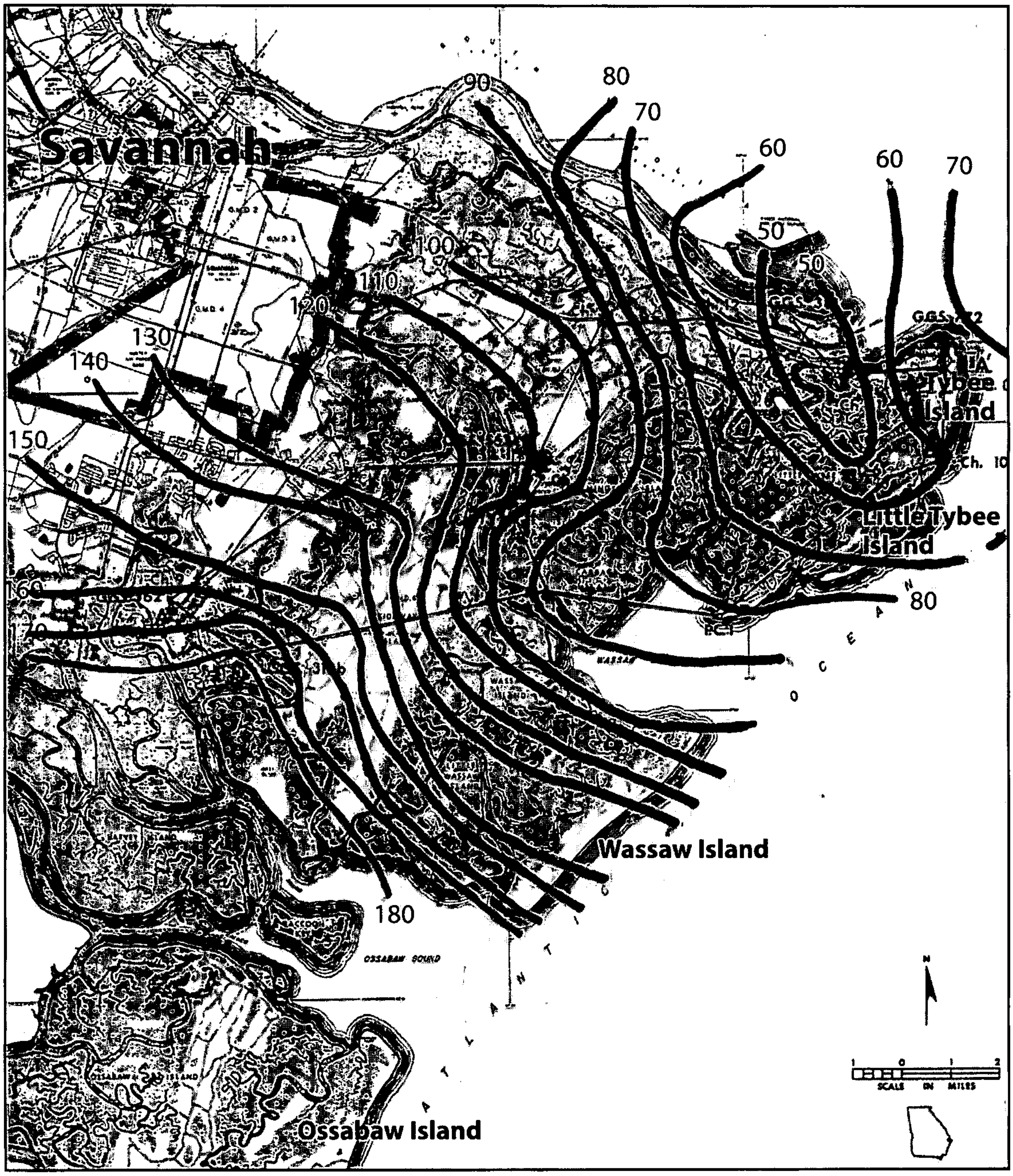


Figure 1-3 Map showing the thickness of the Miocene aquitard in Chatham County, Georgia. The map was derived by subtracting the top-of-Miocene and top-of-Oligocene maps of Furlow (1969). The Miocene comprises the lower Miocene (Tampa Limestone equiv.), the middle Miocene (Hawthorne Formation), and the (then) upper Miocene Duplin Marl. Since the Duplin Marl has since been assigned to the Pliocene, these isopachs over-estimate the thickness of the Miocene and do not match the Miocene isopach map of Hughes et al. (1989) for adjacent parts of South Carolina (see Fig. 1-4).

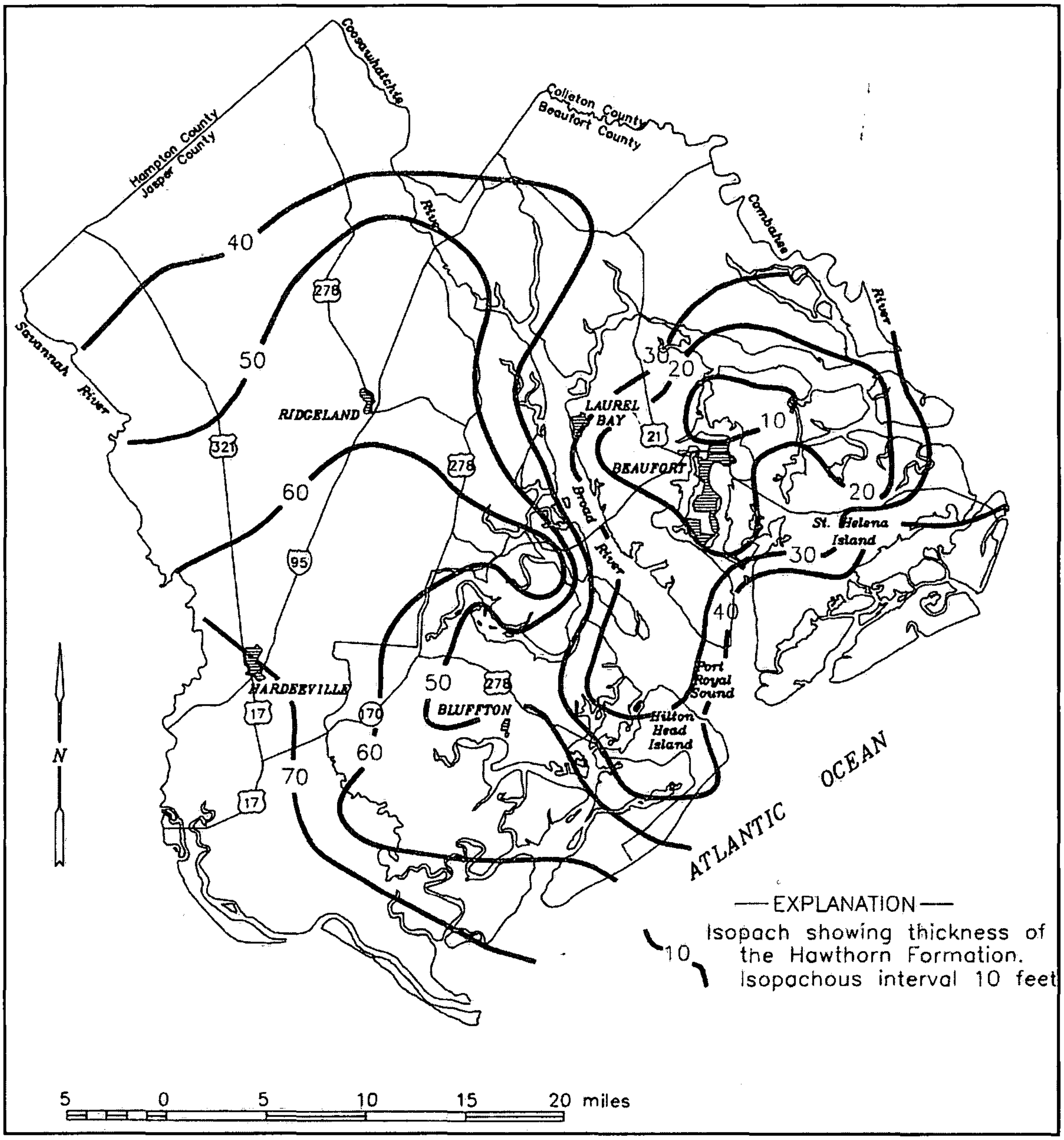


Figure 1-4 Map showing the thickness of the Miocene aquitard in southern South Carolina. The map is adapted from Hughes et al. (1989) and shows the thickness of the middle Miocene Hawthorne Formation (excludes the Duplin Marl).

PART 2: DATA ACQUISITION AND PROCESSING

DATA ACQUISITION

Data Coverage

Figure 2-1 and Plate 2-1 show the trackline locations for Phase I archive data (800 miles) and the new data (415 miles) that form the primary basis upon which the observations made in this report are based. Table 2-1 summarizes information on line coverage and quality for the new data. Appendix A summarizes information on line coverage and quality for the Phase I archive data that were used initially in the Phase I report (Foyle et al., 1999) and subsequently incorporated in this report. Appendix B contains a spreadsheet that shows the type of georeferenced stratigraphic data that was generated during this investigation. The full 6x6700-cell spreadsheet (available upon request from EPD) includes latitude, longitude, water depth, depth to the top of the Upper Floridan aquifer (UFA), and thickness of the Miocene aquitard for all sampled points along all geophysical tracklines in this study, as well as for all borehole sites that were utilized in this report. Appendix C contains information on the vertical and horizontal accuracies of the data used in this report.

Of the 1215 miles of subbottom geophysical data within the study area, 515 miles of trackline cover the intracoastal area (landward of the barrier islands) while 700 miles of trackline cover the inner shelf (Fig. 2-1). Eighty-five percent (1015 miles) of the data was of sufficient quality to permit identification of the top of the UFA and the thickness of the Miocene aquitard (Fig. 2-1). Interpretable data ranged from depths of between 4 and 200 feet below Mean Sea Level (-4 to - 200 feet MSL). Almost all of the low-quality data were archive data collected with a deep-penetration, low-resolution airgun (Appendix A).

Data Collection

Appendix A summarizes information on the archive (1970-1997) data used in the Phase I report (Foyle et al., 1999). New sub-bottom data were collected between May 1999 and April 2001 using a state-of-the-art Applied Acoustic Engineering® source/receiver system and a Triton Elics International (TEI)® digital acquisition and processing system. Georeferencing was achieved with Trimble DGPS ® and Northstar DGPS® differential global positioning systems. Data collection platforms were a 72-foot UNOLS vessel (*RV Blue Fin* ,wooden hull) operated by the Skidaway Institute of Oceanography and a 30-foot vessel *(RV Sea Otter*, aluminum hull) operated by Savannah State University. Survey speeds averaged 4 knots; in intracoastal creeks and inlets, survey speeds were occasionally as high as 6 knots when moving with the tide and as low as 2 knots when moving against tides. Table 2-1 summarizes coverage and data quality information for the new surveys.

The subbottom profiling hardware used in new surveys was an Applied Acoustic Engineering® boomer system. It consisted of a 1000 joule capacitor unit as the energy source, a towed catamaran-mounted boomer plate to emit the acoustic pulse into the water column, and a towed eight-element, single channel, linear hydrophone array to detect acoustic signals returning from the subbottom. This state-of-the-art, lightweight (~250 pounds) system was portable and compact enough to be operated off large and small boat platforms for surveys in both intracoastal creeks and offshore areas.

The 220 volt capacitor unit was powered either by ship's power (*RV Blue Fin*) or by a 5 kilowatt Honda® gas-powered generator (*RV Sea Otter*). The system was operated at a 200 joule energy setting with a firing rate of two shots/second. The returning acoustic signals were typically band-pass filtered between 750 and 3000 Hertz. The catamaran and hydrophone array were typically towed 100-200 feet behind the survey vessel and were located 12-15 feet on either side of the center line (i.e., a 25-30 foot lateral separation).

All signal acquisition and processing was conducted using TEI Delph Seismic® software (Versions 1.37 and 2.10) in a Windows NT® environment. During surveying, Delph Seismic® digitally sampled the analog seismic reflection data, displayed the data real-time on a high-resolution monitor, and simultaneously wrote the data to a magneto-optical (M/O) disk for permanent storage in digital format. An EPC-1086/500® thermal printer plotted the data as hard copy on 9-inch/130-foot rolls of plastic film. The EPC-1086/500® is an industry-standard paper/film recorder for printing analog and digital sonar/subbottom data. Because of triggering difficulties, data collected on line MAS1L1 (see Table 2-1) were controlled by the EPC-1086/500® thermal printer and recorded only in analog form on plastic film; all of the pre-1997 archive data are in analog form only and printed on paper. Digital storage of new survey data on M/O disks allowed data to be replayed and reprocessed (typically filter, gain, and scale adjustments) in the lab if further manipulation was needed to clarify specific subbottom features.

New sub-bottom data was georeferenced with Trimble® or Northstar® Differential Global Positioning Systems (DGPS). During surveys, satellite configurations were periodically monitored and low PDOP values indicated that all positioning was accurate to within three or four meters (10 - 13 feet). Prior to each new geophysical survey, planned tracklines were plotted into Nobeltec® DGPS/chart navigation software that was run on a laptop computer. This allowed for effective cruise planning and for contingency planning when adverse weather hindered surveying in pre-planned areas.

TEI Delph Seismic® automatically annotated the digital data files (stored on magneto-optical disk) and the hardcopy plastic-film printouts to show time, latitude, and longitude at user-defined intervals (typically one or two minutes). The latter information was input to TEI Delph Seismic® as an NMEA-183 data string from either the *RV Blue Fin's* onboard Trimble DGPS® navigation system or from a portable Northstar 951D DGPS® when surveys were run off the *RV Sea Otter*. Coordinates from the DGPS systems were updated once every two seconds, or every seven feet at typical survey speeds of four knots. Data records were typically annotated at one- or two-minute intervals which corresponded to a ground distance of 400 or 800 feet at typical survey speeds of four knots.

DATA PROCESSING

Data Reduction and Presentation

The seabed and *Reflectors 1* through *5* identified on the seismic records (see Part 2: Seismic Sequence Stratigraphy) were sampled for elevations at horizontal intervals of 300-600 feet (i.e., every 100 shotpoints and/or at every DGPS annotation on the record) and at all points of significant elevation and/or aquitard thickness change. For each sample location, the two-way-travel times to the seabed

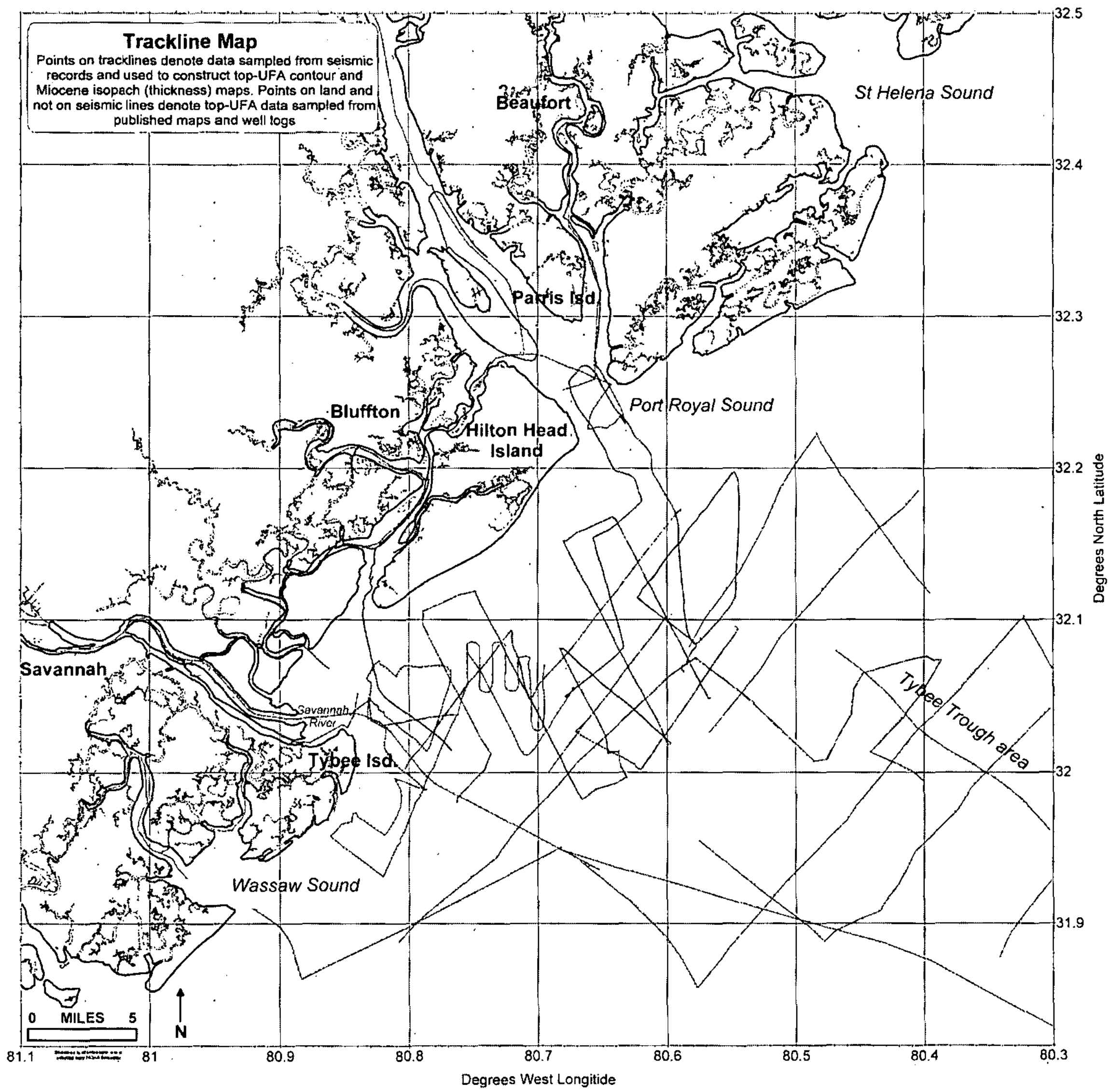


Figure 2-1 Locations of seismic-reflection tracklines. Each dot denotes a sample point where depths and thicknesses were determined for use in cross sections and contour maps. See Plate 2-1 for larger-scale map.

and to *Reflectors 1* through *5* were measured. The latitude and longitude of each sample point was obtained directly from the DGPS annotations or interpolated if the sample site lay between two DGPS fixes.

All data were tabulated into a Corel QuattroPro® spreadsheet. Acoustic travel times (milliseconds) measured from the graphic records were converted into depths (feet) using standard inferred velocities for the water and sediment columns of 4922 feet/sec and 5578 feet/sec, respectively (Appendix C). A slant-path correction was applied to correct for non-vertical incidence of the acoustic pulse at the seabed (due to the 25-30 foot lateral spacing between the catamaran/boomer plate and the hydrophone array). Depths to the seabed and subbottom reflectors were also corrected to mean sea level (MSL) by adding or subtracting a tidal correction obtained from the NOAA tidal station at Fort Pulaski (NOAA, 2000) or from Tides&Currents® software. Tides at Fort Pulaski closely approximate tide levels throughout the study area and a complete dataset of tidal elevations exists with a 6-minute update interval. To make archive Phase I data compatible with the new data in this report, similar depth conversion, slant path correction, and tidal correction procedures were performed on both datasets.

Selected data from the spreadsheets were used to generate distance versus depth cross-sections along tracklines (see Part 3: Study Findings). Selected data from the spreadsheets were also imported into Golden Software's Surfer® contouring program to build a 6700x6-cell spreadsheet matrix containing latitude, longitude, water depth, depth to top of the UFA, and thickness of the Miocene aquitard. The sub-bottom geophysics data set was augmented with additional XYZ data from land areas by "sampling" maps from Hayes (1979) and Clarke et al. (1990) to obtain UFA depths distant from navigable waterways; published drill data were also used to augment the data set. The dataset was then computer contoured to produce structural contour maps for the top of the UFA and isopach (thickness) maps for the Miocene aquitard at approximately 1:100,000 and 1:400,000 scales. Because Surfer® contouring did not work well with the isopach data, the Miocene ispoach map (Plate 3-2b) was generated by manually contouring binned (10-foot isopach bins) isopach data points (Plate 3-2a). The principal problem with Surfer® contouring of the Miocene aquitard was the inability of the program to deal effectively with several complex (and cross-cutting) generations of post-Miocene drainage networks that incise into the Miocene; this problem was exacerbated by unrelated thinning and thickening of the Miocene associated with significant variation in the topography of its lower karstic bounding surface. Contouring was thus performed manually while being cognizant of the dimensions and probable trends of paleochannel features influencing the shape of the upper boundary of the Miocene section, as well as the unrelated variability in the topography of the top-UFA reflector which influenced the shape of the lower boundary of the Miocene section. Each data point in Plate 3-2a, the Miocene isopach map, is the location of a measured Miocene thickness value obtained from the Surfer® data set. Areas where data quality were not good enough to allow identification of both the top and base of the Miocene are shown either as open circles (null values) or as blanks (where the isopach values are estimated based on adjacent data).

Data in this report are graphically presented in Part 3 in two formats. Geologic cross-sections generated in QuattroPro® show structural and stratigraphic information for *Reflectors 1* through *5* in coast-parallel and coast-normal orientations. Maps generated in Surfer® (and CorelDraw®) show trackline coverages across the coastal zone and inner shelf (Fig. 2-1, Plate 2-1), the topography of the top-UFA unconformity (Fig. 3-1, Plate 3-1), classed isopach values (Plate 3-2a), the thickness of the Miocene aquitard (Fig. 3-2, Plate 3-2b), and sites susceptible to seawater intrusion (Figs. 3-3 to 3-18).

Data Interpretation Methods

Standard methods of seismic sequence analysis and seismic facies analysis were used in data interpretation (Mitchum and Vail, 1977; Mitchum et al., 1977a,b; Vail et al., 1977a,b; Vail, 1987). This sequence stratigraphic approach uses the principle that sedimentary basin fills are divisible into genetic packages that are bounded by unconformities and their correlative conformities (Swift et al., 1991). This approach permits analysis of the stratigraphic record, and mapping of stratigraphic units, within a chronostratigraphic framework: the seismic reflection data used in this report are very amenable to this approach. Major unconformities, or erosional sequence boundaries, were identified at the top of the Floridan Aquifer System (generally the Oligocene Suwanee Limestone, or the Eocene Ocala Limestone in the northern part of the study area) and at the top of the Miocene Hawthorne Group (which is the confining unit above the UFA). These top- UFA and top-aquitard unconformities correspond to the base and top of the Miocene aquitard, respectively. The reflectors were picked on seismic records in areas with good well control (such as the Savannah River area) and were also directly correlatable ("ground truthed") with newer wells drilled offshore of Hilton Head Island during 1999 and 2000 by the USGS, the U.S. Army Corps of Engineers, and the South Carolina Department of Health and Environmental Control (see Part 2: Supporting Borehole Data, Maps, and Sections). The generally prominent reflectors associated with these and other unconformities were cross-tied between intersecting seismic lines and "carried" throughout the study area using patterns of truncation and onlap to facilitate identification. This method allowed stratigraphy to be established, and the Miocene aquitard and the top-of- UFA to be mapped, in areas away from direct well control.

Seismic Sequence Stratigraphy

From top to base of section, five principal sub-bottom reflectors were identified on seismic records and are shown schematically in Fig. 2-2. These reflectors are correlated with erosional surfaces that occur at or near the tops of specific stratigraphic intervals described on Pages 19 and 20.

Reflector 1:

Reflector 1 marks a high-relief (lowstand) erosional surface at the base of the Quaternary section. It is associated with an unconformity that was cut during the most recent lowstand of sea level when fluvial systems such as the Savannah and Broad Rivers incised the continental shelf. *Reflector 1* truncates subjacent strata (high-angle and low-angle truncation), while younger strata typically onlap the reflector. Depths to *Reflector 1* are important in areas where the associated unconformity has removed subjacent Pliocene deposits. In these situations, *Reflector 1* defines the top of the Miocene aquitard and may locally define the top of the UFA if intervening Miocene sediments have also been removed by erosion. *Reflector 1* is locally removed in areas where the modern seabed has cut down through the Quaternary section at inlets and creeks.

Reflector 2:

Reflector 2 marks a low- to high-relief (lowstand) erosional surface at the base of the Pliocene section. It is associated with an unconformity that was cut during a late Miocene/early Pliocene lowstand of sea level. *Reflector 2* shows high-angle and low-angle truncation of subjacent strata; younger strata typically onlap the reflector. *Reflector 2* generally overlies Miocene Unit-A (Upper Miocene Coosawhatchie Formation), but overlies Miocene Unit-B (Middle Miocene Marks Head Formation) where the former has been removed by erosion; it

Table 2-1 Summary information for new seismic data for coastal Georgia and South Carolina. Key: G=Good; M or Mod=Moderate; P=Poor. MAS=Miocene Aquitard Study; GMT= Greenwich Mean Time. See Appendix A for details on Phase I data.

Line # / ID	Survey Date	Length / Time of Survey	Surveyed Area	Data
MAS1 L1	5.6.99	22 miles/ 17:58-22:24 GMT	Offshore of Hilton Head Island	Mod
MAS2 L1	6.11.99	12 miles / 17:55-20:46 GMT	Offshore of Hilton Head Island	Mod
MAS2 L2A	6.10 - 6.11.99	6 miles / 23:09-00:47 GMT	Cooper River to May River	Good
MAS2 L2B	6.11.99	7 miles / 01:20-03:00 GMT	May River to Chechessee River	Good
MAS2 L2C	6.11.99	10 miles / 03:13-05:36 GMT	Chechessee River (Skull Creek) to Colleton River (Copp Landing)	Good
MAS2 L2D	6.11.99	17 miles / 07:19-11:17 GMT	Broad River (Skull Creek) to Cooper River (Ribbon Creek)	Good
MAS3 L1A	7.27.99	13 miles / 16:05-18:24 GMT	Offshore of Hilton Head Island	Good
MAS3 L1B	7.27.99	20 miles / 18:24-21:16 GMT	Offshore of Hilton Head Island	Good
MAS3 L1C	7.27.99	18 miles / 21:16-24:00 GMT	Offshore of Hilton Head Island	Good
MAS3 L1D	7.27 - 7.28.99	11 miles / 24:00-01:45 GMT	Offshore of Hilton Head Island	Good
MAS3 L2	7.28.99	9 miles / 03:24-04:15 GMT	Offshore of Hilton Head Island	Good
MAS4 L1	1.5.00	13 miles / 19:54-22:58 GMT	Cooper River to Broad Creek	Poor
MAS4 L2	1.6.00	14 miles / 15:46-18:43 GMT	Calibogue Creek to Mackay Creek	Good
MAS4 L3	1.6.00	7 miles / 20:17-21:45 GMT	Bull Creek and Cooper River to Ramshorn Creek	M-G
MAS5 L1	3.9.00	10 miles / 16:39-19:12 GMT	Savannah Navigational Channel to Calibogue Sound	Good
MAS5 L2	3.9.00	3 miles / 19:52-20:30 GMT	Savannah Navigational Channel to Tybee Island	Good
MAS6 L1	4.10.00	15 miles / 15:16-19:17 GMT	Tybee Island shoreface	M-G
MAS6 L2	4.10.00	10 miles / 19:30-21:56 GMT	Tybee Island shoreface	Mod
MAS6 L3	4.11.00	16 miles / 13:38-17:34 GMT	Daufuskie Island shoreface	Mod
MAS6 L4	4.11.00	7 miles / 17:47-18:55 GMT	Savannah River Channel	Poor
MAS7 L1	5.9.00	29 miles / 14:30-19:34 GMT	Savannah River to Bluffton	Good
MAS7 L2	5.9.00	6 miles / 20:50-22:05 GMT	Broad Creek, Hilton Head Island	Good
MAS7 L3A	5.10.00	11 miles / 15:50-18:17 GMT	Port Royal Sound entrance area	Poor
MAS7 L3B	5.10.00	15 miles / 18:17-20:44 GMT	Port Royal Sound to Beaufort	Good
MAS7 L4A	5.11.00	10 miles / 13:37-16:35 GMT	New River upstream	Good
MAS7 L4B	5.11.00	6 miles / 17:00-18:01 GMT	New River and Intracoastal waterway at Daufuskie Island	Good
MAS7 L5	5.11.00	10 miles / 18:33-20:29 GMT	Daufuskie shoreface to Wright River	Good
MAS8 L1	7.27.00	21 miles / 11:22-15:22 GMT	Hilton Head shoreface	Good
MAS8 L2	7.27.00	14 miles / 15:22-17:51 GMT	Port Royal Sound & Navigation Channel	Good
MAS8 L3	7.27.00	19 miles / 17:51-22:09 GMT	Navigation Channel & Hilton Head shoreface	Good
MAS9 L1,2,3	2.08.01	37 miles / 16:02-23:52 GMT	Offshore of Hilton Head Island	Good

overlies the UFA where both Miocene-A and Miocene-B have been eroded. Locally, therefore, *Reflector 2* may define the top of the UFA in areas where the intervening Miocene sediments have been removed. In some areas, the modern seabed or the unconformity associated with *Reflector 1* have removed *Reflector 2.*

Reflector 3:

Reflector 3 marks a low-relief erosional surface near the base of Miocene Unit-A and marks the approximate top of the Miocene Unit-B (Middle Miocene Marks Head Formation). Younger strata onlap the reflector while older strata show a conformable to low-angle truncation relationship. *Reflector 3* was picked as the lower reflector of a prominent "rail-track" reflector pair. This reflector pair was a distinctive key marker horizon over large parts of the study area. *Reflector 3* marks the top of the UFA in areas where Miocene Unit-B is absent. *Reflector 3* is locally truncated by the modern seabed or by the unconformities associated with *Reflectors 1 and 2.* Topographic highs on *Reflector 3* tend to have a jagged character suggestive of karst development.

Reflector 4:

Reflector 4 marks a low-relief erosional surface near the base of Miocene Unit-B. In sequence stratigraphic terms, it marks the basal sequence boundary for the Miocene section in the study area. Miocene reflectors downlap this reflector which in turn truncates reflectors in the subjacent aquifer. *Reflector 4* thus marks the approximate top of the UFA (the Oligocene Suwanee Limestone, or the Eocene Ocala Limestone where the former is absent). Topographic highs on *Reflector 4* occur where there is upwarping of the subjacent aquifer limestone, such as along the trend of the Beaufort Arch. A jagged character to the reflector on these highs suggests karst development. *Reflector 4* is often truncated by *Reflector 3* and the intervening Miocene-B is consequently absent. Locally, *Reflector 4* is also truncated by the modern seabed and by unconformities associated with *Reflectors 1, and 2.*

Reflector 5:

Reflector 5 marks a low-relief erosional surface between the Oligocene Suwanee (or Lazaretto Creek) Limestone and the subjacent Eocene Ocala Limestone. Low-angle onlap of Oligocene strata is observed above the unconformity and *Reflector 5* in turn shows very low-angle truncation of underlying Eocene strata. In areas where the Oligocene is absent, *Reflector 5* is truncated by unconformities associated with *Reflectors 4* and *3.*

Reflectors 3 and *4* are inferred to correlate with geophysical gamma-log marker horizons A and B, respectively, as used by Clarke et al. (1990). The gamma-A and gamma-B marker horizons are typically associated with indurated, high-phosphate, carbonate beds that generally lie just above the Miocene-A and the Miocene-B basal unconformities, respectively (Furlow, 1969; Clarke et al., 1990). As shown schematically in Fig. 2-2, Miocene-C (see Clark et al., 1990) was not differentiated in this study. It is inferred to be absent or only partly preserved over most of this intracoastal and inner shelf area, and has likely been removed by the erosional surface associated with *Reflector 4* (at the base of Miocene-B) or *Reflector 3* (at the base of Miocene-A). If patchily preserved, Miocene-C is not resolvable seismically either because it is too thin (see Clarke et al., 1990, p. 11-12) or because a reflection may not be occurring at the Miocene-B/Miocene-C contact. The inference concerning the absence or patchy distribution of Miocene-C is supported by (1) Clarke et al. (1990) who indicated that Miocene-B and Miocene-C have minimum thicknesses over the Beaufort Arch and northeastern Chatham County,

(2) seismic data from the lower Savannah River which was interpreted by the U.S. Army Corps of Engineers to show the absence of Miocene-C (U.S. Army Corps of Engineers, 1998), and (3) data that indicate that Miocene-C becomes thicker to the southwest of Chatham County where it has been mapped by Huddlestun (1988) and Clarke et al. (1990). Regardless of the uncertainty concerning the presence or absence of Miocene-C in the study area, *Reflector 4* is mapped as the base of the Miocene section except in those areas where it has been removed by *Reflector 3*.

In the Port Royal Sound area, Colquhoun (1972) noted the presence of a cherty, occasionally phosphatic, resistant horizon (as much as 2 feet thick) at the base of the Miocene section immediately above the aquifer. Hughes et al. (1989) suggested that this "cap rock" is part of the Eocene Ocala limestone, while Duncan (1972) suggested that a top-aquifer reflector on his seismic data from the Port Royal Sound area was likely associated with this horizon. Consequently, *Reflectors 3* and *4* in places may be occurring at the thin carbonate horizon rather than at the subjacent unconformity; hence use of the terms "near" and "approximate" in the above reflector descriptions. *Reflectors 2* through *5* of this study are synonymous with Reflectors 1 through 4, respectively, as used by the U.S. Army Corps of Engineers (1998).

The following discussion summarizes the appearance on the seismic records of the hydrogeologic units of this study. Details on lithology, thickness, and depths of occurrence for these units are described in Part1: Geologic Framework.

Post-Miocene (Pliocene-Holocene) Unit:

This unit is developed between the seabed and *Reflector 2* (Fig. 2-2). Its seismic character is strongly influenced by several major changes in sea level that are known to have occurred during the past 2-5 million years. The unit generally consists of several different reflector types and patterns that are characteristic of, and consistent with, the fluvial, estuarine, intracoastal, and inner shelf depositional environments within which these strata are known to have accumulated. The post-Miocene seismic section in general is dominated by channel-fill features beneath the inner shelf and particularly in the intracoastal area where late Pleistocene channel features have not yet been removed by the Holocene transgression. The larger channel-fill features are generally associated with the Savannah and Broad river systems, while smaller channel-fill features are associated with paleotributaries, paleoinlets, and paleotidal creeks. Large paleochannel features are present beneath the Tybee Trough area and beneath the southern end of Hilton Head Island. Stacked paleochannel horizons within the post-Miocene section indicate a record of at least three sea-level cycles and at least three depositional sequences.

Onshore, interpreted Pliocene strata (for which there is limited core evidence) are partly preserved and appear as a seismically quiet opaque unit, occasionally with very faint subparallel internal reflectors. Paleochannel-associated reflector patterns are generally absent onshore. The base of this Pliocene unit is defined by *Reflector 2* which is generally a less crenulated surface (crenulations being due to paleochannel development) than *Reflector 1*. Offshore, however, the Pliocene has paleochannel-associated reflector patterns present in the Tybee Trough area.

Miocene Aquitard (Confining) Unit:

This unit is developed between *Reflectors 2 and 4* and can be subdivided into an upper and a lower seismic unit that are inferred to be correlative with Miocene-A and Miocene-B, respectively (Fig. 2-2). The hiatus-bounded Miocene-A and Miocene-B are inferred to be partially preserved parasequences that, when preserved in their entirety, consist of a shoaling upward succession of carbonates (at the base), clays, silts, and sands (at the top). Each of the Miocene units is inferred to have accumulated during a relative sea-level stillstand or regression when basin-margin clastic sediments prograded basinward over a shelf carbonate system. Just offshore of Hilton Head and Tybee Islands, seismic records show basinward prograding clinoforms developed in the mid to upper parts of both the Miocene A and B units. Clinoforms typically downlap subjacent *Reflectors 3 and 4*, respectively, in a basinward (seaward) direction. Farther basinward, the clinoform pattern evolves into shingled, parallel, and sub-parallel reflector patterns indicative of more distal sedimentary facies. At the base of Miocene-A, *Reflector 3* is generally a very pronounced reflector and may be associated with limestone layers at the base of the unit rather than specifically with the unconformity at the base of the unit. Similarly, strong and discontinuous reflectors near the base of Miocene-B may be associated with discontinuous limestone strata located above the unconformity associated with *Reflector 4*.

Miocene-A in offshore areas is characterized by strong, continuous, parallel and subparallel reflectors throughout the unit. The reflectors may be associated with phosphatic horizons which are known to occur in this unit. Beneath Miocene-A, Miocene-B is generally seismically "quiet" offshore and easily distinguishable from Miocene-A. Faint parallel and subparallel reflectors are generally present; reflectors at the base of the unit downlap *Reflector 4*.

Upper Floridan Aquifer (UFA):

The top of the UFA is most commonly marked by the base-Miocene unconformity associated with *Reflector 4* (Fig. 2-2). Within the aquifer, Oligocene carbonates disconformably (*Reflector 5*) overlie Eocene carbonates. Both Oligocene and Eocene strata are characterized by very continuous parallel and sub-parallel reflectors. In updip areas behind Hilton Head Island where the Oligocene is thin, the base of the Oligocene "pinchout wedge" is marked by large mound-shaped reflector patterns which may be indicative of reef formation above the base-Oligocene *Reflector 5*.

Supporting Borehole Data, Maps, and Sections

Published borehole lithology-log and gamma-log data from coastal Chatham and Beaufort Counties and from offshore were used to ground-truth seismic stratigraphic interpretations and reflector picks. These data were obtained from Counts and Donsky (1963), Furlow (1969), Colquhoun (1972), Burt and Belval (1987), Hughes et al. (1989), Clarke et al. (1990), Manheim (1992), and Huddlestun (1993). New (unpublished) borehole gamma-log data from intracoastal South Carolina and adjacent shelf waters were also used for ground-truthing and were provided by South Carolina Department of Health and Environmental Control, U.S. Army Corps of Engineers, and USGS. Published maps and cross-sections were also used to ground-truth the seismic data set and were obtained from Duncan (1972), Woolsey (1976), Hayes (1979); Kellam (1981), Henry and Rueth (1986), Kellam and Henry (1987), Clarke et al. (1990), and Henry and Idris (1992). The selected borehole and onshore map data were generally added to the Surfer data set prior to contouring and helped to constrain maps in areas distant from navigable waterways (Figs. 3-1, 3-2b).

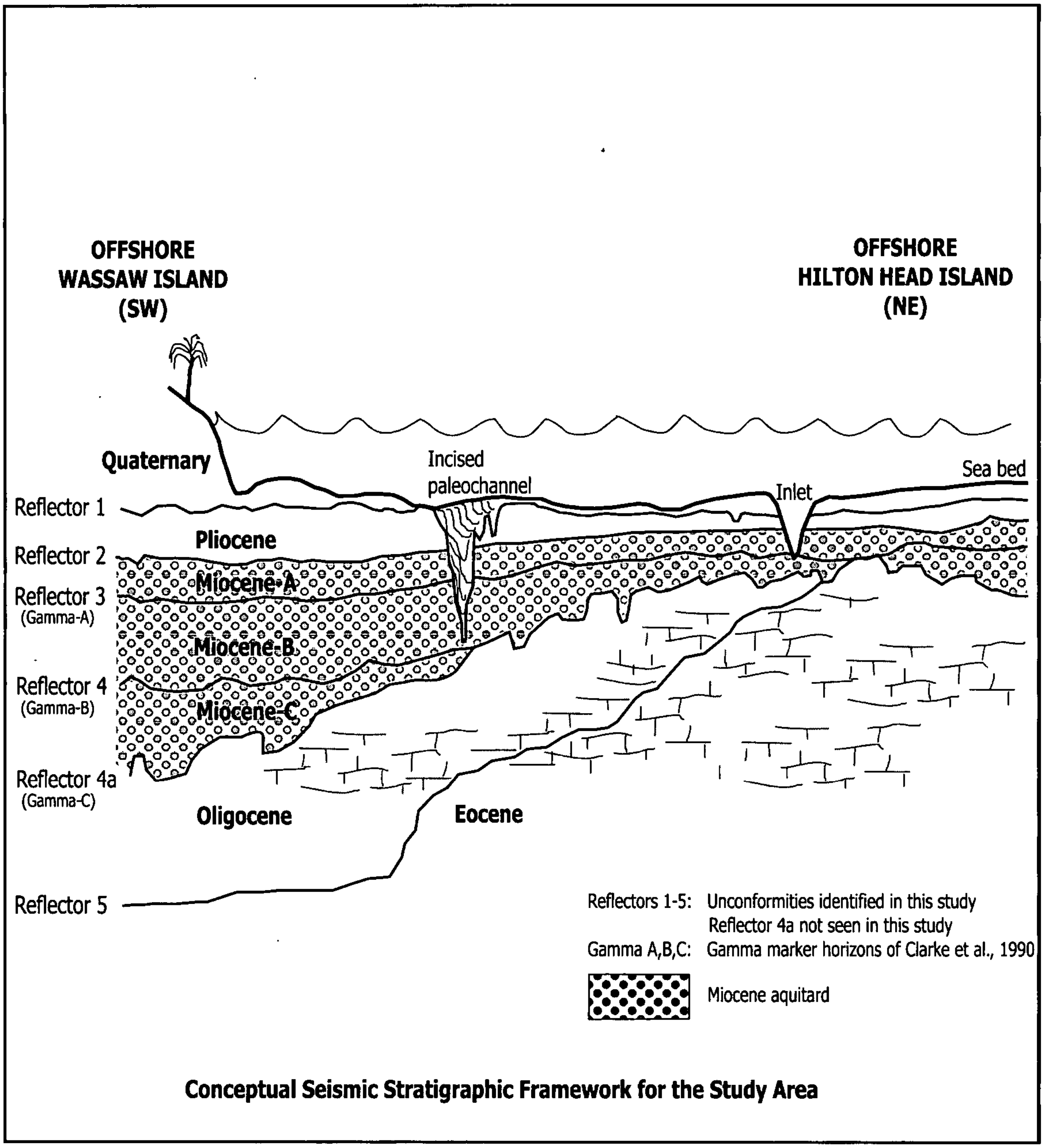


Figure 2-2 Schematic illustration of the stratigraphic framework of the UFA, the Miocene aquitard, and the post-Miocene section in northern coastal Georgia and southern coastal South Carolina. Section is oriented approximately parallel to the coast.

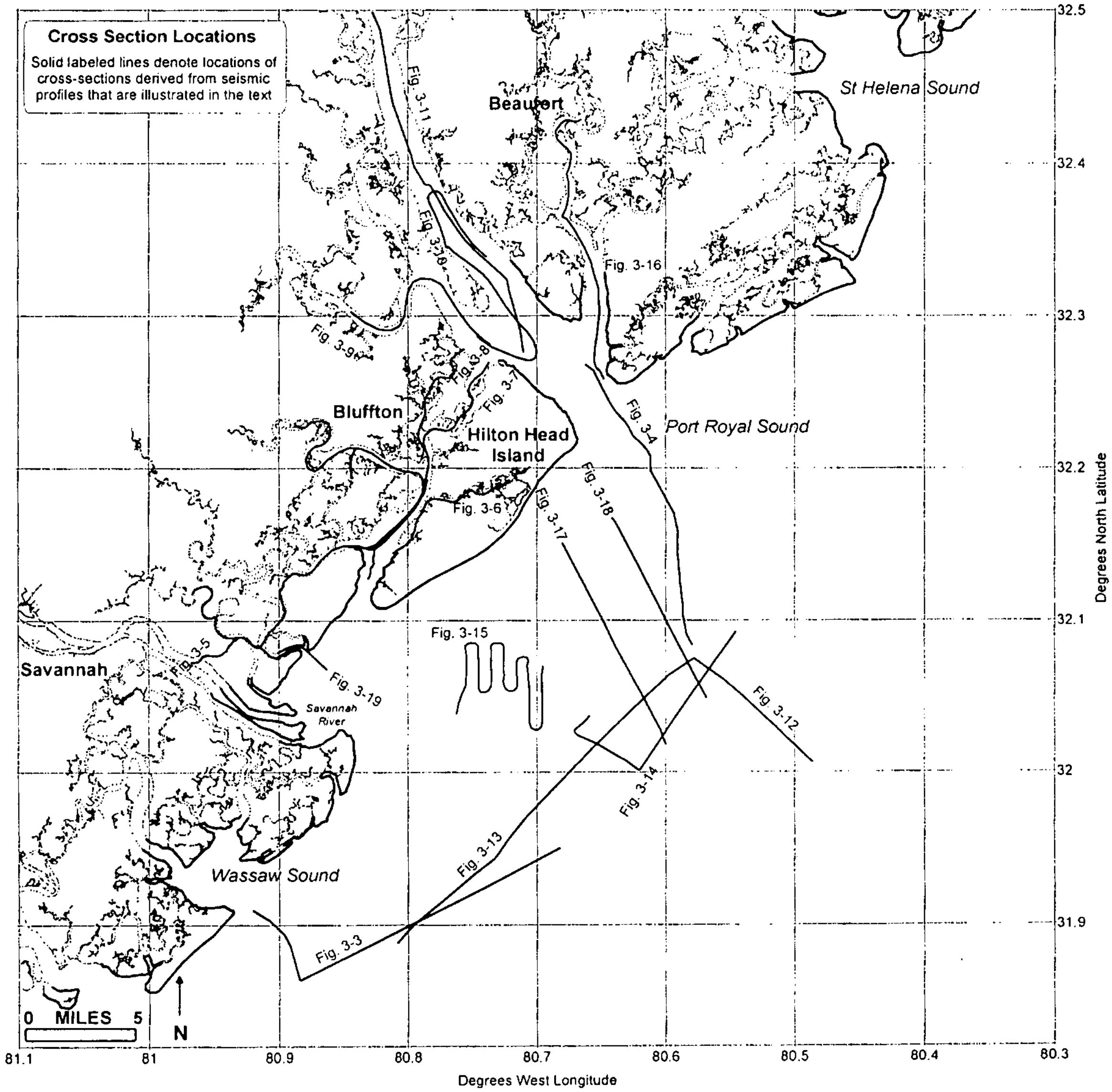


Figure 2-3 Locations of seismic-stratigraphic cross sections used in Part 3 of this report.

PART 3: STUDY FINDINGS

SEISMIC-STRATIGRAPHIC RELATIONSHIPS

Geometry of the top of the Upper Floridan aquifer (UFA)

The uppermost part of the UFA in the study area consists of either the Oligocene Suwanee Limestone or the Eocene Ocala Limestone. In intracoastal areas to the north of Calibogue Sound and landward of Hilton Head Island and Port Royal Sound, the Oligocene pinches out onto the subjacent Eocene so that the unconformably overlying Miocene aquitard generally rests directly on Eocene limestone. The upper surface of the UFA, which marks the contact with the overlying aquitard, is marked by *Reflector* 4, or by *Reflector 3* where Miocene-B has been eroded (Fig. 2-2).

Depths to the top of the UFA (derived from the seismic data and ground-truthed with drill hole data) are shown in Fig. 3-1 and Plate 3-1. Depth contours in areas distant from navigable waterways were obtained by "sampling" top-of-UFA contours from maps available in Hayes (1979) and Clarke et al. (1990). Depths to the top of the UFA range from as shallow as -19 feet MSL in the vicinity of Ladies Island north of Beaufort, S.C. (Johnson and Geyer, 1965; Duncan, 1972; Hayes, 1979; Hughes et al., 1989), to as deep as -260 feet MSL southwest of Savannah, GA, and -280 feet MSL southeast of the study area (Fig. 3-1, Plate 3-1). The irregular "karstic" erosional surface defining the top of the UFA generally dips southeastward and southwestward away from the Beaufort Arch. Locally, karstic relief can be as much as 20 feet over horizontal distances of as little as 300 feet (1:15 slope). Throughout intracoastal and offshore Georgia, the UFA everywhere lies at depths of at least -100 feet MSL. However, on the South Carolina shelf, the Beaufort Arch passes seaward beneath Hilton Head Island so that the UFA is shallower than -60 feet MSL in an area located 3 to 7 miles offshore and to the southeast of central Hilton Head Island. Shallowest elevations on this offshore high are about -48 feet MSL, in an area located about 3.5 miles offshore (Fig. 3-1, Plate 3-1). In the Phase I report (Foyle et al., 1999), the topographically high part of the UFA offshore of Hilton Head was informally referred to as the Hilton Head High. Seismic data indicate that the Beaufort Arch is both a structural high and an erosional remnant. Uplift affecting the UFA occurred in the South Carolina/Georgia area during the late Oligocene to early Miocene (prior to deposition of Miocene-C) and again during the middle Miocene (prior to deposition of Miocene-A) (Furlow, 1969; Hughes et al., 1989).

Slopes on the top-UFA erosional surface are generally low, on the order of 1:750. However, steeper slopes as high as 1:150 occur beneath the Savannah River just east of Savannah. Offshore, gradients can be as steep as 1:75 on the east flank of the Beaufort Arch (Fig.3-1, Plate 3-1).

Depth and Thickness Trends for the Miocene Aquitard

Plate 3-2a is a plot of Miocene thicknesses at georeferenced sample points along all survey tracklines where both the top and base of the Miocene aquitard could be identified from seismic records. Plate 3-2b and Fig. 3-2 are manually contoured isopach maps of these data points and show the thickness and thickness trends for the aquitard. The thickness of the aquitard varies significantly over short

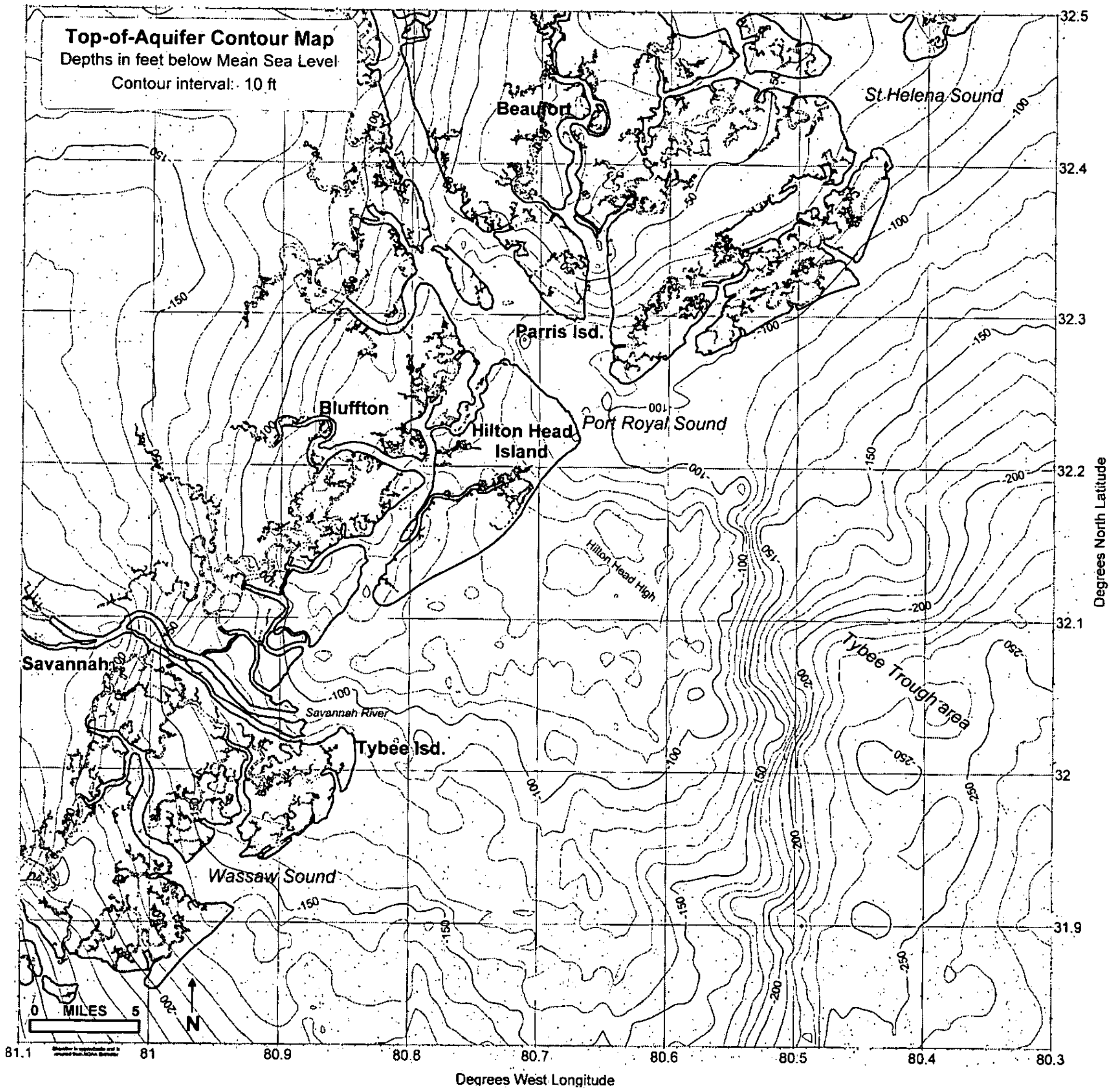


Figure 3-1 Contour map showing depths to the top of the UFA in northern coastal Georgia and southern coastal South Carolina. See Plate 3-1 for a larger-scale version of this map. This surface is generally defined by seismic *Reflector 4* but can be associated with shallower reflectors in areas where the latter have truncated *Reflector 4* (see Fig. 2-2).

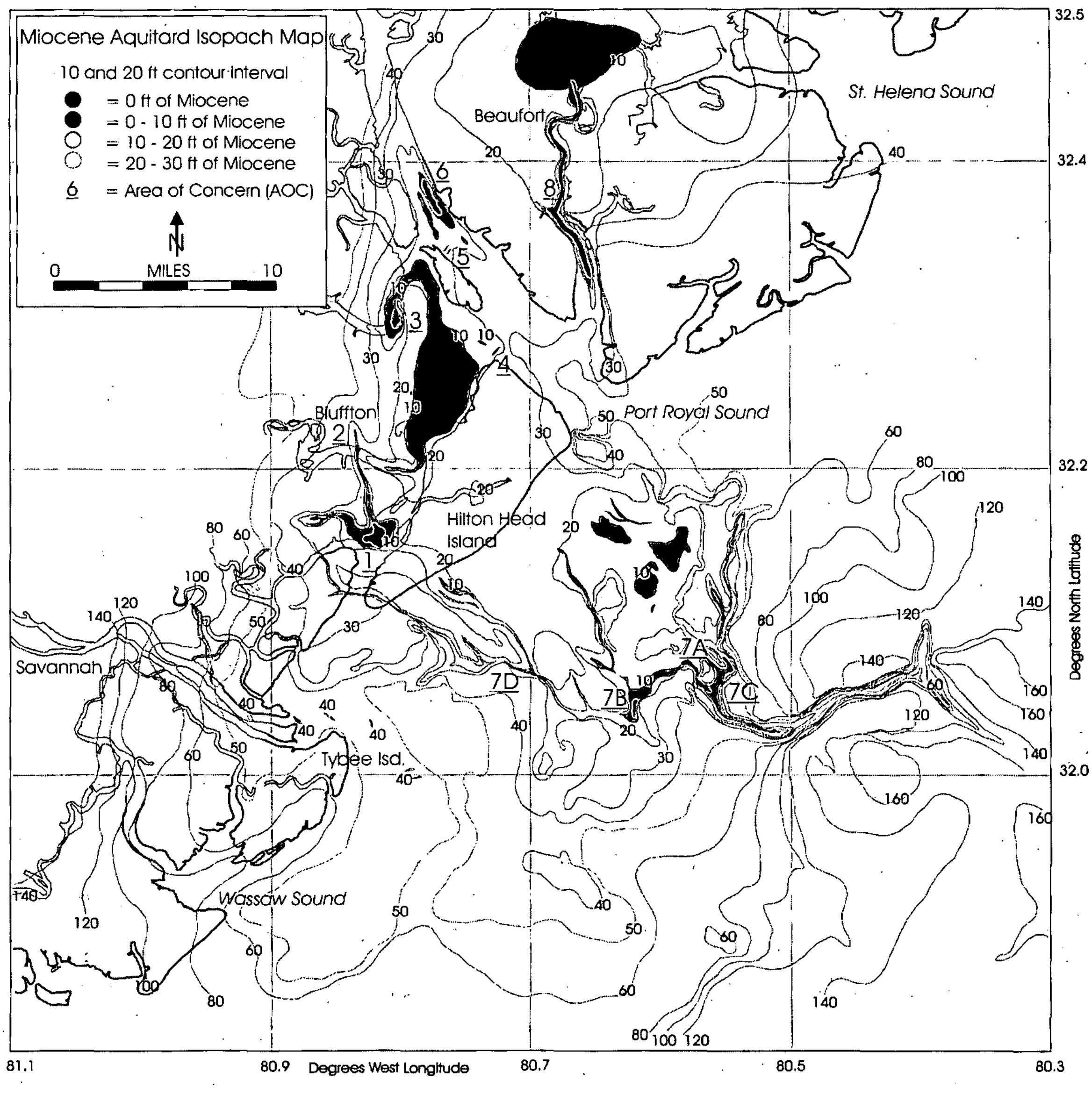


Figure 3-2 Miocene aquitard isopach map for northern coastal Georgia and southern coastal South Carolina. Map shows eleven Areas of Concern (AOCs) where the Miocene aquitard is absent (shaded black). AOC dimensions are estimated outside of the plane of the seismic trackline. See Plate 3-2b for a larger-scale color version of this map which is derived from data shown in Plate 3-2a. See Table 3-1 for summary data for each site.

horizontal distances because it is determined by the vertical separation between overlying and underlying composite erosional surfaces, namely a very crenulated Plio-Pleistocene composite erosional surface (Reflectors *1* and *2*) that defines the top of the aquitard and a very irregular karstic erosional surface that defines its base (generally Reflector *4*; see Fig. 3-3). Greatest thickness differentials generally occur along the flanks of the Savannah River paleochannel, especially offshore beneath the Tybee Trough.

Erosion associated with the base of multiple generations of the Savannah River paleochannel and associated tributary streams has had a major control on the preserved thickness of the Miocene aquitard. Complex reflector patterns within the Savannah River paleochannel, and paleochannel development beneath Pleistocene islands landward of Hilton Head Island, preserve a record of at least two sea-level lowstands during the Plio-Pleistocene. During the most recent lowstand (~18,000 years ago), the data suggest that the Savannah River exited the Savannah area near its present location. Seaward of Turtle and Daufuskie Islands, the paleo Savannah River traversed what is now the inner continental shelf, wrapped around the southern flanks of the Hilton Head High (Fig. 3-1), and then passed seaward beneath the Tybee Trough. During a preceding lowstand (probably ~150,000 years ago), the Savannah River did not occupy its present-day lower reaches but diverged to the north from an inferred location to the west of Savannah. The river then passed beneath present-day Bull Creek, Calibogue Sound, and the south end of Hilton Head Island. It then trended southeastward beneath the Hilton Head shoreface to underlie the path of the more recent (~18,000 year old) paleochannel at a point about 6 miles southeast of Hilton Head. From this location, the paleo Savannah River is inferred to have passed around the southern flanks of the Hilton Head High and across the inner shelf, again beneath the Tybee Trough area. These two generations of the paleo Savannah River account for the anastomosing and cross-cutting river drainage patterns that can be inferred from the Miocene isopach map (Fig. 3-2, Plate 3-2b).

Depths to the top of the Miocene aquitard generally range from approximately -10 feet MSL beneath Ladies Island, SC (Hughes et al., 1989), to -75 feet MSL beneath Wassaw Sound, GA (Furlow, 1969; Fig. 3-3), to approximately -170 feet MSL offshore and in the Tybee Trough area. The shallowest parts of the aquitard overlie topographically high areas of the subjacent UFA, notably along the Beaufort Arch in the Beaufort area, behind Hilton Head Island, and seaward of Hilton Head Island at the Hilton Head High. Depths to the base of the aquitard are synonymous with depths to the top of the UFA as shown in Plate 3-1 and Fig. 3-1. Basal depths consequently range from as shallow as -19 feet MSL in the vicinity of Ladies Island to as deep as -280 feet MSL southeast of the study area (Fig. 3-1, Plate 3-1).

Part 1 of this report (Review of Phase 1 Results) indicates that in areas south of the Savannah River and within the cone of depression, the UFA is deep enough, the Miocene aquitard thick enough, and the tidal and paleochannels shallow enough that the probability of occurrence of areas of thin or absent aquitard is very low; no such areas were detected during this study. A similar stratigraphic scenario exists seaward of a coast-parallel line located about 20 miles off the Georgia/South Carolina coast. Additionally, this area is outside of the cone of depression on the UFA. The probability of seawater intrusion due to aquitard thinning or breaching in both general areas is inferred to be very low.

Thin-Miocene Areas

As illustrated schematically in Fig. 1-2, the thickness of the Miocene aquitard is controlled primarily by the elevation of the top of the UFA (generally *Reflector 4*) and the depth of downcutting by either present-day channels or Plio-Pleistocene paleochannels (*Reflector 1* and *Reflector 2*). The Miocene has the greatest probability of being thinnest over topographic highs on the UFA where either (1) modern tidal creeks (or dredged channels) cut down into or through the Miocene or (2) paleochannels incised during Quaternary glacioeustatic lowstands of sea level cut down into or through the Miocene.

On the Georgia coast and inner shelf, seismic data indicate that the Miocene is almost everywhere thicker than 40 feet. The exception to this statement occurs at about ten small localized areas on the lower Savannah River and the outer part of the Savannah Navigation Channel (Plate 3-2b). These localized thin spots (arbitrarily defined as locations where less than 40 feet of Miocene are present) mark where buried Quaternary paleochannels underlie seismic tracklines. The exact orientation and extent of these thin zones in the Savannah River and navigation channel outside of the plane of the seismic lines is uncertain, but they likely intersect the modern channel at oblique angles.

The principal area of thinned Miocene strata occurs beneath the intracoastal and inner shelf region of South Carolina (Plate 3-2b) where approximately 540 square miles are underlain by less than 40 feet of Miocene. Of this area, approximately 420 square miles are underlain by less than 30 feet of Miocene (green shading), approximately 195 square miles are underlain by less than 20 feet of Miocene (yellow shading), and approximately 53 square miles are underlain by less than 10 feet of Miocene (amber shading). The 20-foot isopach defines four large thin-Miocene swaths, three of which occur with the Savannah cone of depression on the UFA. Numerous no-Miocene zones which occur within these swaths are described in the next section.

Over 50% of the thin-Miocene area (arbitrarily defined as locations where less than 40 feet of Miocene are present) occurs south and southeast of the Broad River and within the northeastern quadrant of the Savannah cone of depression (Fig. 1-1, Plate 3-2b). These areas are directly associated with the south-southeast trending Beaufort Arch. Miocene strata locally crop out on the sea bed in Port Royal Sound in areas where present water depths are almost -70 feet MSL (Fig. 3-4); however, in these areas, the aquitard remains relatively thick (~35 feet). Outside of the Savannah cone of depression and north of the Broad River-Port Royal Sound area, the Miocene aquitard is absent over extensive areas along the thalweg of the Beaufort River between southern Parris Island (at Ballast Creek) and the town of Beaufort, SC. Along this stretch of the Beaufort River, the UFA either crops out at the sea floor or is covered by only a thin veneer (less than 2 feet) of post-Miocene strata. This is the only part of the study area where the UFA was observed to be in direct, or nearly-direct, contact with saline water.

No-Miocene Areas

A total of eleven localized sites exist where the Miocene aquitard is no longer preserved. Collectively, these sites comprise a total area of about 7 square miles and are shown as black-shaded areas on Plate 3-2b and Fig. 3-2. However, the areas of these no-Miocene "windows" on the isopach maps are not well constrained because the widths (normal to the trackline orientation) of several of the features are uncertain. Ten of the eleven no-Miocene areas are within the Savannah cone of depression. At all of these sites, 10 to 55 feet of post-Miocene strata overlie the UFA. The eleventh and most extensive no-Miocene area, located along the axis of the Beaufort River, lies outside the 0-foot contour on the Savannah cone of depression (see Peck et al., 1999, and Ransom and White, 1999, for the most recent potentiometric maps for this area). At this site, 0 to 10 feet of non-confining material overlie the UFA.

The areas where the Miocene is absent are described below and are listed in Table 3-1. The position of each site relative to the potentiometric surface on the UFA, which allows the potentiometric head to be estimated, is derived from a September 1998 potentiometric map generated by Ransom and White (1999). With the exception of Site 8, post-Miocene strata overlie the UFA at each location. Even though these strata are generally permeable and non-confining, they physically (and may in part, hydraulically) separate the UFA from overlying saline estuarine or inner shelf water. For example, at Site 1 where the Miocene is absent along approximately 3,500 feet of trackline, the non-confining material averages 55 feet in thickness. The thickness of the non-confining material is of importance because possible impermeable horizons and low hydraulic conductivities within the material may give it some confining properties. This may particularly be the case at locations where a significant thickness of the non-confining material is preserved. Buried paleochannel fills beneath the Savannah River are known to be dominated by silty sands and silts (U.S. Army Corps of Engineers, 1998) and would be expected to have somewhat lower vertical permeabilities.

Table 3-1 Summary information for eleven no-Miocene potential seawater-intrusion sites (Areas of Concern) identified in the study area. AOCs are listed in unranked order. Breach lengths are derived from Plate 3-2a and Figs. 3-5 through 3-18.

Location of Site (Area of Concern)	Trackline incision length (ft)	Approximate Latitude & Longitude	Estimated potentiometric elevation (ft)	Thickness of post-Miocene non-confining material (ft)
(1) Confluence of Cooper River and inner Calibogue Sound	3,500	32.16 deg N 80.82 deg W	-18 to -20	55
(2) Near confluence of May River and Bull Creek	500	32.21 deg N 80.75 deg W	-14	35
(3) Colleton River at Victoria Bluff	3,000	32.30 deg N 80.82 deg W	-5	25-40
(4) Inner Port Royal Sound near northern tip of Hilton Head Island	500	32.27 deg N 80.72 deg W	-2	40
(5) Broad River north of Daws Island	500	32.27 deg N 80.72 deg W	-2	38
(6) Broad River southeast of US Hwy 170 bridge	6,000	32.38 deg N 80.78 deg W	-2	10
(7A) Beaufort Arch offshore Hilton Head	3,500	32.07 deg N 80.58 deg W	-1	15-35
(7B) Beaufort Arch offshore Hilton Head	1,500	32.05 deg N 80.62 deg W	-1	20
(7C) Beaufort Arch offshore Hilton Head	1,500	32.06 deg N 80.57 deg W	-1	40
(7D) Beaufort Arch offshore Hilton Head	700	32.07 deg N 80.72 deg W	-5	45
(8) Beaufort River between Paris Island (Ballast Creek) and Beaufort	42,200	32.38 deg N 80.66 deg W	0 to +5	0-10

(1) Confluence of Cooper River and inner Calibogue Sound (vicinity of 32.16 deg N, 80.82 deg W):
Between the -18 and -20 foot potentiometric contours, a mid-late Pleistocene aged paleochannel of the Savannah River incises to depths of as much as -82 feet MSL (Fig. 3-5, 3-6). Beneath the paleochannel, which has a cross-sectional, shoulder-shoulder width of 5000 to 10000 feet, the Miocene is absent along a trackline length of approximately 3500 feet (Fig. 3-5). Within short distances upstream and downstream along the paleochannel axis, 10 to 20 feet of Miocene are preserved which suggests that this downcutting is a localized phenomenon and may not be more than 4000 feet wide (Figs. 3-6, 3-7, 3-8). About 55 feet of post-Miocene non-confining material is preserved above the incision point in Fig. 3-5.

(2) Near confluence of May River and Bull Creek (vicinity of 32.21 deg N, 80.75 deg W):
Near the -14 foot potentiometric contour, a probable paleotributary to the paleochannel in (1) above incises through the Miocene to a depth of -68 feet MSL (Fig. 3-5). Beneath the paleochannel, which has a cross-sectional, shoulder-shoulder width of approximately 2500 feet, the Miocene is absent along a trackline length of approximately 500 feet (Fig. 3-5). As the buried paleochannel trends obliquely beneath the May River, the width of the incision may be on the order of 3000 feet (the width of the May River at this point); however, the incision may extend along the axis of the paleotributary beneath adjacent marshes. Approximately 35 feet of non-confining material is preserved above the incision point.

(3) Colleton River at Victoria Bluff (vicinity of 32.30 deg N, 80.82 deg W):
Near the -5 foot potentiometric contour, the Miocene aquitard is locally absent on the crest of the Beaufort Arch due to the presence of an inferred sinkhole (Fig. 3-9). The sinkhole extends at least 20 feet into the UFA and is filled primarily with post-Miocene strata. The Miocene aquitard is absent along a trackline length of approximately 3000 feet. If the sinkhole is assumed to be approximately symmetrical, the diameter of this feature may be on the order of 3000 feet. Approximately 25 to 40 feet of non-confining material is preserved above the incision point.

(4) Inner Port Royal Sound near northern tip of Hilton Head Island (vicinity of 32.27 deg N, 80.72 deg W):
Near the -2 foot potentiometric contour, a narrow Quaternary paleochannel (that probably exits from Skull Creek) incises through the Miocene to a depth of -80 feet MSL. Beneath the paleochannel, which has a cross-sectional, shoulder-shoulder width of approximately 2500 feet, the Miocene is absent along the channel thalweg for a trackline length of approximately 500 feet (Fig. 3-10); the lateral dimension of this incision is uncertain. Approximately 40 feet of non-confining material is preserved above the incision point.

(5) Broad River north of Daws Island (vicinity of 32.27 deg N, 80.72 deg W):
Near the -2 foot potentiometric contour, a pair of small Quaternary paleochannels (probably exiting from Chechessee Creek) incise through the Miocene to a depths of -70 to -72 feet MSL. Beneath the paleochannel pair, which have a combined cross-sectional, shoulder-shoulder width of approximately 2000 feet, the Miocene is absent along the channel thalwegs for a trackline length of approximately 500 feet (Fig. 3-10). The lateral dimension of this incision pair is uncertain and the pair may pass beneath Daw's Island. Approximately 38 feet of non-confining material is preserved above the incision points.

(6) *Broad River southeast of US Hwy 170 bridge (vicinity of 32.38 deg N, 80.78 deg W):*

Near the -2 foot potentiometric contour, the Miocene section has been truncated by the base-Quaternary erosion surface (*Reflector 1)* along the axis of the Beaufort Arch. The Miocene is absent along a trackline length of approximately 6000 feet in an area where water depths attain almost -50 feet MSL (Fig. 3-11). This no-Miocene window is inferred to have a limited lateral width (less than 2000 feet) as tracklines on either side of this trackline (see trackline MAS2 L2D, Fig. 3-10), and cross-sections from C olquhoun (1972), indicate a shallower seabed approximately -25 feet MSL) and 10 to 15 feet of Miocene preserved. Approximately 10 feet of non-confining material is preserved above the truncation point.

(7) *Beaufort Arch offshore Hilton Head (general vicinity of 32.06 deg N, 80.60 deg W):*

Because potentiometric contours defining the Savannah cone of depression have not been mapped offshore, Sites 7A-D are located between the estimated positions of the -1 and -5 foot potentiometric contours. In this area, a composite paleochannel of the Savannah river system locally removes the Miocene section at four separate locations (Sites 7A, 7B, 7C, and 7D) within a 2x8 mile area centered approximately 16 miles due east of Daufuskie and Turtle Islands, SC (Figs. 3-12, 3-13, 3-14, and 3-15).

At Site 7A *(vicinity of 32.07 deg N, 80.58 deg W)*, the Miocene is absent along a trackline length of approximately 3500 feet. Approximately 15-35 feet of non-confining material is preserved above the incision point (Figs. 3-12, 3-13).

At Site 7B *(vicinity of 32.05 deg N, 80.62 deg W)*, the Miocene is absent along a trackline length of approximately 1500 feet. About 20 feet of non-confining material is preserved above the incision point (Fig. 3-13).

At Site 7C *(vicinity of 32.06 deg N, 80.57 deg W)*, the Miocene is absent along a trackline length of 1500 feet. The UFA is overlain by about 40 feet of non-confining material (Fig. 3-14).

At Site 7D *(vicinity of 32.07 deg N, 80.72 deg W)*, the Miocene is absent along a trackline length of 700 feet near the -5 foot potentiometric contour. The UFA is overlain by about 45 feet of non-confining material (Fig. 3-15).

At the above four sites, the UFA lies at a depth of between -75 and -100 feet MSL. The four incision sites occupy an estimated area of approximately 0.3 square miles (the widths of the incisions are not accurately known).

(8) *Beaufort River between Paris Island (Ballast Creek) and Beaufort (vicinity of 32.38 deg N, 80.66 deg N):*

Between the 0 and +5 foot potentiometric contours, the upper Beaufort River channel has removed all of the Miocene confining unit in an area where the UFA occurs at depths of -20 to -50 feet MSL (Plate 3-1, Fig. 3-1). The UFA is either exposed at the river bed or covered with a thin veneer (0 to 10 feet) of post-Miocene non-confining strata (Fig. 3-16). The no-Miocene zone along the axis of the river channel extends for approximately 8 miles between Ballast Creek and the town of Beaufort. Lower-quality seismic data from Phase 1 suggest that the Miocene is also absent to the north, between Beaufort and the Coosaw River. Based on channel-flank bathymetry, the no-Miocene swath is expected to be no more than 1000 feet wide. Figure 1-4 (Part 1 of this report) indicates that the Miocene section in this area thickens to 15 to 40 feet outside of channels (see also Hughes et al., 1989).

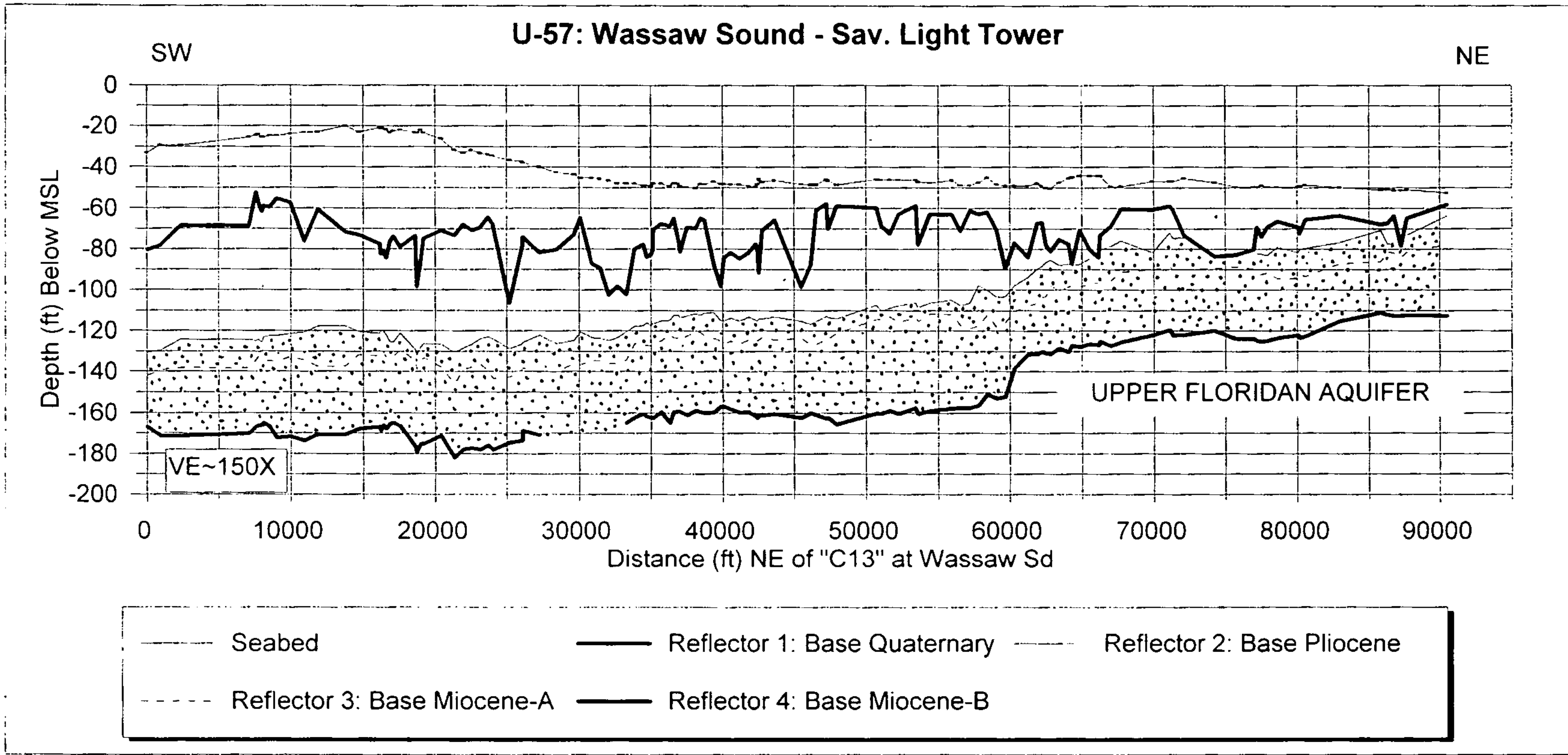


Fig. 3-3 Coast-parallel oriented cross section along Seismic Line U-57 extending from Wassaw Sound offshore to the location of the (former) Savannah Light Tower. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

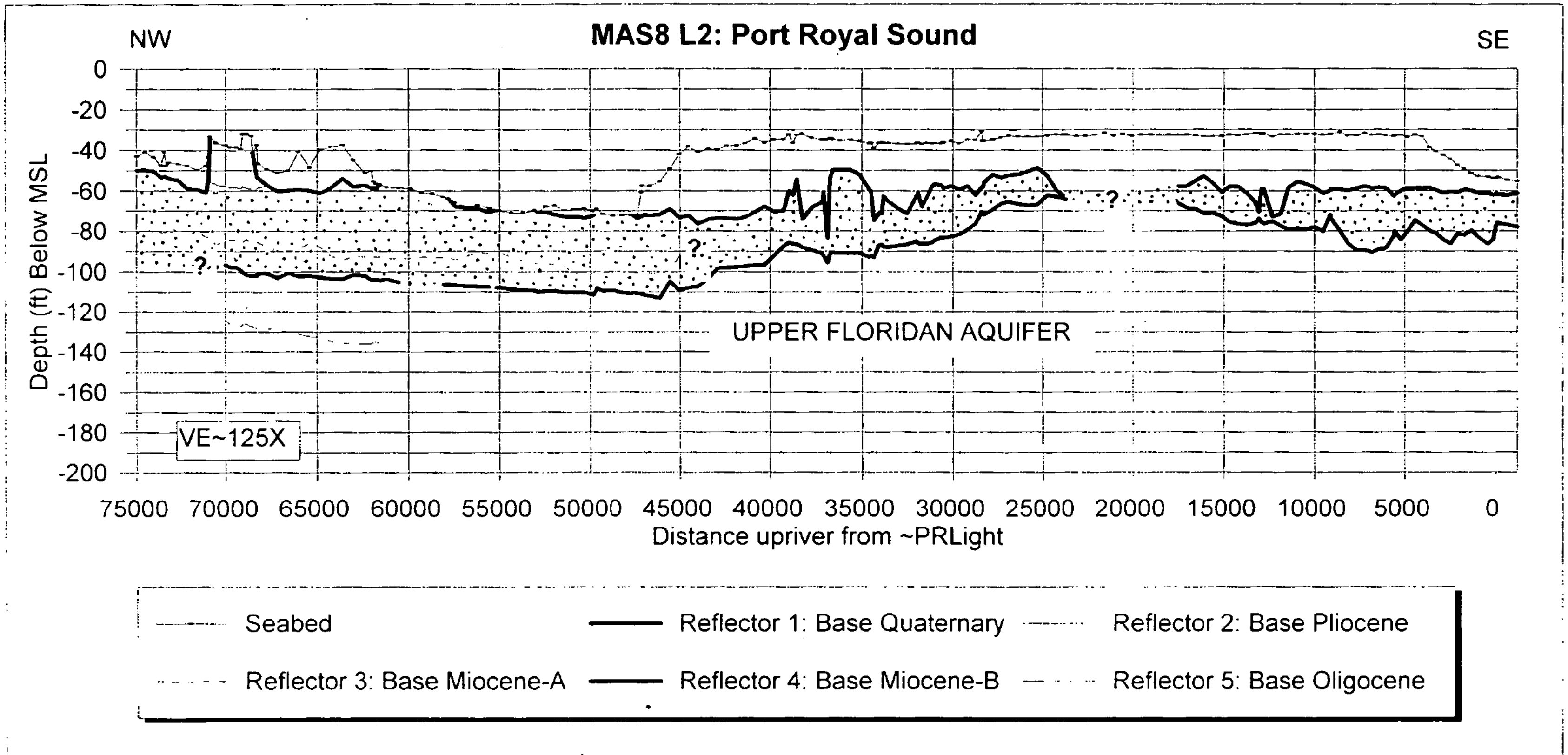


Fig. 3-4 Coast-oblique oriented cross section along Seismic Line MAS8 L2 between the outer end of the Port Royal Sound navigation channel and the mouth of Port Royal Sound. Note Miocene outcrops or near-outcrops on the inlet floor at X = 60000feet. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

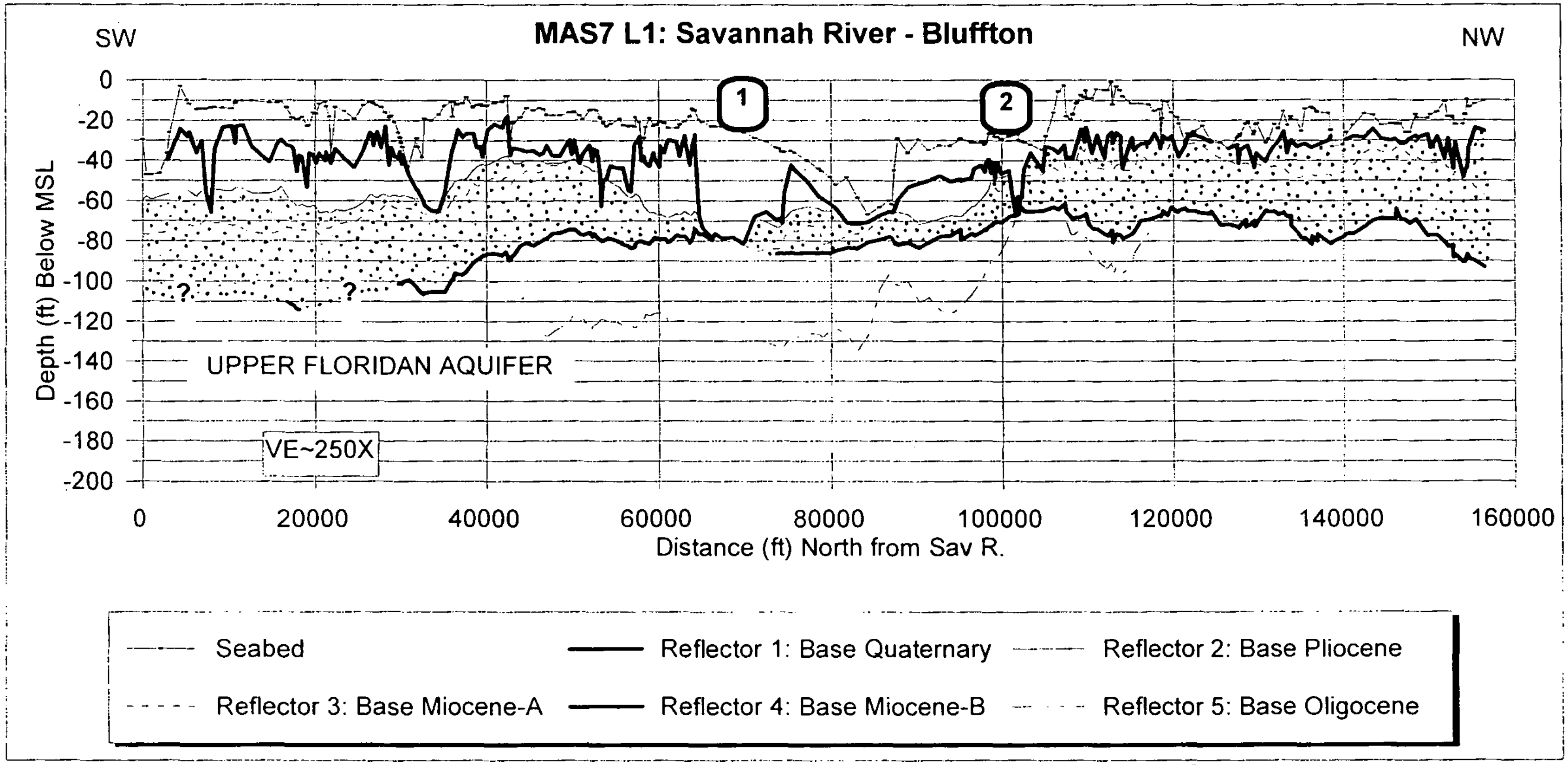


Fig. 3-5 Coast-subparallel oriented cross section along Seismic Line MAS7 L1. Section is located in the intracoastal waterway between Field's Cut on the Savannah River and Beaufort, SC, on the May River. Potential seawater intrusion sites are shown where the Miocene is absent beneath a paleochannel of the Savannah River (Site 1 in Table 3-1 and Fig. 3-2) and beneath a paleotributary (Site 2 in Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

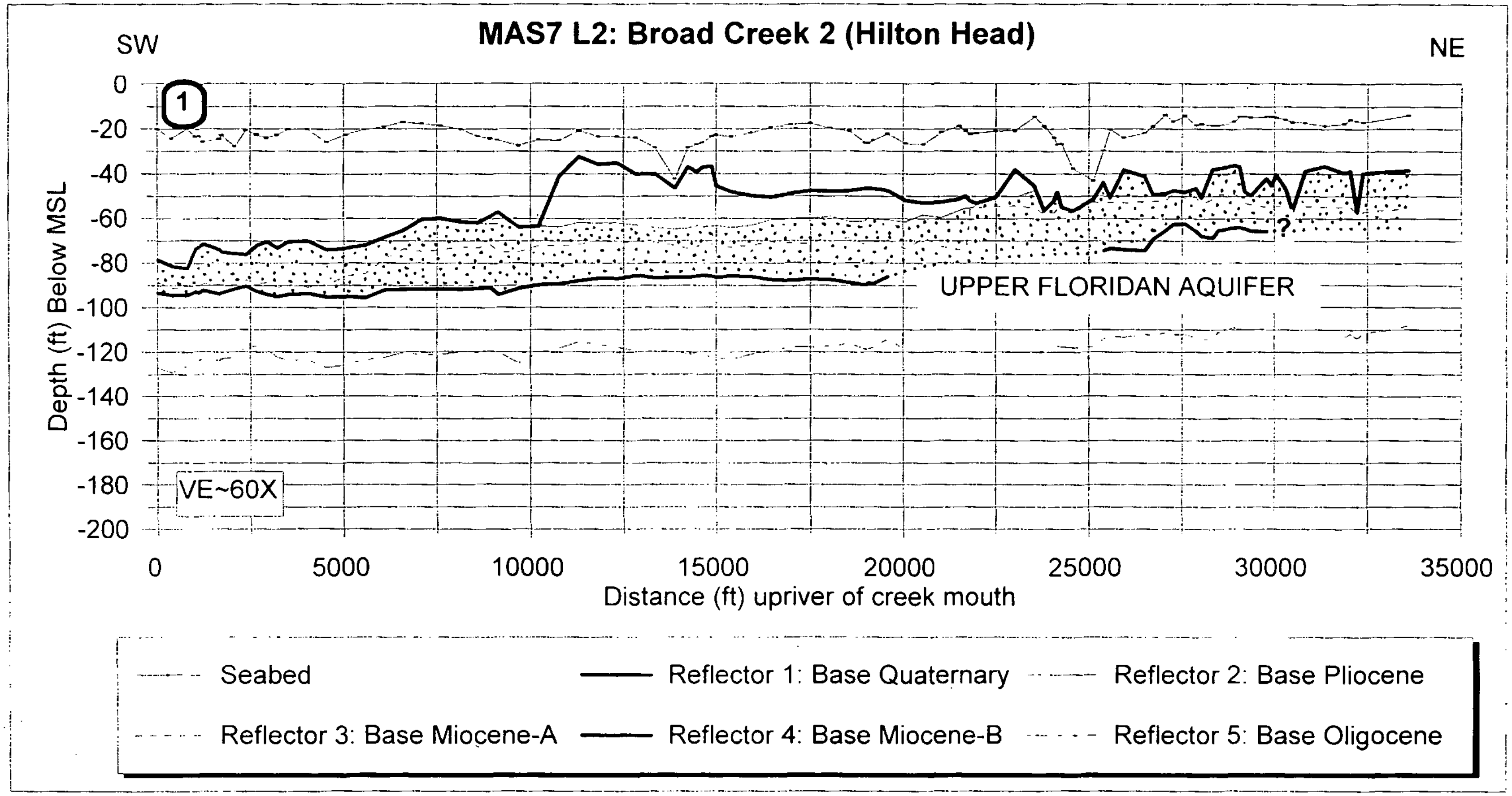


Fig. 3-6 Coast-subparallel oriented cross section along Seismic Line MAS7 L2. Section extends from the mouth of Broad Creek in Calibogue Sound to the upriver end of Broad Creek in central Hilton Head Island. The thinned Miocene strata beneath a paleochannel of the Savannah River on the left side of the section are located southeast (downriver) of Site 1 shown in Figs. 3-2 and 3-5. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

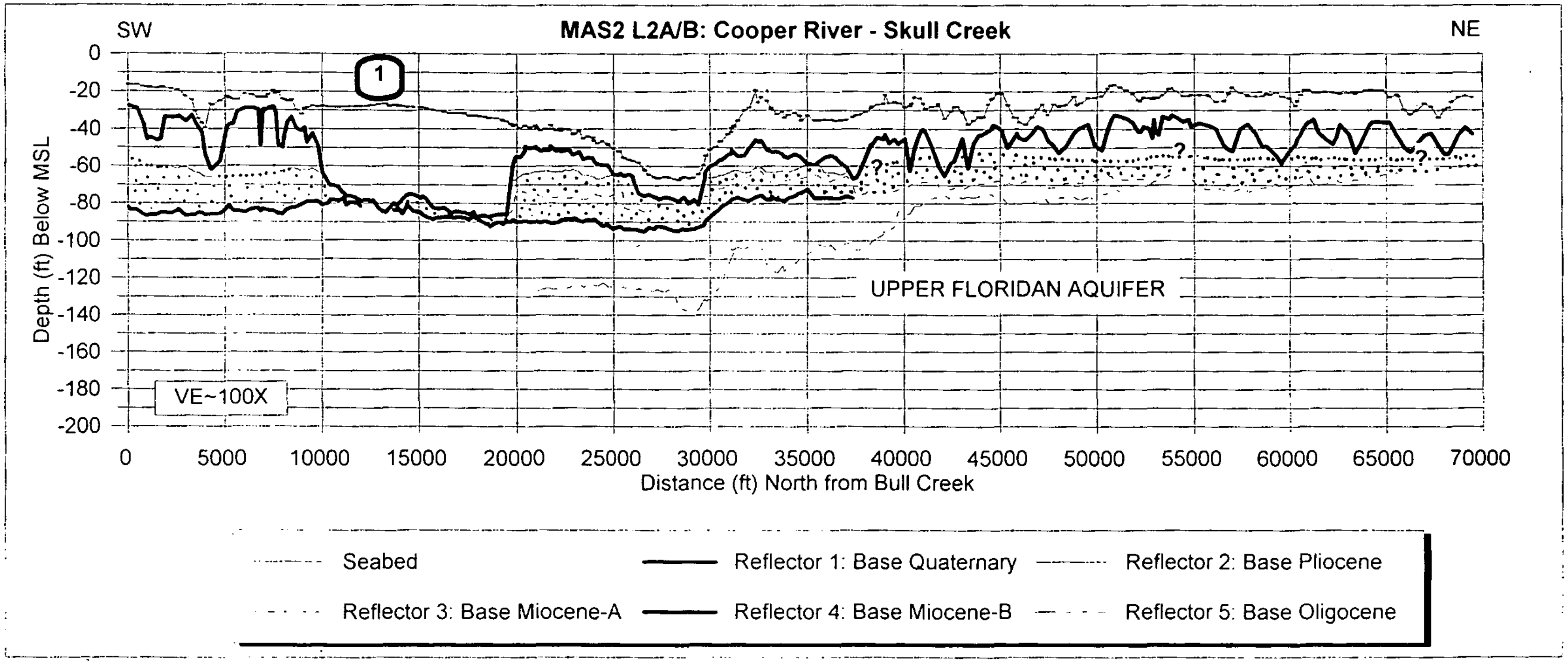


Fig. 3-7 Coast-subparallel oriented cross section along Seismic Line MAS2 L2AB. Section is located in the intracoastal waterway between the Cooper River at Bull Creek and Skull Creek near the north end of Hilton Head Island. The thinned to absent Miocene strata beneath a paleochannel of the Savannah River on the left side of the section are part of Site 1 as shown in Figs. 3-2 and 3-5. On the right side of the section, Reflector 2 could not be resolved but is inferred to be present. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

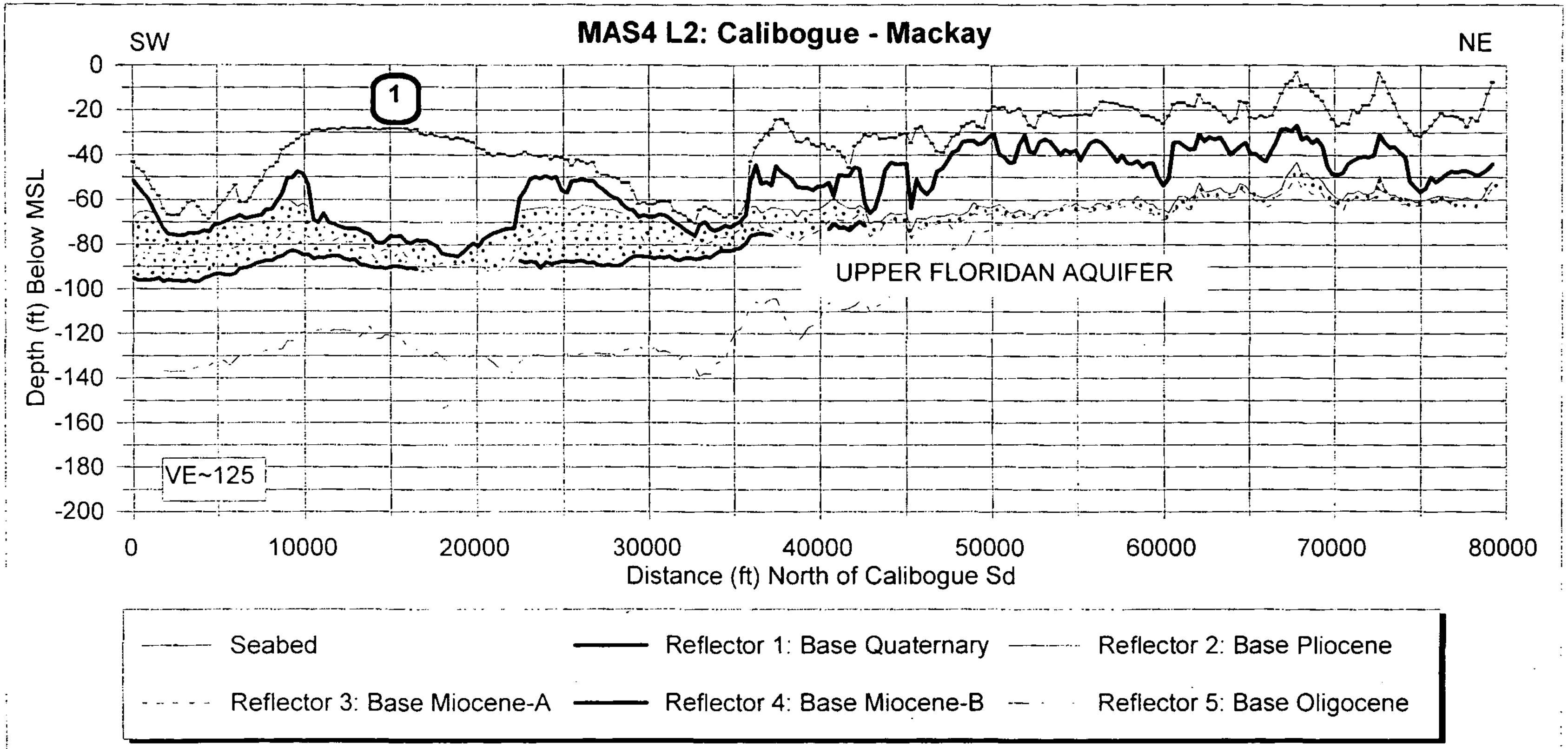


Fig. 3-8 Coast-subparallel oriented cross section along Seismic Line MAS4 L2. Section is located in the intracoastal waterway between the mouth of Calibogue Sound and the north end of MacKay Creek at the north end of Pinckney Island. The thinned Miocene strata beneath a paleochannel of the Savannah River on the left side of the section are located adjacent to Site 1 as shown in Figs. 3-2 and 3-5. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

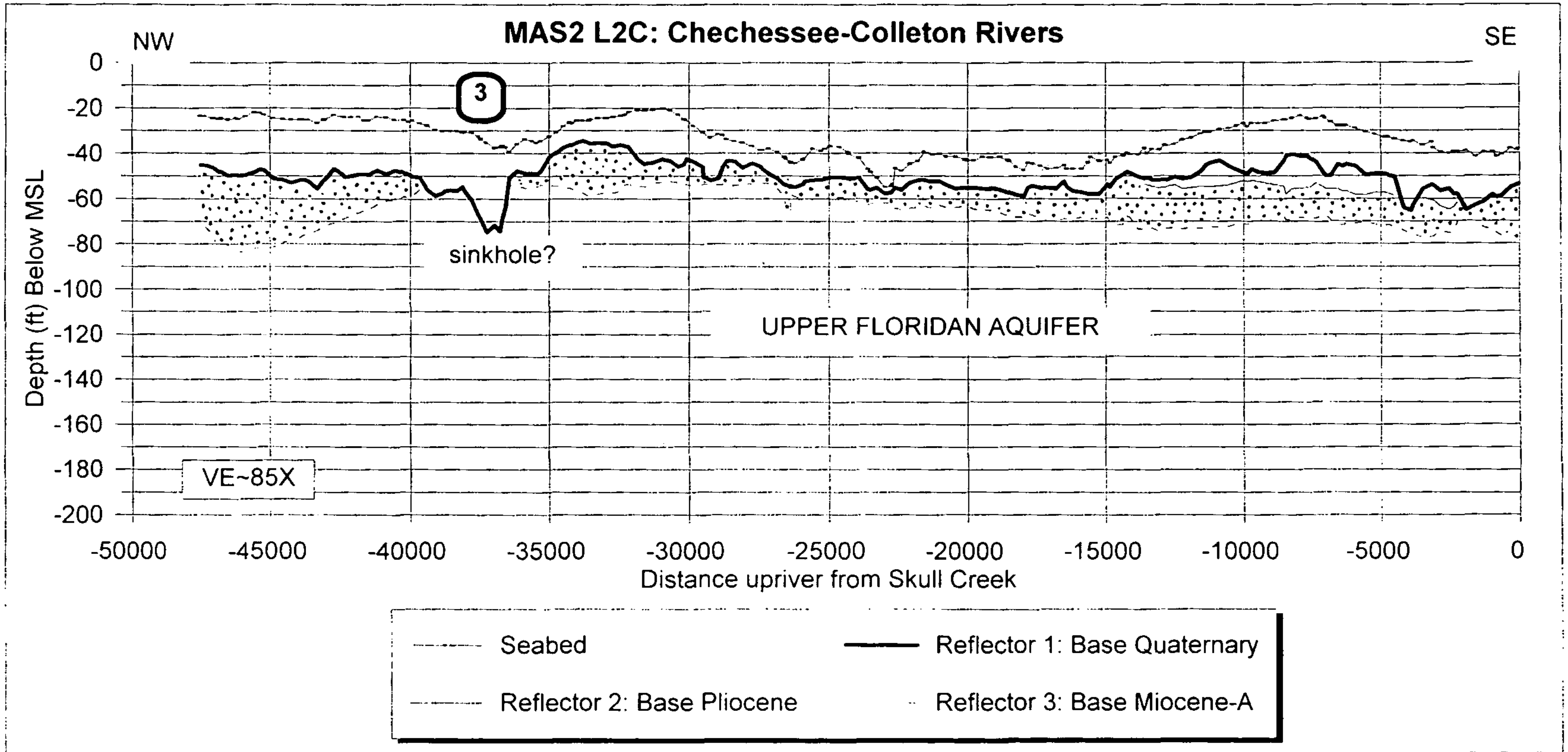


Fig. 3-9 Coast-oblique oriented cross section along Seismic Line MAS2 L2C between the north end of Skull Creek at Hilton Head Island and Victoria Bluff on the Colleton River. A potential seawater intrusion site is shown where the Miocene aquitard is absent at a probable sinkhole (Site 3 in Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

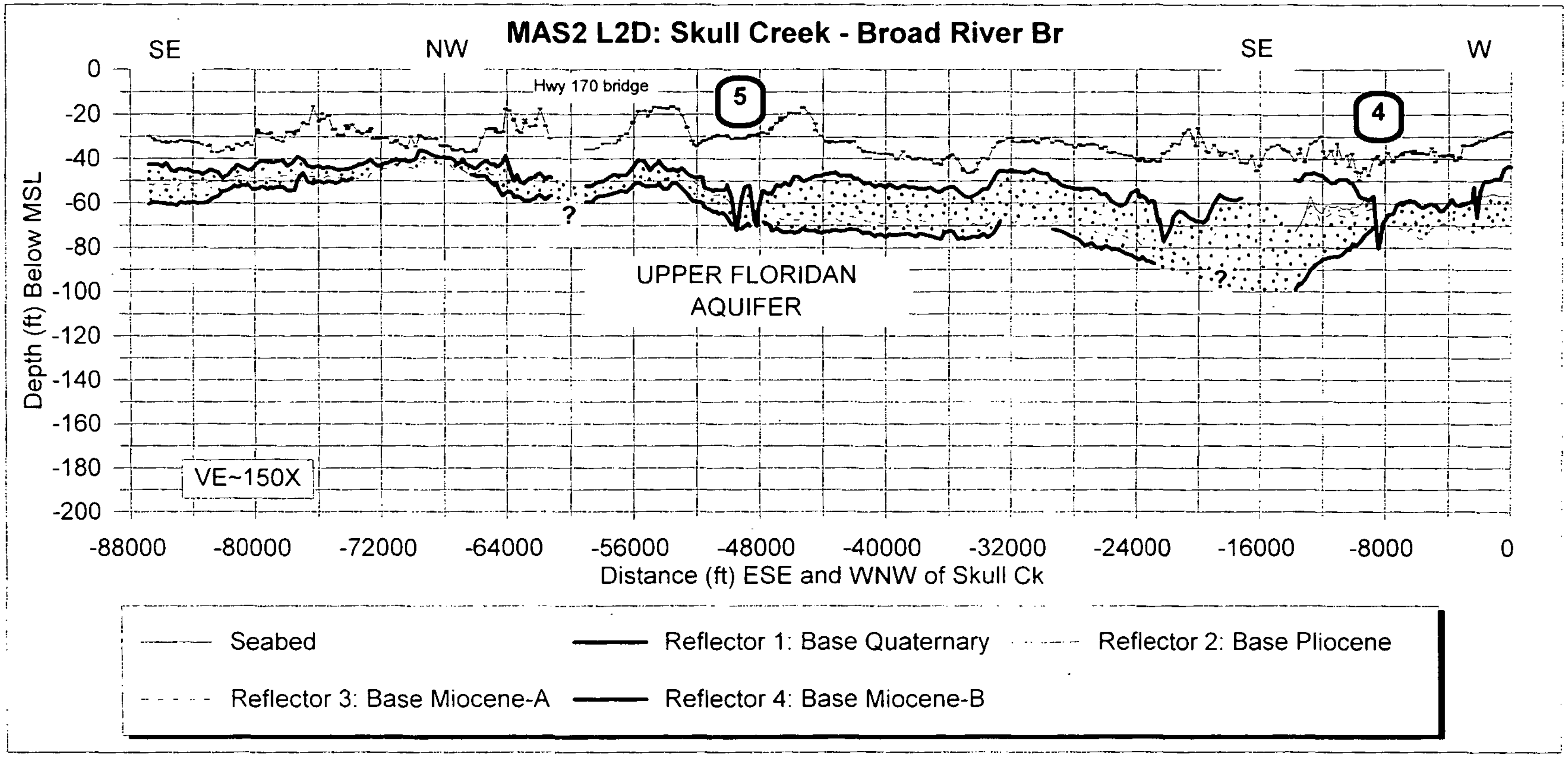


Fig. 3-10 Coast-normal oriented cross section along Seismic Line MAS2 L2D between Port Royal Sound and the lower Broad River at the U.S. Highway 170 bridge. Two potential seawater intrusion sites are shown where the Miocene aquitard is absent (Sites 4 and 5; see Table 3-1 and Fig. 3-2) beneath small paleochannels. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

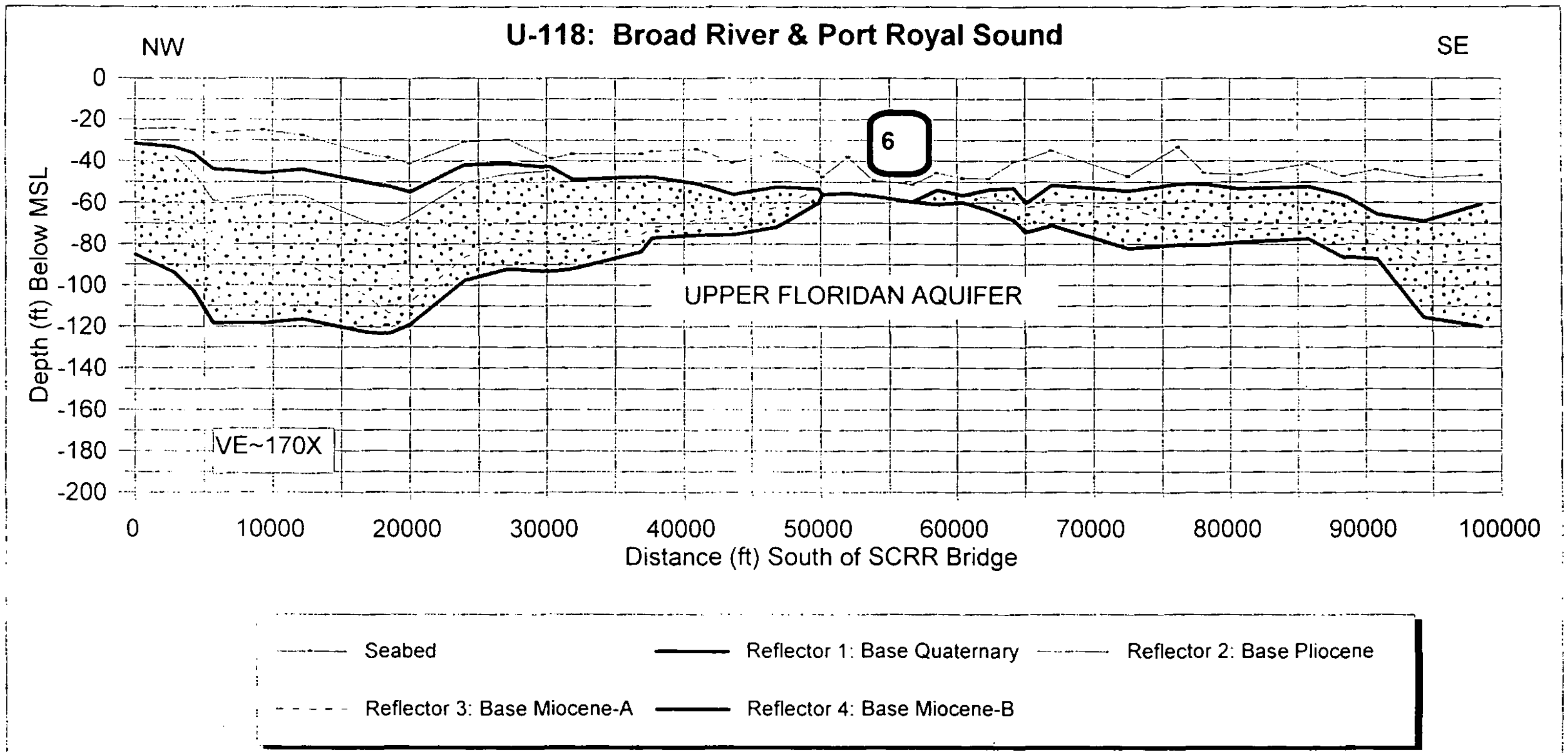


Fig. 3-11 Coast-normal oriented cross section along Seismic Line U-118 between Port Royal Sound and the lower Broad River at the US Highway 170 bridge. A potential seawater intrusion site is shown where the Miocene is absent over a high on the UFA (Site 6; see Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

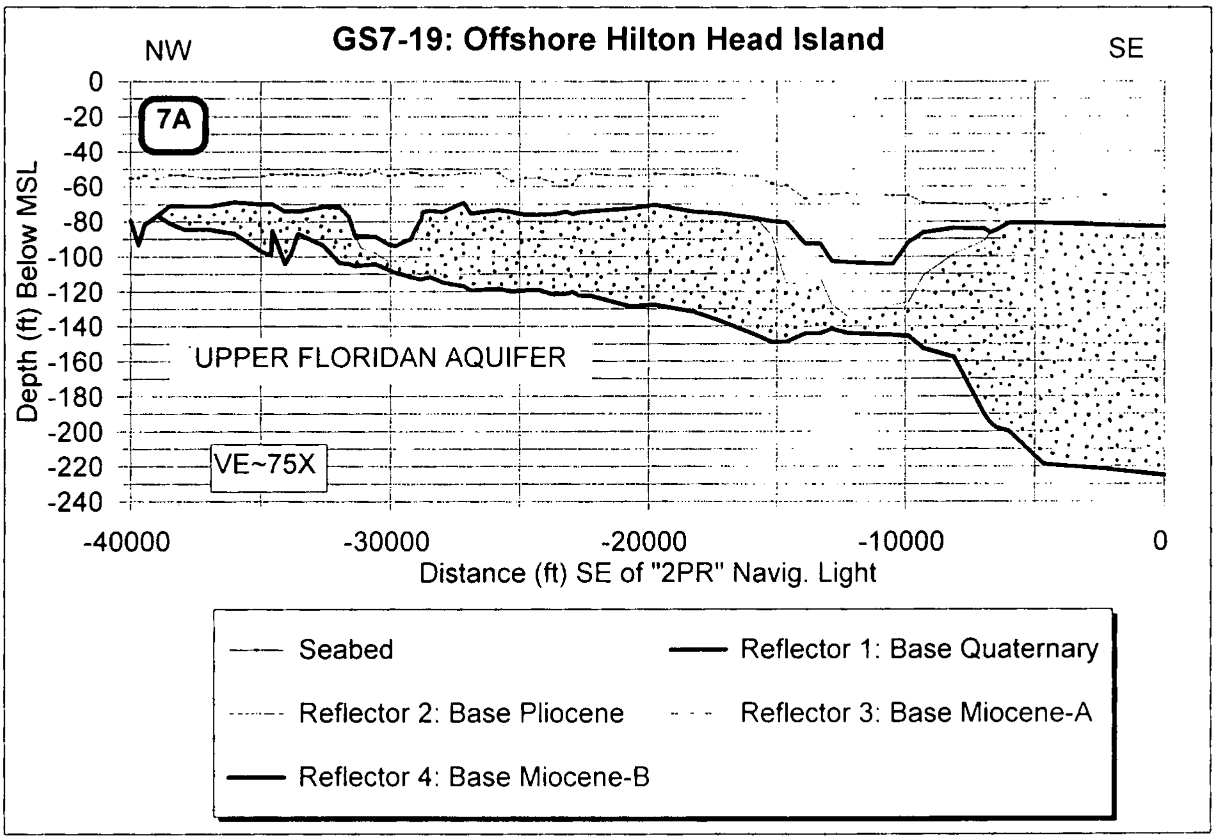


Fig. 3-12 Coast-normal oriented cross section along Seismic Line GS7-19 located offshore of Hilton Head Island at the Hilton Head High. A potential seawater intrusion site is shown on the left (northwest) edge of the section (Site 7A; see Table 3-1 and Fig. 3-2) where the Miocene is absent. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

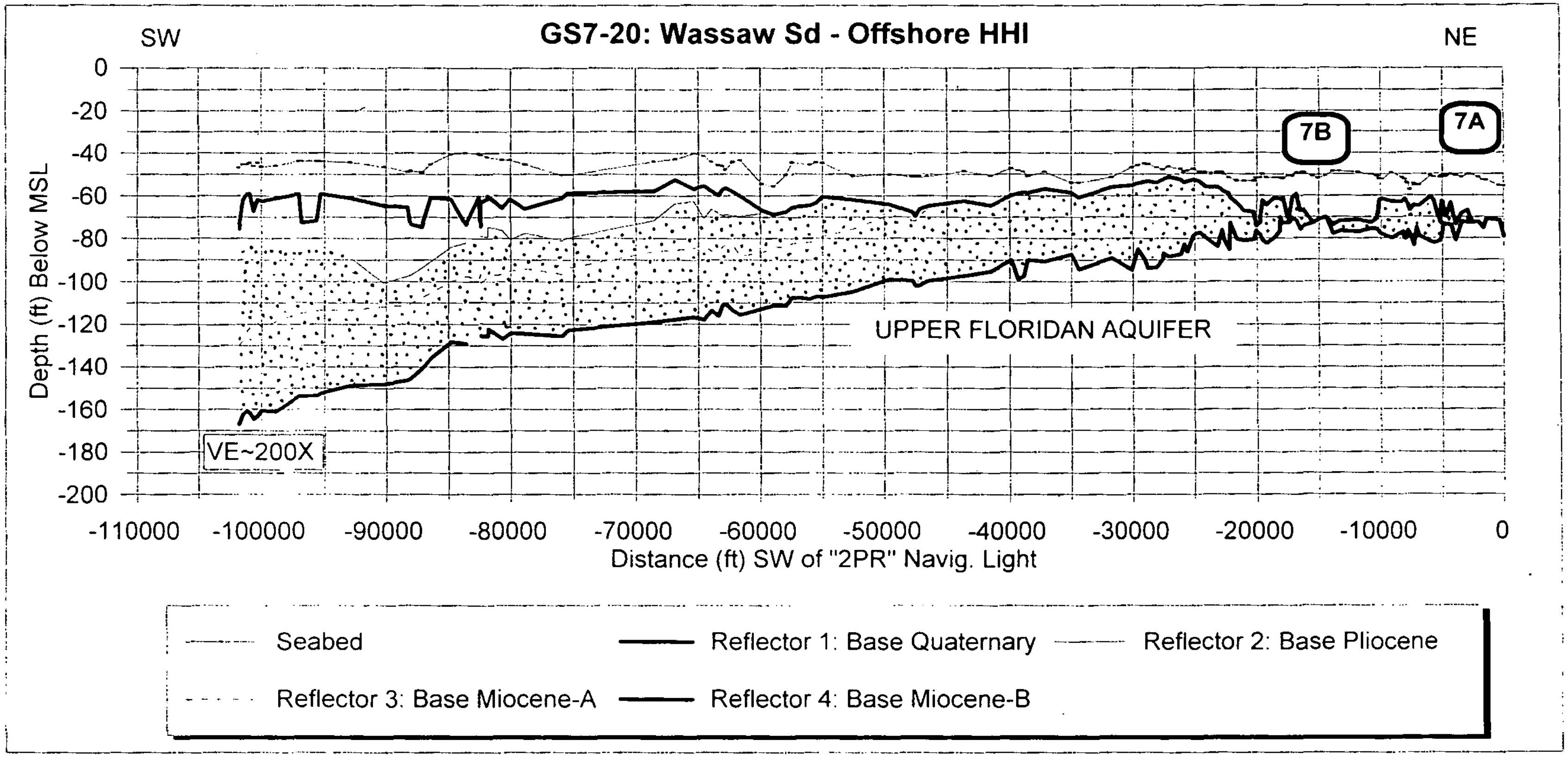


Fig. 3-13 Coast-parallel oriented cross section along Seismic Line GS7-20 located offshore of Hilton Head Island at the Hilton Head High. Potential seawater intrusion sites are shown where the Miocene aquitard is absent on the right (northeast) side of the section (Sites 7A, 7B; see Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

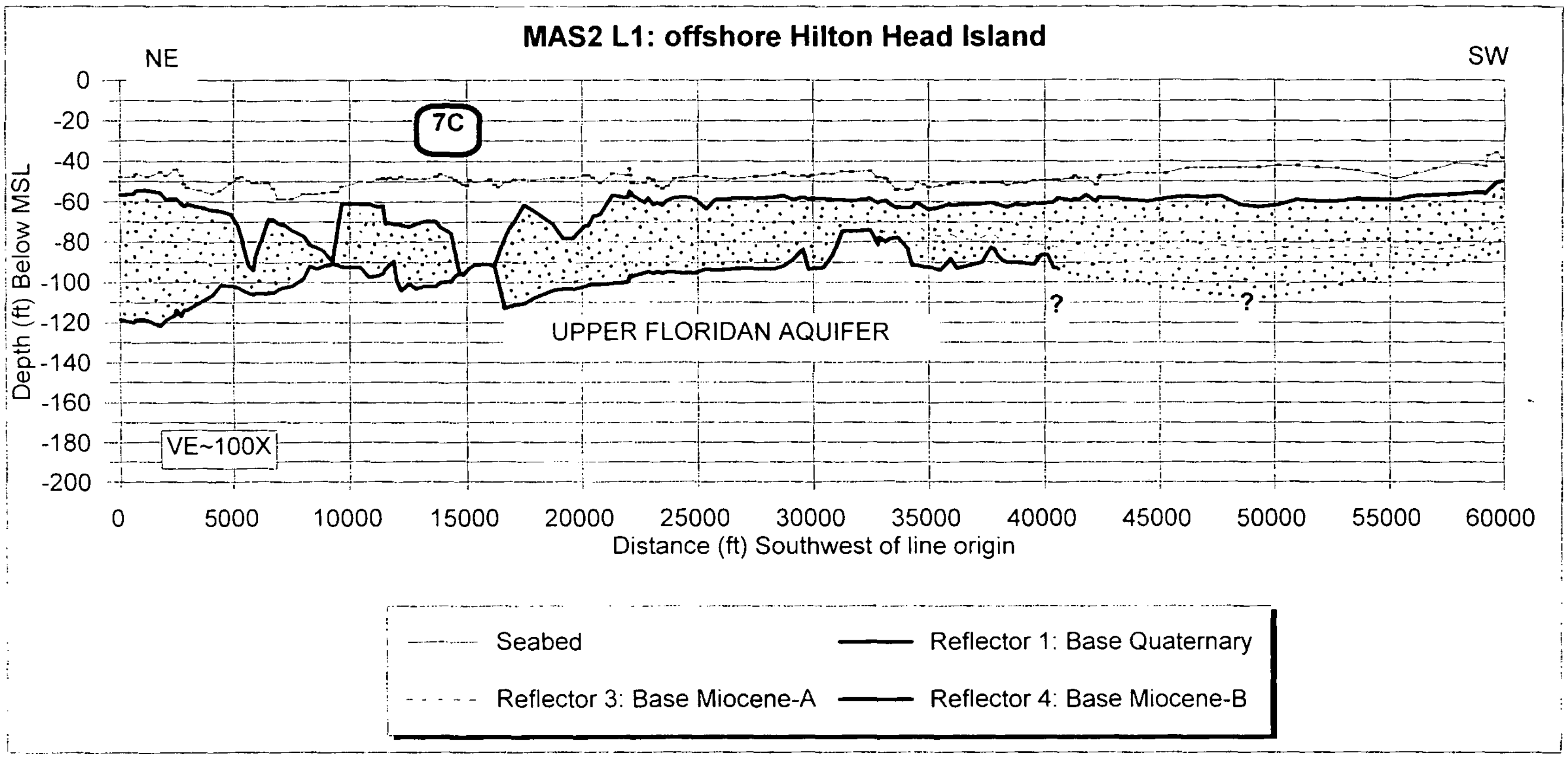


Fig. 3-14 Coast-normal oriented cross section along Seismic Line MAS2 L1 located offshore of Hilton Head Island at the Hilton Head High. A potential seawater intrusion site is shown where the Miocene aquitard is absent beneath the paleochannel of the Savannah River (Site 7C; see Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

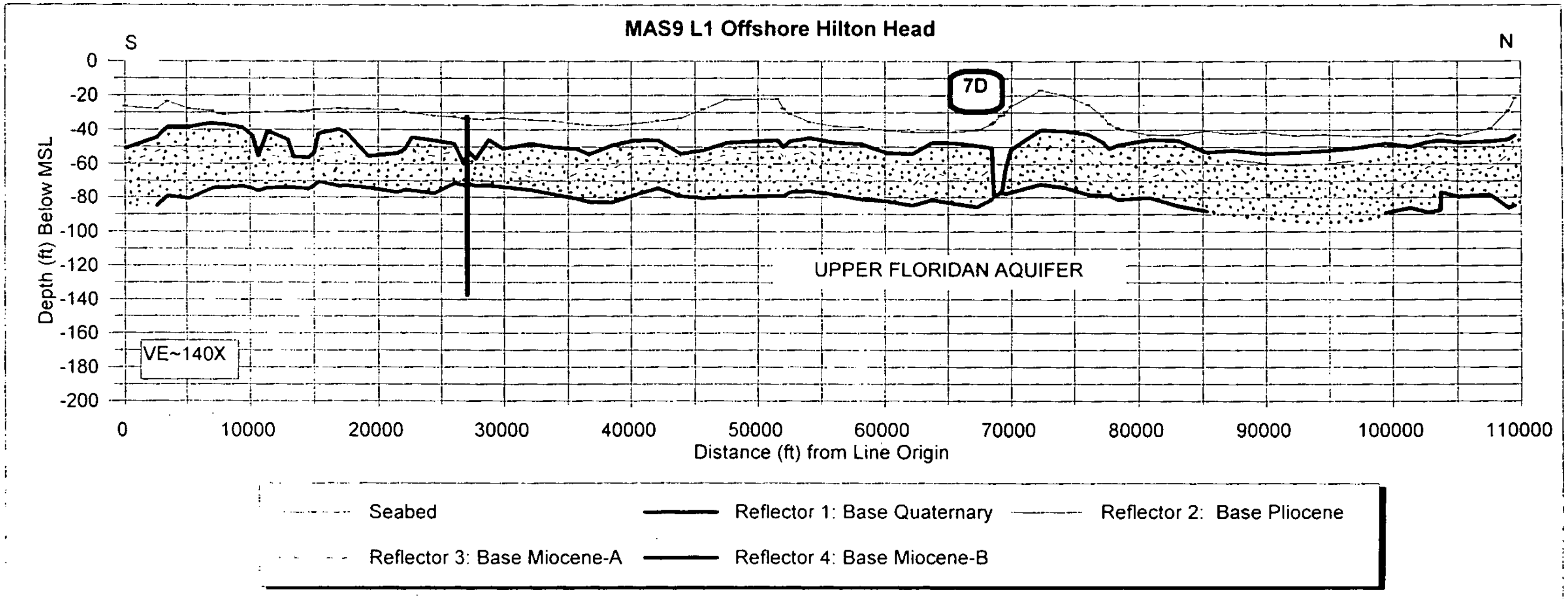


Fig. 3-15 Coast-oblique oriented cross section along Seismic Line MAS9 L1 located offshore of Hilton Head Island at the Hilton Head High. A potential seawater intrusion site is shown where the Miocene aquitard is absent beneath the paleochannel of the Savannah River (Site 7D; see Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. The location of borehole BFT-2249 (7-mile) is shown within the axis of the Savannah River paleochannel at a point inshore of Site 7D. See Figure 2-3 for location of section.

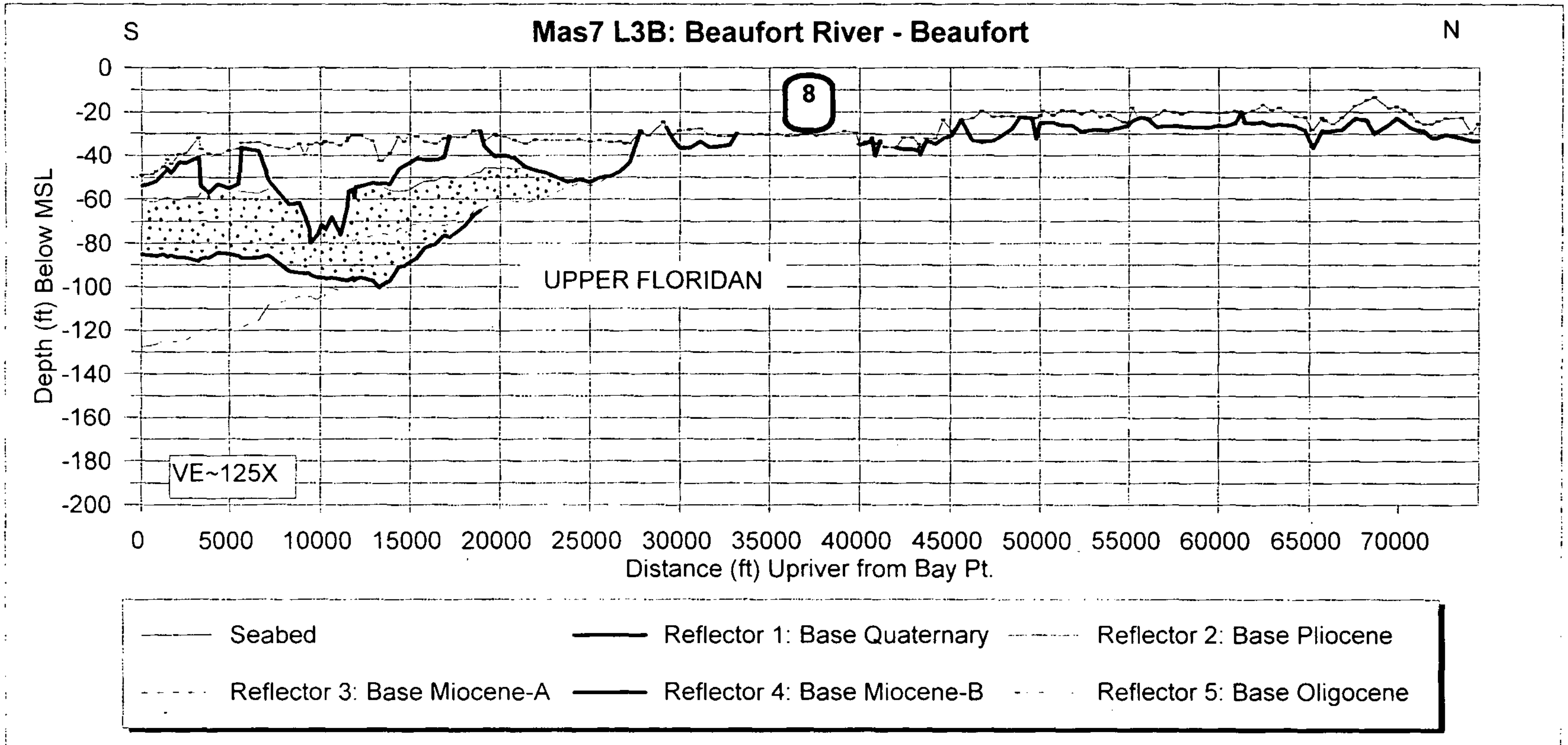


Fig. 3-16 Coast-normal oriented cross section along Seismic Line MAS7 L3B in the Beaufort River between Port Royal Sound and Beaufort, SC. An extensive potential seawater intrusion zone occurs along the right hand side of the section where the Miocene aquitard is absent (Site 8; see Table 3-1 and Fig. 3-2). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

AREAS OF CONCERN

The eleven no-Miocene areas described above constitute Areas of Concern (AOCs) where a risk of seawater intrusion exists. Each of the no-Miocene AOCs has the potential to be an area of seawater intrusion (recharge) because: (1) the aquitard is (absolutely or detectably) absent, (2) the potentiometric surface for the UFA is near or below mean sea level, and (3) the overlying water column is saline. Potential recharge of seawater (in $feet^3$/day) at each site could not be consistently and accurately determined due to uncertainties in the areal dimension of each site. However, each AOC is qualitatively ranked in Table 3-2 using a *potential pseudo-recharge rate* (discharge per unit width in $feet^2$/day) which is calculated using the length of each incision zone and a normalized incision width of 1 foot. The pseudo-recharge rate calculations are based on the leakage (modified Darcy's) equation previously used by Clarke et al. (1990) and the U.S. Army Corps of Engineers (1998) in their analyses of the Miocene confining unit on adjacent parts of the Georgia coast. The *pseudo-recharge* equation and its component terms are as follows:

$$Q' \doteq (K')\,(dh'/dl')\,(L)$$

where:

- Q' is the quantity of potential seawater recharge (Q) per unit width (W) of incision zone at each AOC (in $feet^2$/day).
- K' is the vertical permeability for the non-confining material (in feet/day). An inferred value of $7.5*10^{-3}$ feet/day is used for all AOCs and is an average of the rates measured from post-Miocene paleochannel deposits beneath the Savannah River (U.S. Army Corps of Engineers, 1998).
- dh' is the difference in potentiometric elevation (in feet) between the top of the UFA and the top of the non-confining material. At each AOC this number is derived from recent potentiometric maps for the UFA (Peck et al.,1999; Ransom and White, 1999) and from the assumption that the potentiometric head in the non-confining material is at 0 feet Mean Sea Level (MSL).
- dl' is the average thickness of the non-confining material (in feet) at each AOC. It is measured from seismic sections.
- dh'/dl' is the vertical hydraulic gradient between the top and the base of the non-confining material (in feet/foot).
- L is the length of the incision at each AOC (in feet). It is measured from seismic sections.

Because of the lack of certainty in the width dimension of each AOC, susceptibilities to seawater intrusion derived from the above equation are necessarily qualitative (Table 3-2). The ranking is also qualitative because variation in the incision widths of each AOC could result in the true (potential) recharge rates for any given AOC being very different to the calculated pseudo-recharge rate.

Table 3-2 Qualitative ranking of Areas of Concern from Table 3-1. Ranking is based on the amount of leakage possible at each site. Relative ranking scale: I = highest susceptibility; XI = lowest susceptibility. K' for the non-confining material = $7.5*10^{-3}$ feet/day.

Location of Area of Concern (Location Numbers keyed to Fig. 3-2 and Plate 3-2b)	Incision length (L; in ft)	Potentiometric change across the post-Miocene (dh'; in ft)	Average thickness of non-confining material (dl'; in ft)	Vertical hydraulic gradient (dh'/dl')	**POTENTIAL PSEUDO RECHARGE (FT^2/DAY) RANKING**
(1) Cooper River at Calibogue Sound	3,500	-19	55	-0.35	**9.2** **I**
(6) Broad River near US Hwy 170 bridge	6,000	-2	10	-0.20	**6 9** **II**
(3) Colleton River at Victoria Bluff	3,000	-5	32	-0.16	**3.6** **III**
(2) Confluence of May River/Bull Creek	500	-14	35	-0.40	**1.5** **IV**
(7A) Beaufort Arch offshore Hilton Head	3,500	-1	25	-0.04	**1.1** **V**
(7B) Beaufort Arch offshore Hilton Head	1,500	-1	20	-0.05	**0.6** **VI**
(7D) Beaufort Arch offshore Hilton Head	700	-5	45	-0.1	**0.6** **VII**
(7C) Beaufort Arch offshore Hilton Head	1,500	-1	40	-0.025	**0.3** **VIII**
(4) Port Royal Sound at Hilton Head Island	500	-2	40	-0.05	**0.2** **IX**
(5) Broad River north of Daws Island	500	-2	38	-0.05	**0.2** **X**
(8) Beaufort River north of Paris Island	42,200	+2	2	+1.0	**out-flow** **XI**

The extensive thin-Miocene areas shown in Plate 3-2b (see also Figs. 3-4 to 3-18) defined by the 20-foot isopach contour are also sites of potential seawater intrusion. However, the rate of intrusion for any given location is expected to be lower (per unit area) than for the no-Miocene areas because both the aquitard and the post-Miocene section are present. The susceptibility to intrusion would be directly dependent on (1) the vertical permeability of the Miocene aquitard and the overlying non-confining strata, (2) the vertical thickness of aquitard and non-confining strata present, (3) the areal dimension of the site being considered, and (4) the location of the site on the potentiometric gradient within the cone of depression. Relating to Item (1), data from the Savannah River area (U.S. Army Corps of Engineers, 1998) indicates that the Miocene A unit is less "tight" than the Miocene B unit because the former is sandier, less silty, and less clay-rich than the latter. K′ for the Miocene A unit is about an order of magnitude higher than K′ for the Miocene B unit. However, with the exception of each AOC and a small area south of AOCs 7A, 7B, and 7C offshore of Hilton Head, the Miocene B unit is well developed, particularly in areas landward of Hilton Head Island (Fig. 3-19). Until vertical permeability data for the Miocene and post-Miocene strata in the South Carolina intracoastal and shelf areas are better quantified by other studies, these thin-Miocene areas cannot be meaningfully ranked in terms of susceptibility to seawater recharge. However, it can be stated that those areas where the Miocene is less than 10 feet thick in the vicinity of Sites 1, 2, 3, 7A, 7B, 7C, and 7D (in particular) are probable areas of enhanced leakage.

All AOCs in Tables 3-1 and 3-2 are characterized by an overlying water column with salinities that range from estuarine through oceanic. Mean annual salinities generally range from the high teens to the mid 30s (Thompson, 1972; Atkinson, 1985; Menzel et al., 1993). With the exception of AOC 8, all areas would potentially be subject to seawater intrusion. At AOC 8 (the lowest ranked breach site), the UFA is exposed at the seabed or is only thinly covered by post-Miocene strata. The elevation of the potentiometric head on the UFA at AOC 8 means that the UFA would likely be threatened by seawater intrusion for relatively short time periods during spring high tides, and less frequently by extreme tides associated with northeasterly storm events and hurricanes. This site consequently receives the lowest ranking in Table 3-2.

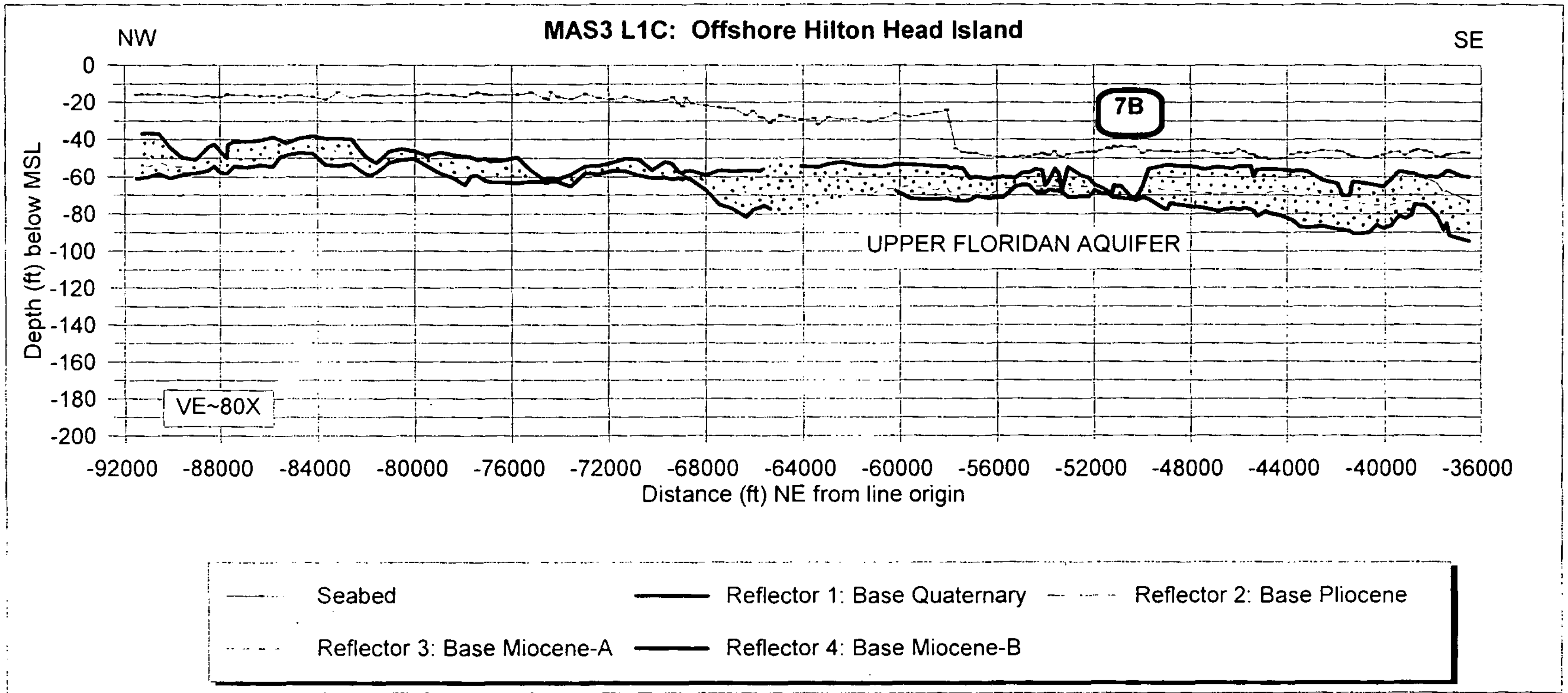


Fig. 3-17 Coast-normal oriented cross section along Seismic Line MAS3 L1C located offshore of Hilton Head Island at the Hilton Head High. The Miocene aquitard is very thin in several locations, including beneath the paleochannel of the Savannah River (Site 7B; see Figs. 3-2 and 3-13). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

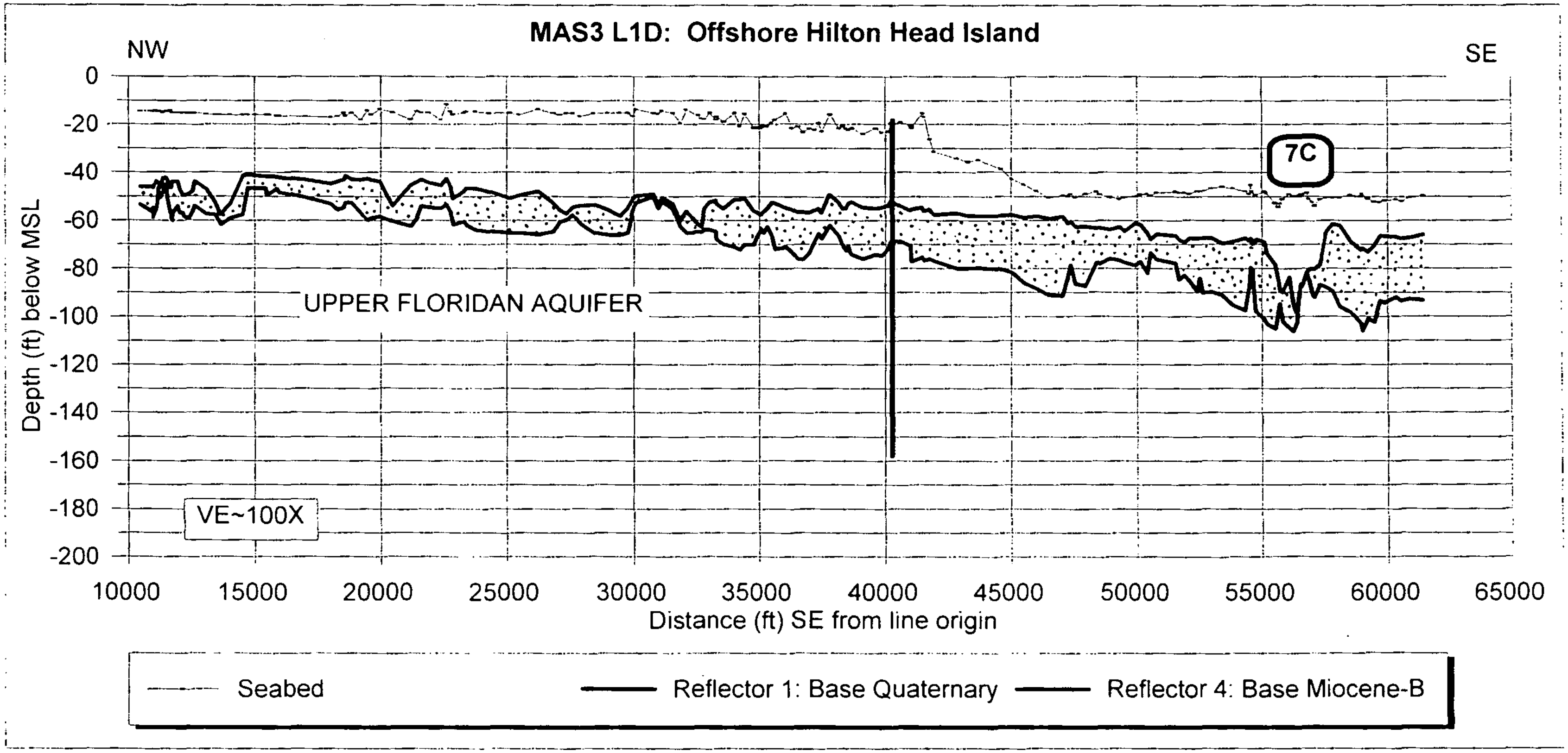


Fig. 3-18 Coast-normal oriented cross section along Seismic Line MAS3 L1D located offshore of Hilton Head Island at the Hilton Head High. The line runs parallel and to the northeast of Fig. 3-16. The Miocene aquitard is very thin beneath Gaskin Banks (at the 32,000 foot mark) and absent beneath the Savannah River paleochannel (Site 7C; see Figs 3-2 and 3-14). Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. The approximate location of borehole BFT-2258 (15-mile) is shown (actual location was about 1000 feet to the northeast and out of the plane of this section). See Figure 2-3 for location of section.

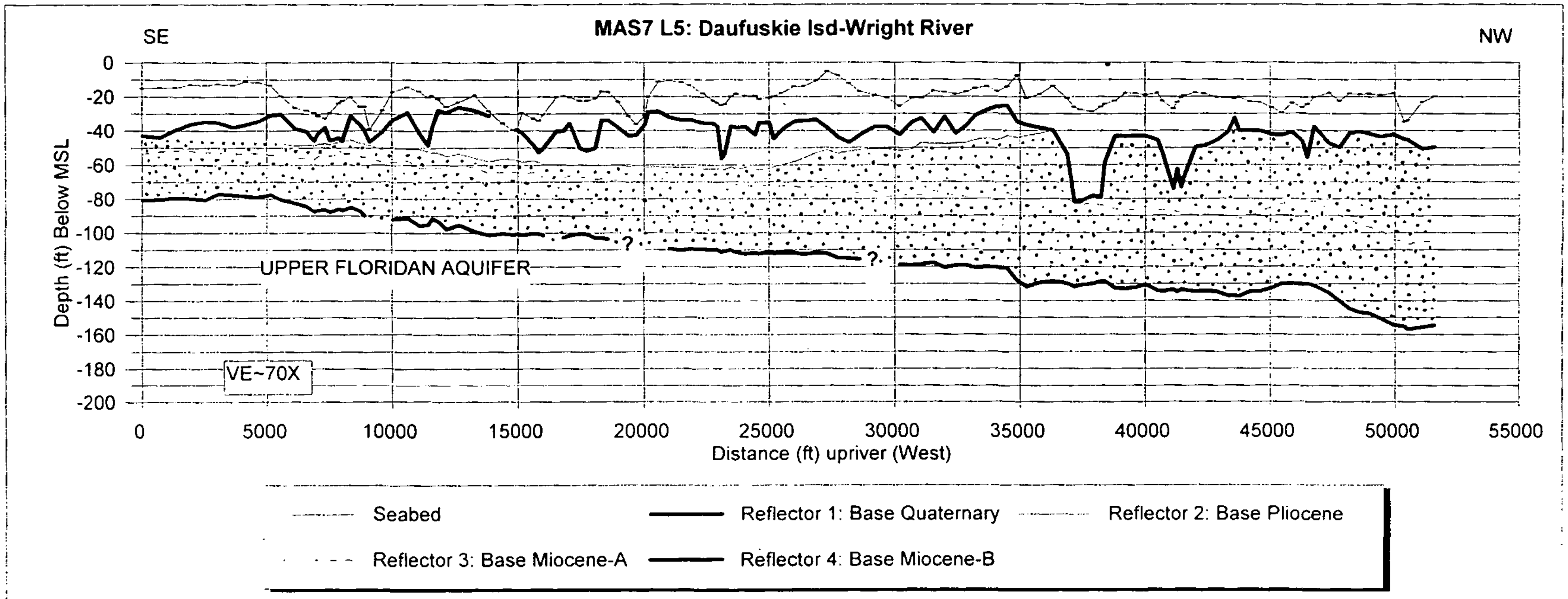


Fig. 3-19 Coast-normal oriented cross section along Seismic Line MAS7 L5 located in the Wright River landward of Daufuskie Island. The section shows the Miocene aquitard thickening significantly in the landward direction. The section also shows the extent of a Pliocene depocenter (strata between Reflectors *1* and *2*) that extends to the north behind Hilton Head Island out of the plane of section. Data sample points are shown as black points on the seabed reflector. Miocene strata are denoted with a stippled pattern and are underlain by the UFA. See Figure 2-3 for location of section.

PART 4: SUMMARY

1. This report was prepared to provide the Georgia Department of Natural Resources, Environmental Protection Division with geophysically derived information pertinent to identifying areas where the Upper Floridan aquifer (UFA) is susceptible to seawater intrusion in coastal Georgia and South Carolina. The study area covers about 1400 square miles of nearshore and estuarine areas between Wassaw Sound, GA, and Port Royal Sound, SC), a coastline length of approximately 37 miles. The approximate onshore boundary to the study is US Highway 17/170 linking Savannah, GA, and Beaufort, SC, while the seaward boundary is a coast-parallel line located approximately 30 miles offshore. Most of the study area lies within the eastern portion of the Savannah cone of depression on the UFA.

2. The principal objective of the study is to identify coastal areas where the Miocene aquitard overlying the UFA is thin or absent. The Miocene has the greatest probability of being thin or absent where the UFA occurs at shallow depth and where either (1) modern tidal creeks (or dredged channels) cut down into or through the Miocene or (2) paleochannels incised during lowstands of sea level cut down into or through the Miocene. The primary means of identifying these areas involved applying principles of seismic sequence stratigraphy to marine seismic reflection data.

3. 1215 miles of sub-bottom, single-channel, seismic reflection data form the primary dataset for this report. Eight hundred miles of archive data collected between 1970 and 1997 were augmented with 415 miles of new data collected during 1999-2001. Available borehole lithology-log and gamma-log data were used to ground-truth the seismic-stratigraphic interpretations and to provide control in areas where seismic coverage was limited.

4. Depths to the top of the UFA range from as shallow as -19 feet MSL just north of Beaufort, S.C., to as deep as -260 feet MSL southwest of Savannah, GA, and -280 feet MSL in the southeast part of the study area. Throughout intracoastal and offshore Georgia, the aquifer everywhere lies at depths of at least -100 feet MSL. On the South Carolina shelf, the Beaufort Arch passes seaward beneath Hilton Head Island so that the aquifer is locally as shallow as -48 feet MSL on the Hilton Head High located about 3.5 miles offshore.

5. The thickness of the Miocene aquitard varies significantly over short horizontal distances because it is determined by the vertical separation between overlying and underlying composite erosional surfaces. These surfaces are, respectively, a very crenulated Plio-Holocene erosional surface that defines the top of the aquitard; and an irregular karstic erosional surface that defines the base of the aquitard and the top of the UFA.

6. Depths to the top of the Miocene aquitard generally range from approximately -10 feet MSL near Beaufort, SC, to -75 feet MSL beneath Wassaw Sound, GA, to approximately -170 feet MSL offshore and in the Tybee Trough area. The shallowest parts of the aquitard overlie topographic highs on the UFA, notably along the Beaufort Arch in the Beaufort area, behind Hilton Head Island, and seaward of Hilton Head Island at the Hilton Head High. Depths to the

base of the aquitard are synonymous with depths to the top of the UFA.

7. In areas south of the Savannah River and within the cone of depression, the UFA is deep enough, the Miocene aquitard thick enough, and the tidal creeks and paleochannels shallow enough that the probability of occurrence of areas of thin or absent aquitard is very low; no such areas were detected during this study. A similar scenario exists seaward of a coast-parallel line located about 20 miles off the Georgia/South Carolina coast. Additionally, this latter area is outside of the cone of depression on the UFA. The probability of seawater intrusion due to aquitard thinning or breaching in both areas is inferred to be very low.

8. On the Georgia coast and inner shelf, seismic data indicate that the Miocene is in most areas thicker than 40 ft. Exceptions occur at ten small localized areas on the lower Savannah River and Navigation Channel. These localized thin spots (28-40 feet of Miocene) mark where buried Quaternary paleochannels pass beneath seismic tracklines.

9. The principal areas of thinned or absent Miocene strata occur beneath the intracoastal and inner shelf region of South Carolina. Approximately 540 square miles are underlain by less than 40 feet of Miocene. Of this area, approximately 420 square miles are underlain by less than 30 feet of Miocene, approximately 195 square miles are underlain by less than 20 feet of Miocene, and approximately 53 square miles are underlain by less than 10 feet of Miocene.

10. Over 50% of the thin-Miocene area (less than 40 feet of Miocene) occurs south and southeast of the Broad River and within the eastern portion of the Savannah cone of depression. These areas are directly associated with the south-southeast trending Beaufort Arch. Outside of the Savannah cone of depression and north of the Broad River-Port Royal Sound area, the Miocene aquitard is absent along at least 8 miles of the Beaufort River channel between southern Parris Island and the town of Beaufort, SC. Here, the Floridan aquifer either crops out at the sea floor or is covered by only a thin veneer (generally 0 to 10 feet) of post-Miocene strata. This is the only part of the study area where the UFA was observed to be in direct, or close-direct, contact with the seabed.

11. A total of eleven localized Areas of Concern (AOCs) exist where the Miocene aquitard is no longer preserved. Collectively, these sites comprise an estimated area of about 7 square miles (Plate 3-2b). Each AOC is susceptible to seawater intrusion because (1) the aquitard is absent, (2) the potentiometric surface for the UFA is near or below mean sea level, and (3) the overlying water column is saline. A qualitative ranking scheme based on potential seawater pseudo-recharge rates allows AOCs to be ranked in order of susceptibility to seawater intrusion. The ranking is as follows (highest susceptibility = I, lowest susceptibility = XI):

    Rank I: Inner Calibogue Sound (AOC 1). Beneath a paleochannel of the Savannah River, the Miocene is absent along a trackline length of approximately 3,500 ft. About 55 feet of post-Miocene strata overlie the incision point.

    Rank II: The Broad River near the US Highway 170 bridge (AOC 6). The Miocene is absent along a trackline length of about 6000 feet. Approximately 10 feet of non-confining strata overlie the incision point.

Rank III: The Colleton River near Victoria Bluff (AOC 3). The Miocene aquitard is locally absent along a trackline length of about 3000 feet at an inferred sinkhole. Approximately 25 to 40 feet of non-confining strata overlie the incision point.

Rank IV: Near the confluence of the May River and Bull Creek (AOC 2). Beneath a probable paleotributary of the Savannah River, the Miocene is absent along a trackline length of about 500 ft. Approximately 35 feet of non-confining strata overlie the incision point.

Rank V: On the Beaufort Arch offshore of Hilton Head Island (AOC 7A). The Miocene is absent beneath the main paleochannel of the Savannah River along a trackline length of about 3500 feet. Approximately 15-35 feet of non-confining strata overlie the incision point.

Rank VI: On the Beaufort Arch offshore of Hilton Head Island (AOC 7B). The Miocene is absent beneath the main paleochannel of the Savannah River along a trackline length of about 1500 ft. About 20 ft of non-confining strata overlie the incision point.

Rank VII: On the Beaufort Arch offshore of Hilton Head Island (AOC 7D). The Miocene is absent along a trackline length of about 700 feet. About 45 feet of non-confining strata overlie the incision point.

Rank VIII: On the Beaufort Arch offshore of Hilton Head Island (AOC 7C). The Miocene is absent beneath the main paleochannel of the Savannah River along a trackline length of about 1500 feet. About 40 feet of non-confining strata overlie the incision point.

Rank IX: Inner Port Royal Sound near northern tip of Hilton Head Island (AOC 4). Beneath a paleochannel, the Miocene is absent along a trackline length of about 500 feet. Approximately 40 feet of non-confining strata overlie the incision point.

Rank X: Broad River north of Daws Island (AOC 5). Beneath a pair of small paleochannels, the Miocene is absent along a trackline length of approximately 500 feet. Approximately 38 feet of non-confining strata overlie the incision point.

Rank XI:Beaufort River between Paris Island and Beaufort (AOC 8). Beneath the axis of the Beaufort River, the Miocene aquitard is absent along a trackline length of over 8 miles. The UFA is either exposed at the river bed or covered with a thin veneer (0 to 10 feet) of post-Miocene strata. The area lies just outside of the Savannah cone of depression and consequently has a positive potentiometric head most of the time.

12. The eleven Areas of Concern listed above were ranked on the basis of potential pseudo-recharge rates. It should be recognized that the AOCs do not represent an exhaustive list of potential seawater intrusion sites in the coastal Georgia/South Carolina area.

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APPENDIX A: INFORMATION ON THE ARCHIVE DATA USED IN THE PHASE I REPORT

Eight hundred miles of pre-existing high-resolution seismic-reflection (boomer and airgun) data were compiled for Phase I. Table A-1 summarizes information on line coverage and quality for these data that were collected between 1970 and 1997. The intracoastal area was covered by approximately 360 miles of data, while the inner shelf was covered by the remaining 440 miles of data. Eighty percent (630 miles) of the data was of sufficient quality to permit interpretation for the purposes of this project. Interpretable data were generally confined to depths within 200 ft of Mean Sea Level (MSL).

Approximately 700 of the 800 miles of data were obtained from archives at the Georgia Southern University Applied Coastal Research Laboratory (GSU-ACRL). These data were collected during several studies in 1972-1976, 1979-1980, 1985, and 1989 in coastal South Carolina and Georgia, and on the Atlantic inner shelf in areas west and south of the Tybee Trough. About fifty-five miles of data from coastal South Carolina were provided by the South Carolina Department of Health and Environmental Control (DHEC) from a 1970 survey conducted in the Port Royal Sound area of Beaufort County (South Carolina Water Resources Commission, 1972). Approximately forty miles of data from coastal Georgia were provided by the U.S. Army Corps of Engineers from a 1997 survey conducted in the Savannah River and Navigation Channel (U.S. Army Corps of Engineers, 1998; Ocean Surveys Inc., 1998).

Reflectors on the seismic records were sampled for elevations at horizontal intervals of 750 - 1000 ft and at all points of significant elevation change. In areas where the stratigraphy had a simple "layer-cake" character, the records were sampled approximately every 1500 - 3000 ft. For each sample location, the survey time mark was noted and the two-way-travel times to the seabed and subbottom reflectors were measured. The geographic location (distance along the profile line) of each sample "site" was then calculated using trackline plots that showed timed position fixes. All data were then tabulated into a Corel QuattroPro® spreadsheet, where a routine was run to convert acoustic travel times (milliseconds) into depths (feet). Distance versus depth cross-sections were then generated to show structural and stratigraphic information. Data points from these cross sections were transferred to 1:100,000-scale mylar smooth-sheets to show elevations of the top of the Floridan aquifer and thicknesses of the Miocene aquitard along each trackline. These data points were then hand contoured, photo-reduced, and scanned into CorelDraw® to produce page-size (~8.5 x 11") maps at a scale of approximately 1:400,000.

In terms of data georeferencing, the positional accuracy of the data has limitations imposed by the marine positioning systems used when the data were collected. Each reflector on the cross-sections and maps generated for the Phase I Report (Foyle et al., 1999) has inherent vertical (elevation) and horizontal (latitude/longitude) errors.

Several sources of potential vertical (Z) error arise when the graphic printouts showing survey time (abscissa) versus acoustic travel time (ordinate) are converted to geologic cross sections showing location (latitude-longitude) versus depth (feet). The principal potential sources of error in calculating the depth of a specific reflector are, in order of importance: (1) acoustic velocity variation, (2) tidal stage, (3) record interpretation, and (4) signal incidence angle. Overall, it is estimated that depths to specific reflectors shown on cross sections and maps in the Phase I Report are, as a worst-case scenario, accurate to +/-12 ft. Because these four sources of error affect depth calculations for the top of the Miocene and the top of the aquifer similarly, isopachs for the Miocene aquitard are affected only by the acoustic-velocity error. Isopach contours are therefore, as a worst-case scenario, accurate to +/-5 ft or better.

Horizontal errors affect the geographic (X-Y) accuracy of a given data point. This error ranges from +/- 1300 ft for Loran-C navigation used in the 1970-1985 surveys to +/- 30 ft or less for DGPS navigation used in the most recent 1998 surveys.

To make the archive data described above more compatible with the new data in this report, the archive data were corrected to Mean Sea Level datum prior to merging with the new data in a master Surfer® dataset for computer-contouring purposes. This was achieved using NOAA archive tidal data from Fort Pulaski on the lower Savannah River (NOAA, 2000). Tides at Fort Pulaski closely approximate tide levels throughout the study area and the NOAA archive for that station contained the most complete tidal data set for the study area. A slant-path correction was also applied to the archive geophysical data to reduce the effects of non-vertical acoustic signal incidence at the seafloor. These two adjustments to the archive data improved their vertical accuracy by about 5 ft. For compatibility with the Surfer® database, all sample points on the archive seismic records were assigned actual or interpolated geographic (latitude/longitude) coordinates. These were derived from cruise tracklines for which navigation fixes were typically plotted on nautical charts at 1-mile (or 15 minute) intervals.

Table A-1 Summary information for archive seismic trackline data

Line number / id	Date of survey	Length and time of survey	Surveyed area	Quality
SCWRC Colleton River (WRC-D)	7.22.70	13 miles 10:28 - 12:25	Colleton River - PRS entrance.	Good
SCWRC Broad River (WRC-C)	7.21.70	16 miles 16:02 - 16:44; 12:35 - 14:45	Cole Creek - Port Royal Sound (PRS) entrance.	Moderate-Good
SCWRC Skull Creek (WRC-E)	7.22.70	12 miles 13:30 - 15:52	Chechessee River - Skull Creek - May River.	Good
SCWRC Beaufort River (WRC-B)	7.23.70	14 miles 07:34 - 09:43	Beaufort River (Ballast Creek) - Coosaw River (Buoy #203).	Poor-Moderate
VJH Line U-56	6.13.72	5 miles 14:39 - 16:16	Wassaw Sound at C11 - Wilmington River at Tybee Cut	Moderate
VJH Line U-57	2.12.74	17 miles 14:15 - 16:50	Wassaw Sound at C11 - R2W - Savannah Light	Moderate
VJH Line U-58	4.23.73	10 miles 11:56 - 13:32	Wassaw Sound - Tybee Cut - Wassaw Sound	Moderate
VJH Line U-61	4.26.73	7 miles 07:55 - 09:29	I-80 at Screvens Pt - St Augustine Ck - Wilmington R - Savannah River at R50	Good
VJH Line U-62	4.23.72	10 miles 14:33 - 16:29	I-80 at Screvens Pt - Wassaw Sound	Good
VJH Line U-63	4.28.72	7 miles 10:37 - 12:10	Wilmington River from Priest Ldg - Thunderbolt at R34	Good
VJH Line U-63A	4.28.72	5 miles 12:15 - 13:52	Wilmington Riv @ R34 -> SkIO Dock	Good
VJH Line U-72-73	4.25.73	23 miles 12:26 - 16:11	Savannah River at Onslow Island - Savannah River at G17/R18	Moderate
VJH Line U-74	6.12.72	5 miles time? - time?	St Aug Ck at R10 - Elba Is Cut - Fields Cut - Wright R at R44B	Poor-Moderate
VJH Line U-78	?	10 miles 17:08 - 18:43	Wilm River at R40 - Skidaway River - Vernon River - Possum Pt at G79	Poor-Moderate
VJH Line U-91	3.3.74	29 miles 15:50 - 19:17	S Edisto R at G159 - Coosaw River - Beaufort River - Beaufort at G241A	Poor
VJH U-92-93	3.14.74	33 miles 06:54 - 10:42	Beaufort River at G41 -Fields Cut - Savannah River at R48	Poor-Moderate
VJH U-113	?	6 miles 08:47 - 09:37	Calibogue Sound at R32 - New River at G41 -	Good
VJH U-115	?	6 miles 09:47 - 10:34	New Riv at R42 - Wilmington River at R12	Moderate

VJH U-116	3.25.75	11 miles 07:40 - 09:26	Skull Ck at R6 - Port Royal Sound - G19	Poor-Moderate
VJH U-117	3.26.75	38 miles 11:00 - 16:35	Hilton Hd - Port Royal Sound- Coosaw River - St Helana Sound at R12	Poor-Moderate
VJH U-118	3.27.75	18 miles 09:52 - 13:06	Broad River Bridge - Port Royal Sound	Poor
VJH U-119	3.27.75	23 miles 14:50 - 17:47	Callawassie Ck - Colleton River - Skull Creek - Calibogue Sd R32	Moderate-Good
VJH U-121	7.11.76	11 miles 14:10 - 15:25	Halfmoon River - Wassaw Sound at R14 - Priest Ldg - Sister Island	Good
VJH U-122	7.11.76	17 miles 09:26 - 12:04	Skidaway River at G27 - Wilmington River - Lazaretto Creek - Tybee Inlet	Good
VJH U-122A	7.11.76	2 miles 12:56 - 13:16	Bull River - Shad River	Good
VJH U-128	?	2 miles	Skidaway River test at R46	Moderate
VJH U-259 GS-TT Lines 1-8	9.3/4.80	106 miles 14:57 - 23:40 07:37 - 14:35	Gaskin Banks - Port Royal Sound - Savannah Light	Good
VJH U-241 GS-7 Lines 14-20	5.8/9.80	53 miles 15:19 - 03:15	Tybee Trough area - Port Royal Sound Light - offshore Tybee Island	Moderate-Good
VJH U-221 GS-4 Lines 41, 41-rerun	5.9.79	26 miles 06:10 - 08:19 08:24 - 12:10	Tybee Trough area (SE - NW)	Moderate-Good
MP-1 Lines 32 - 36	7.16/17. 1985	63 miles 21:06 - 06:40	Near Savannah Light to offshore Wassaw Island	Poor
PRS-1 Lines 6 - 14	7.16.85	23 miles 11:40 - 21:06	Station Ck - Daws Island - Port Royal Sound - Savannah Light	Poor
GS-6 Lines 1, 2, 20	10.22/23 & 10.25/26.1979	77 miles 13:56 - 00:45 12:15 - 14:00	Tybee Trough area	Poor
GS-5 Line 1	6.18/22. 1979	34 miles 13:00 - 18:13	Tybee Trough area (SW-NE)	Poor
USACE 1997 Lines 1, 2, 3	10.3/6. 1998	39 miles	Onslow Island - Savannah River - Savannah Light	Good
AMP2-2	8.16.89	25 miles 13:11 - 17:33	Savannah Light - TACTS-A platform	Moderate

APPENDIX B: SAMPLE SURFER® SPREADSHEET FOR THE MIOCENE AQUITARD STUDY

	A	B	C	D	E	F	G	H
1	LAT	LONG	BATHYFT	TOPAQFT	LINE #	MIO-ISOP	OPTAQ	OPTMIO
2	31.9800	80.7632	-28.0	-116.1	START	51.9		
3	31.9810	80.7630	-29.4	-113.1	MAS3L1A	44.6		
4	31.9827	80.7628	-30.8	-120.0		54.4		
5	31.9833	80.7628	-37.5	-124.0		53.0		
6	31.9838	80.7622	-45.9	-123.7		55.5		
7	31.9843	80.7617	-45.4	-122.9		60.0		
8	31.9847	80.7612	-46.7	-122.0		64.1		
9	31.9848	80.7610	-46.7	-122.9		59.4		
10	31.9850	80.7607	-30.9	-125.7		64.1		
11	31.9863	80.7592	-30.1	-123.5		60.0		
12	31.9883	80.7565	-30.9	-126.3		60.5		
13	31.9890	80.7557	-30.9	-123.0		57.2		
14	31.9900	80.7545	-31.5	-120.8		53.8		
15	31.9925	80.7518	-32.9	-115.2		50.2		
16	31.9932	80.7513	-33.5	-114.4		47.4		
17	31.9943	80.7500	-33.8	-113.2		43.8		
18	31.9967	80.7473	-34.4	-113.8		47.4		
19	31.9982	80.7455	-36.5	-116.0		50.2		
20	31.9998	80.7437	-35.2	-113.3		48.8		
21	32.0003	80.7430	-35.5	-116.4		53.0		
22	32.0013	80.7420	-36.6	-116.1		51.0		
23	32.0017	80.7415	-36.6	-115.5		51.0		
24	32.0022	80.7412	-37.4	-115.8		50.5		
25	32.0027	80.7410	-37.4	-118.9		53.5		
26	32.0033	80.7407	-36.6	-117.5		53.0		
27	32.0042	80.7403	-38.0	-115.5		51.0		
28	32.0053	80.7397	-38.5	-120.2		53.8		
29	32.0067	80.7390	-38.0	-116.1		50.2		
30	32.0072	80.7388	-38.3	-113.6		47.7		
31	32.0085	80.7382	-38.0	-113.3		48.8		
32	32.0090	80.7380	-38.0	-113.3		46.0		
33	32.0095	80.7378	-38.0	-113.3		50.8		
34	32.0103	80.7373	-39.1	-113.0		51.6		
35	32.0112	80.7368	-39.4	-111.9		51.6		
36	32.0117	80.7365	-39.4	-111.9		51.6		
37	32.0120	80.7363	-39.4	-110.5		49.4		
38	32.0148	80.7385	-38.6	-111:1		53.0		
39	32.0157	80.7392	-38.6	-111.2		53.5		
40	32.0165	80.7398	-39.5	-109.2		48.8		
41	32.0172	80.7403	-36.9	-109.4		50.8		
42	32.0178	80.7408	-34.2	-999.0		>37		
43	32.0185	80.7415	-38.2	-999.0		>37		
44	32.0200	80.7427	-36.9	-999.0		>37		
45	32.0213	80.7438	-36.9	-999.0		>37		
46	32.0238	80.7455	-37.0	-107.0		>37		

Notes:

1 ... 46:	Spreadsheet row numbers (range from 1 to 6700)
A ... H:	Spreadsheet column numbers
LAT/LONG:	Latitude and Longitude of the sample point, in degrees and decimal degrees
BATHYFT:	Water depth at the sample point, in feet corrected to Mean Sea Level (MSL)
TOPAQFT:	Depth to the top of the UFA, in feet below MSL. Assigned "-999" value where uncertain
LINE #:	Seismic survey line number (see Tables 2-1 and A-1 in text)
MIO-ISOP:	Thickness of the Miocene aquitard at the sample point, in feet. Estimated (e.g. >37) where uncertain

APPENDIX C: INFORMATION ON DATA ACCURACY

Data presented in this report have horizontal and vertical accuracies determined by the DGPS systems used during surveys and uncertainties concerning the velocity of acoustic waves in water and sediments. Each point on a reflector in a cross-section, and each contour on a contour map, therefore has a small inherent horizontal (latitude/longitude) and vertical (elevation or depth) error.

Horizontal errors affect the geographic (latitude and longitude (X and Y)) accuracy of a given data point. The DGPS systems generally allowed the position of the GPS antenna to be determined to within 10-13 ft (3-4 m). The acoustic boomer plate and hydrophone array were typically towed 100 ft behind the antenna during surveys. The Phase I data has horizontal errors ranging from +/- 1300 ft for Loran-C navigation used during 1970-1985 surveys to +/- 30 ft or less for DGPS navigation used during 1998 surveys.

Vertical (depth or Z) errors can occur when the graphic printouts showing location or time (abscissa) versus acoustic travel time (ordinate) are converted to geologic cross sections showing location (distance from line origin or latitude-longitude) versus depth (feet). The principal potential sources of error in calculating the depth of a specific reflector are, in order of importance:

1. Acoustic Velocity Variation: The vertical travel time to a given reflector on the graphic printouts (a known quantity) is converted to depth to that reflector using an acoustic velocity (generally an estimated quantity). For this study, an average acoustic velocity of 4922 ft/sec was inferred for the water column. Acoustic velocities in the water column are known to generally range from 4922 to 4987 ft/sec (Pickard and Emery, 1982) and tend to increase with temperature (13 ft/sec/degree C), salinity (5 ft/sec/salinity unit) and depth (0.02 ft/sec/foot). An average velocity of 5578 ft/sec was inferred for the sediment column down to the top of the aquifer (generally *Reflector 4*). An average velocity of 6955 ft/sec was inferred for Oligocene strata in those areas where they were preserved between *Reflectors 4 and 5.* Acoustic velocities in the sediment column can also show variation due to changes in the degree of induration of the sediments (e.g., hard limestone layers in the Miocene would have higher velocities than adjacent sands). The inferred sediment velocity values were based on best-fit comparisons between borehole data (or published structure maps) and seismic records, as well as on previous seismic-reflection work conducted on the South Atlantic Bight (Duncan, 1972; Henry and Idris, 1992; Ocean Surveys, Inc., 1998; U.S. Army Corps of Engineers, 1998). A 150 ft/sec variation from the mean acoustic velocity used in time-to-depth conversions can yield a vertical error of +/- 5 feet.

2. Tidal Effects: The relative elevation of the survey vessel during surveying is controlled by the tidal stage. Between successive surveys, this dependence can result in vertical offsets of a given reflector of as much as +/-4 .5 feet relative to mean sea level, depending on the tidal stage during a survey. This effect can be greatest during spring tides but decreases in a seaward direction and during neap tides. This source of error was minimized by correcting all data to Mean Sea Level (MSL) datum using tidal elevation data from the NOAA Fort Pulaski tide station.

3. Signal Incidence: Acoustic energy traveling to and returning from shallow reflectors may not have true vertical incidence, as is generally assumed in the seismic-reflection method. This is particularly the case if the seismic source and streamer are deployed with a wide spacing on either side of the survey vessel. This effect results in an overestimation of reflector depth upon time-to-depth conversion. The error decreases with increasing depth to the reflector (20% error at 10 ft, 1% error at 50 ft). This source of error was minimized by applying a slant-path correction to the time-to-depth conversions.

Overall, it is estimated that depths to specific reflectors are generally accurate to +/- 6 ft. Because the three sources of error affect depth calculations for the top of the Miocene and the top of the aquifer similarly, isopachs for the Miocene aquitard are affected only by the acoustic-velocity error. Isopach contours are therefore estimated to be accurate to +/-5 ft or better.

Vertical resolution refers to the ability of the seismic system to resolve the upper and lower boundaries to a stratigraphic unit. It is a function of the pulse energy emanating from the acoustic source and the depth to the stratigraphic interval of interest. For the seismic records used in this report, the resolution varies from about two feet for new data collected under ideal sea-state conditions to about 10 feet for the archive data collected with older seismic systems during rough-sea conditions.

PLATE 2-1

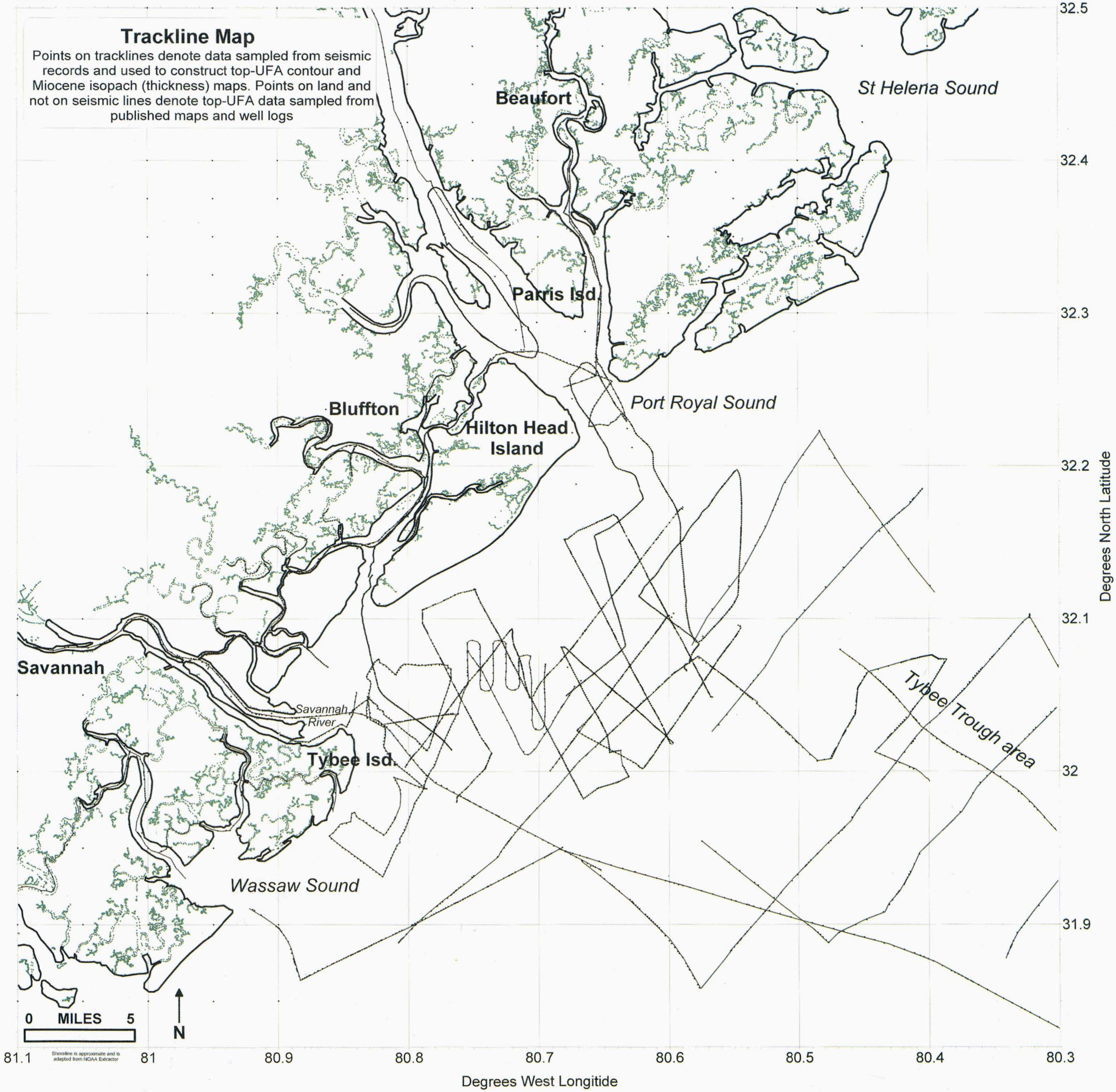
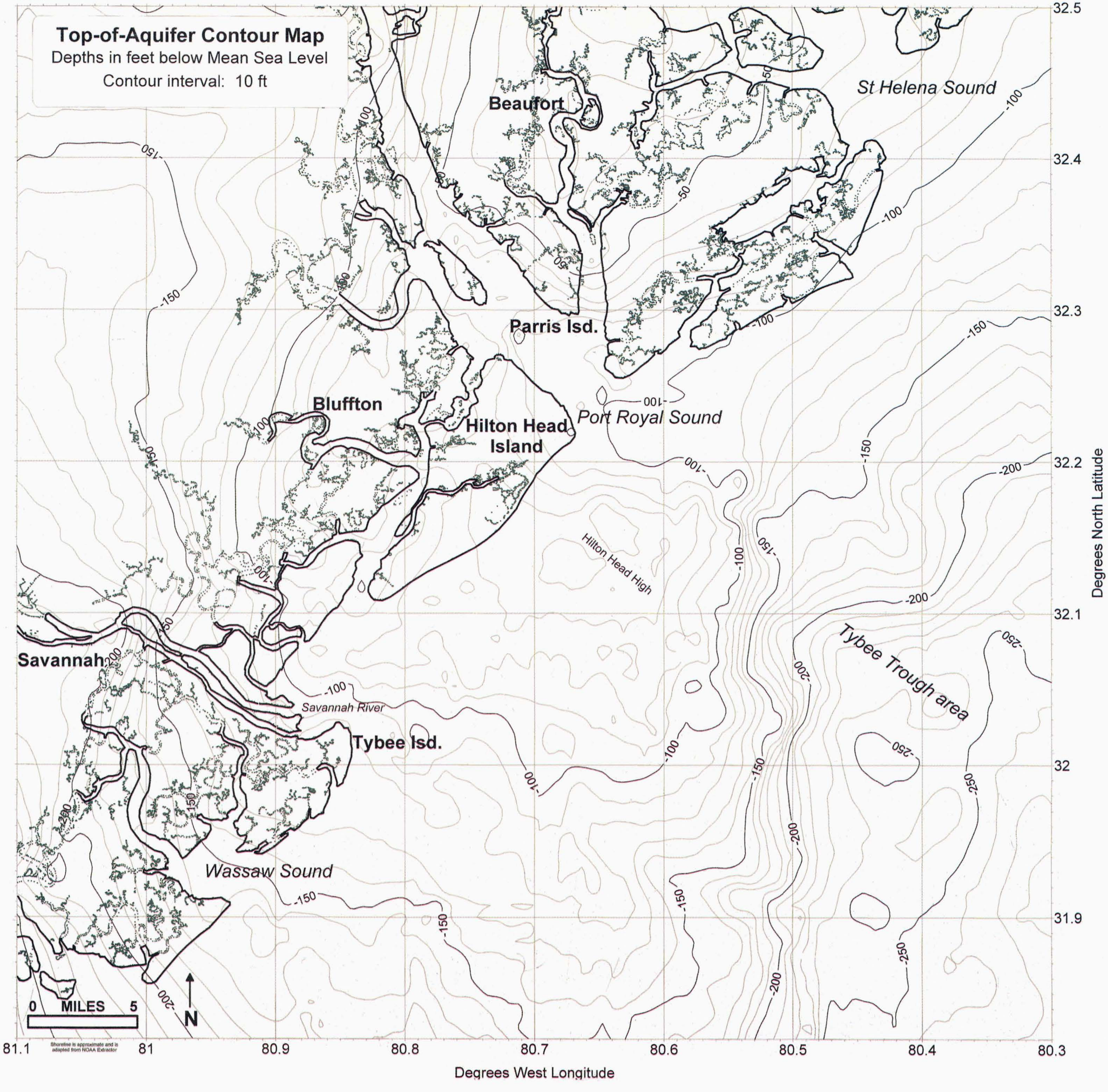
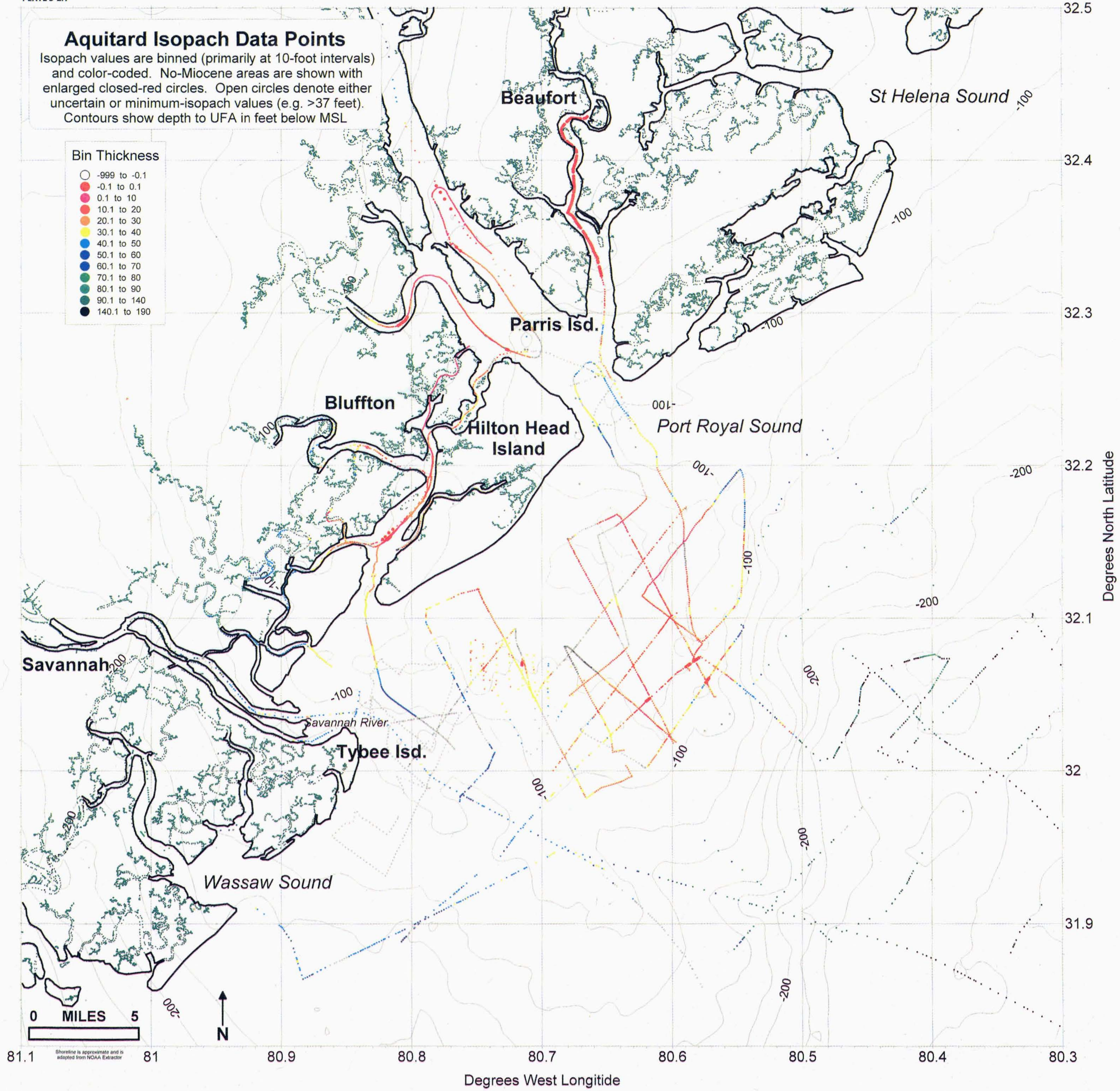

Trackline Map
Points on tracklines denote data sampled from seismic records and used to construct top-UFA contour and Miocene isopach (thickness) maps. Points on land and not on seismic lines denote top-UFA data sampled from published maps and well logs
Beaufort
St Helena Sound
Parris Isd.
Port Royal Sound
Bluffton
Hilton Head Island
Savannah
Savannah River
Tybee Isd.
Tybee Trough area
Wassaw Sound
0 MILES 5
N
Shoreline is approximate and is adapted from NOAA Extractor
32.5
32.4
32.3
32.2
32.1
32
31.9
Degrees North Latitude
81.1
81
80.9
80.8
80.7
80.6
80.5
80.4
80.3
Degrees West Longitide

PLATE 3-1

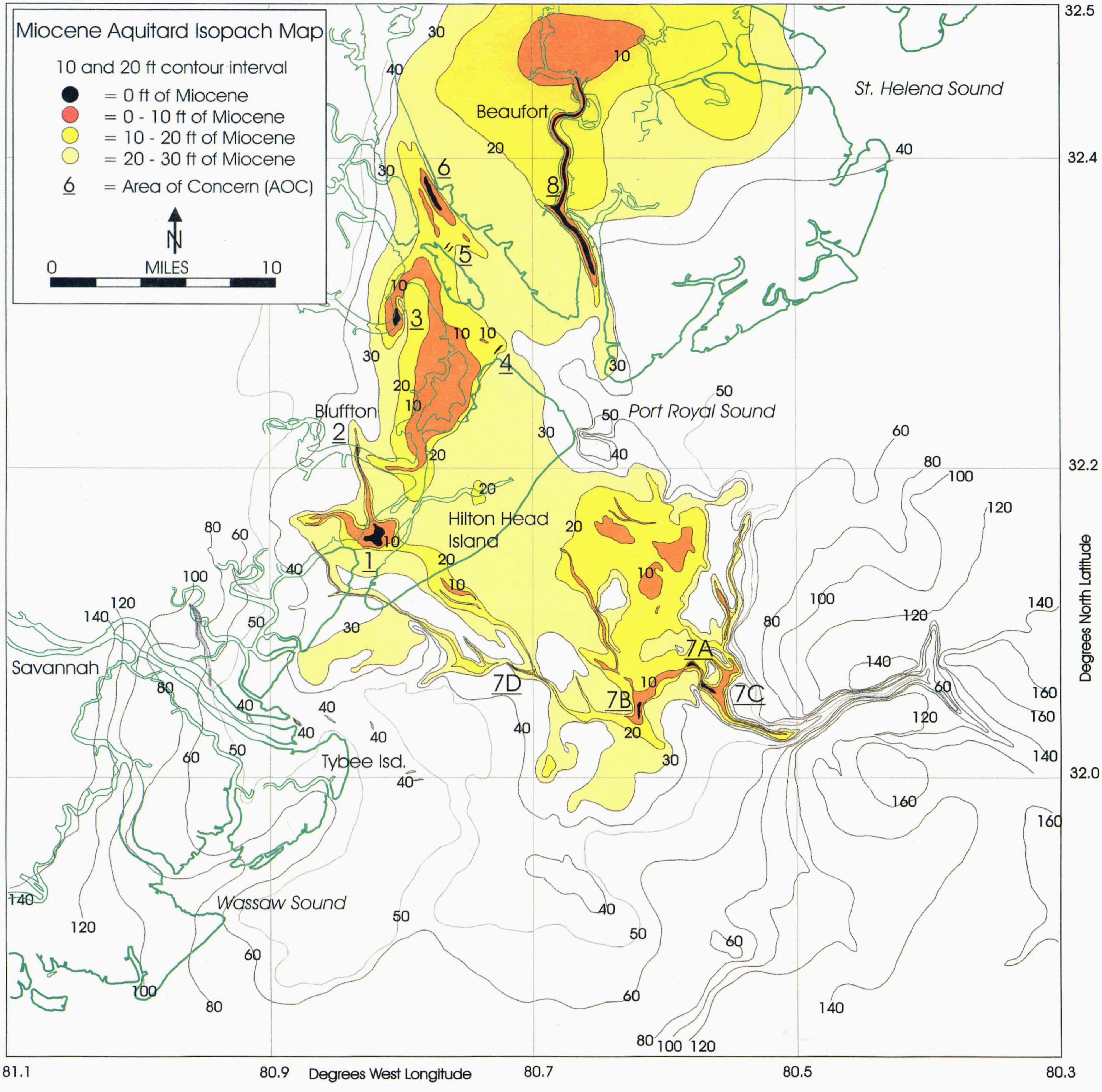


Top-of-Aquifer Contour Map
Depths in feet below Mean Sea Level
Contour interval: 10 ft
Beaufort
St Helena Sound
Parris Isd.
Bluffton
Hilton Head Island
Port Royal Sound
Hilton Head High
Tybee Trough area
Savannah
Savannah River
Tybee Isd.
Wassaw Sound
0 MILES 5
N
Shoreline is approximate and is adapted from NOAA Extractor
-50
-100
-150
-200
-250
32.5
32.4
32.3
32.2
32.1
32
31.9
81.1
81
80.9
80.8
80.7
80.6
80.5
80.4
80.3
Degrees West Longitude
Degrees North Latitude

PLATE 3-2A



Aquitard Isopach Data Points
Isopach values are binned (primarily at 10-foot intervals) and color-coded. No-Miocene areas are shown with enlarged closed-red circles. Open circles denote either uncertain or minimum-isopach values (e.g. >37 feet). Contours show depth to UFA in feet below MSL
Bin Thickness
-999 to -0.1
-0.1 to 0.1
0.1 to 10
10.1 to 20
20.1 to 30
30.1 to 40
40.1 to 50
50.1 to 60
60.1 to 70
70.1 to 80
80.1 to 90
90.1 to 140
140.1 to 190
Beaufort
St Helena Sound
Parris Isd.
Bluffton
Hilton Head Island
Port Royal Sound
Savannah
Savannah River
Tybee Isd.
Wassaw Sound
-100
-200
0 MILES 5
N
Shoreline is approximate and is adapted from NOAA Extractor
32.5
32.4
32.3
32.2
32.1
32
31.9
81.1
81
80.9
80.8
80.7
80.6
80.5
80.4
80.3
Degrees North Latitude
Degrees West Longitide


Miocene Aquitard Isopach Map
10 and 20 ft contour interval
= 0 ft of Miocene
= 0 - 10 ft of Miocene
= 10 - 20 ft of Miocene
= 20 - 30 ft of Miocene
6 = Area of Concern (AOC)
N
0 MILES 10
Beaufort
St. Helena Sound
Port Royal Sound
Bluffton
Hilton Head Island
Savannah
Tybee Isd.
Wassaw Sound
1
2
3
4
5
6
7A
7B
7C
7D
8
32.5
32.4
32.2
32.0
Degrees North Latitude
81.1
80.9
80.7
80.5
80.3
Degrees West Longitude

Cost: $
Quantity: 500