Supplemental Studies to Determine Potential Ground-Water Impacts to the Upper Floridan Aquifer

Savannah Harbor Expansion Project

FINAL REPORT

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EXECUTIVE SUMMARY

Supplemental studies conducted as part of the Tier II Environmental Impact Statement (EIS) were intended to expand upon previous studies and address comments from the *Potential Ground-Water Impacts* feasibility study (USACE, 1998). The current study was conducted according to several major tasks, each of which provided an array of information that, when combined, provided the most comprehensive picture of the geology and hydrogeology underlying the Savannah River navigation channel and surrounding area to date.

The field work entailed conducting a detailed subbottom seismic survey, performing marine and land drilling, and collecting porewater data, hydraulic conductivity data, and head data. Results from the field work were analyzed and incorporated into both a three-dimensional coupled flow and transport ground-water model and a comprehensive Geographic Information System (GIS).

The subbottom survey was performed from river station 30+000 to –30+000, where the Miocene confining unit is naturally thin and paleochannels are known to have further incised into the confining layer. Results of the survey provided detailed information about all major paleochannels within the area of concern. The location, attitude, and extent of all paleochannels were mapped and incorporated into the Miocene surfaces created for the GIS and the ground-water model.

The three-dimensional coupled flow and transport ground-water model simulated the specific effects of dredging the navigation channel on water quality in the Upper Floridan aquifer. The model outputs used two values of hydraulic conductivity and provided two sets of results that are believed to bracket true conditions, yielding a range of plausible responses under both dredging and no dredging conditions.

Model simulation results indicated that the proposed dredging activities would contribute a minimal amount of increased total downward flow through the confining layer, and the resulting differences between the dredging and no dredging scenarios were minor. The simulations also projected that, regardless of dredging, chloride concentrations in the Upper Floridan aquifer are expected to increase significantly in the lower reaches of the Savannah River over the next 100 to 300 years if the present rate of aquifer withdrawal remains constant. Under current conditions, the maximum expected chloride concentrations in the Upper Floridan aquifer directly beneath the river ranged from 500 to 1,400 mg/L depending on the hydraulic conductivity of the confining layer, and the proposed dredging was projected to contribute an additional 10 to 200 mg/L to these concentrations.

Simulated chloride concentration time-histories were generated for Upper Floridan production wells located along or near the river from downtown Savannah to Tybee Island. The mid-range hydraulic conductivity simulations indicated that downward migration of chloride from the river would contribute 10 to 50 mg/L to total chloride concentrations in Savannah area production wells by the year 2200, and the difference between the dredging and no dredging scenarios ranged from negligible to less than 10 mg/L for each well location.

Model results showed that the impact of the proposed dredging activities on the change in chloride concentration through the confining layer is insignificant when compared with predicted concentrations that assume no dredging conditions. The simulated concentrations decrease significantly upon entering the Upper Floridan aquifer due to considerable horizontal flow of fresh water within the aquifer mixing with and diluting the relative very low volume of salt water migrating downward from the Savannah River.

The negative head gradient induced by pumping in Savannah appears to have caused limited breakthrough of chlorides to occur in the downstream reaches of the Savannah River. The porewater profiles and model results from this study indicated that both the increased salinity along the bottom of the Savannah River and the reduced thickness of the confining layer due to dredging will not significantly affect the timing of breakthrough of chlorides along the navigation channel in the Upper Floridan aquifer. Furthermore, the study results showed that the proposed dredging would have negligible impacts on water quality in production wells that tap the Upper Floridan aquifer in and around the city of Savannah.

1. INTRODUCTION

The Savannah Harbor Expansion Project is a multi-faceted study to determine the feasibility of expanding and deepening the present Savannah Harbor and Ocean Bar Channel (Figure 1-1). The initial phase of the study was conducted under the authority of Section 203 of the Water Resources Development Act of 1986. Completed in 1998, the Savannah Harbor Expansion Feasibility Study and Tier I Environmental Impact Statement (EIS) recommended deepening Savannah Harbor from the Ocean Bar Channel upstream to the Georgia Ports Authority. Although authorized in 1999, the US Army Corps Chief of Engineers Report required additional analyses and approvals before commencement of expansion activities, namely a consensus mitigation plan, Tier II EIS, and General Reevaluation Report. The Geology/Hydrogeology and HTRW Design Section, US Army Corps of Engineers, Savannah District prepared this supplemental studies report as part of the Engineering Appendix of the Tier II EIS that will serve as a basis for future decisions concerning the expansion of Savannah Harbor.

OVERVIEW MAP OF SAVANNAH HARBOR

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

Figure 1-1

2. PROJECT OVERVIEW

2.1. PURPOSE AND SCOPE

The methods employed in this study were intended to build and expand on the information from previous studies, particularly the 1998 *Potential Ground-Water Impacts* for the Savannah Harbor Expansion Feasibility Study that was prepared as part of the Tier I EIS (USACE, 1998). Following the release of the 1998 study, the Savannah District, with input from the United States Geological Survey (USGS), Georgia Environmental Protection Division (GAEPD), South Carolina Department of Health and Environmental Control (SCDHEC), and the Stakeholders Evaluation Group (SEG), developed a conceptual plan and work outline to address comments from the 1998 report and establish new supplemental study objectives.

The principal objective of the current study was to determine how much proposed dredging activities (Table 2-1) would contribute to increased chloride levels in the Upper Floridan aquifer and evaluate the associated impacts on aquifer water quality. Based on the "6-foot improvement" option, the proposed dredging activities to deepen the navigation channel would impact materials contained between -42 feet and -58 feet Mean Low Water (MLW), which is comprised primarily of Miocene-aged sediments. Consequently, the study focused on the Miocene-aged upper confining unit (i.e. confining layer) along the navigation channel, especially from Fields Cut (Intra-Coastal Waterway) to approximately two miles offshore of Tybee Island, where the confining layer naturally thins and relict channels have cut further down into the confining layer (Figure 2-1).

The Savannah District evaluated the study objectives according to six major tasks that included completing additional seismic surveying, conducting additional land and marine drilling that incorporated porewater and hydraulic testing, developing a ground-water model, determining the feasibility of conducting an aquitard test, and incorporating data, past and present, into a comprehensive Geographic Information System (GIS).

Table 2-1. Proposed Dredging Depths for Savannah Harbor and Ocean Bar Channel

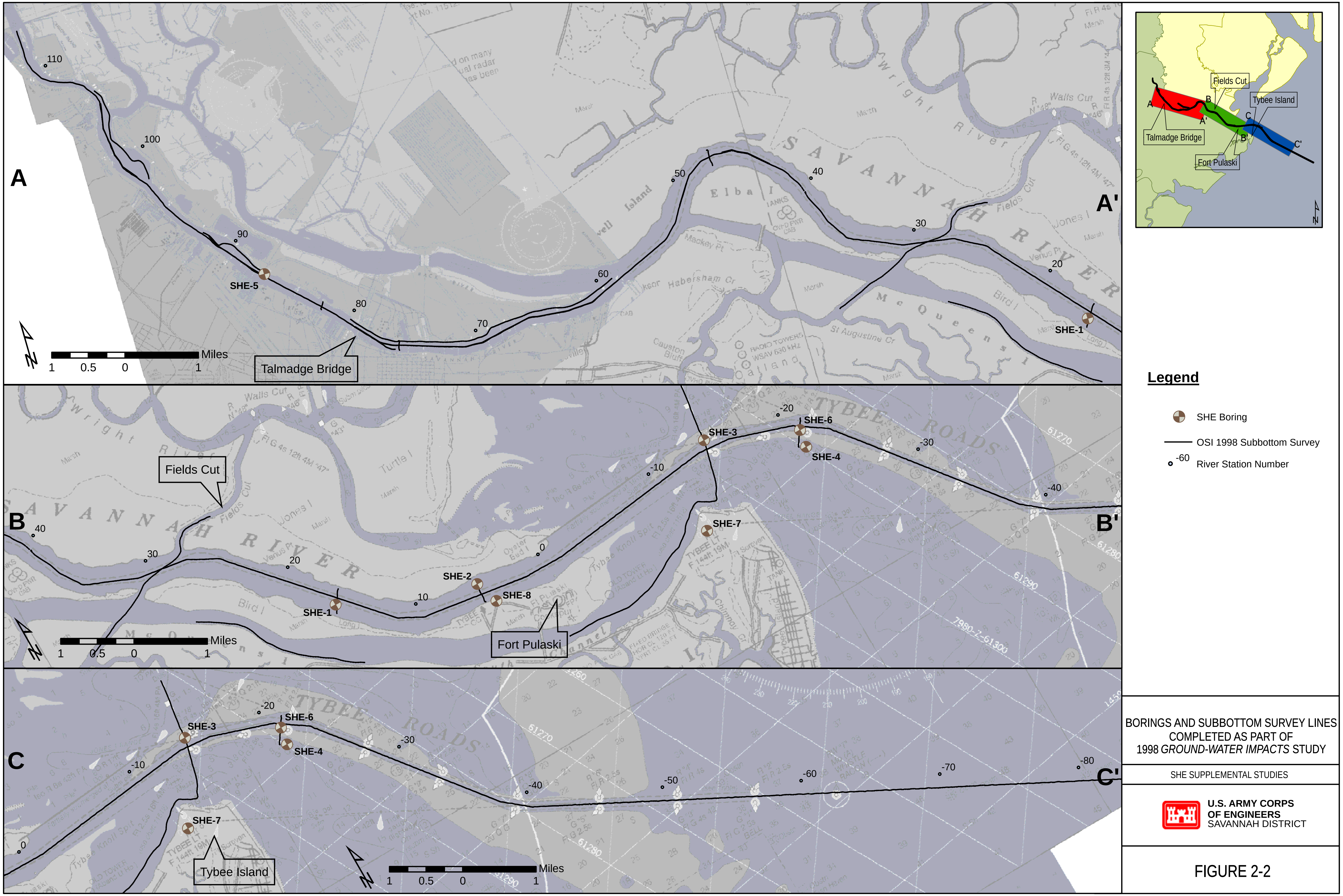
Location (River Station)	Current Project Depth (ft below MLW)	Advance Maintenance (ft)	Allowable Overdepth (ft)	Current Total O&M Dredging Depth (ft below MLW)	Proposed 6-Foot Improvement (ft below MLW)
-60+000 to -14+000	44	0	2	46	52
-14+000 to 0+000	42	2	2	46	52
0+000 to 24+000	42	2	2	46	52
24+000 to 35+000	42	4	2	48	54
35+000 to 37+000	42	6	2	50	56
37+000 to 70+000	42	4	2	48	54
70+000 to 102+000	42	2	2	46	52
102+000 to 103+000	42	0	2	44	50
103+000 to 105+500	36	2	2	40	N/A
105+500 to 112+500	30	2	2	34	N/A
Oyster Island Turning Basin	40	0	2	42	N/A
Fig Island Turning Basin	34	4	2	40	N/A
Marsh Island Turning Basin	34	0	2	36	N/A
Kings Island Turning Basin	42	8	2	52	58
Argyle Island Turning Basin	30	0	2	32	N/A
Port Wentworth Turning Basin	30	0	2	32	N/A
Sediment Basin (Back River)	40	0	2	42	N/A
0 to 13+300	38	0	2	40	N/A

2.2. PREVIOUS STUDIES

The Savannah District US Army Corps of Engineers first addressed potential impacts to the Upper Floridan aquifer due to dredging in 1980 (USACE, 1980). The report, completed as part of a larger long term planning document, was limited in scope and involved conducting a review of existing boring logs to outline the harbor stratigraphy on a large-scale basis. The Savannah Harbor Comprehensive Study (USACE, 1982) was the first study to contain detailed information as to potential ground-water effects in the Upper Floridan aquifer due to dredging. A field investigation completed as part of the report included drilling two deep core holes (SH-65 and SH-66) and performing a limited subbottom geophysical survey. The report concluded that the aquifer strata would not be impacted given the proposed project depth at that time.

In 1992, the Savannah District issued a contract to Dr. Vernon J. Henry to further evaluate the potential for salt-water intrusion in the aquifer due to dredging. Henry compiled and examined existing seismic reflection data and boring logs along the navigation channel. The investigation revealed several buried relict stream channels (i.e. paleochannels) had downcut into the Miocene confining unit and were later in-filled with younger sediments of different lithology than that of the confining unit. The report concluded that dredging associated with a proposed –46.0 feet MLW project depth would not directly breach the confining layer, and seepage associated with paleochannels underlying the navigation channel would depend on the transmissivity of both the channel fill sediments and the confining unit. Furthermore, the report recommended drilling additional cores in the paleochannel material to determine hydraulic properties (Henry, 1992).

The findings of the 1992 report focused on paleochannels intersecting the navigation channel, and subsequent studies were conducted to evaluate their role in potential impacts to the Upper Floridan aquifer. Specifically, the studies aimed to evaluate the postulation that if the paleochannel in-fill material were more permeable than the underlying confining unit, then seawater would have a more direct path through the confining unit, thus increasing the rate of salt-water intrusion into the Upper Floridan aquifer. In 1998, the Savannah District US Army Corps of Engineers published the resulting efforts in a report entitled *Potential Ground-Water Impacts* as part of the Savannah Harbor Expansion Project Feasibility Study (USACE, 1998). The field investigation included drilling eight core borings (SHE-1 through SHE-8), conducting laboratory analyses on core samples, and examining well data to determine the physical properties of sediments underlying the proposed project area. In addition, the Savannah District conducted an extensive, site-specific subbottom geophysical survey to better determine the physical relationship between the various stratigraphic units below the existing Savannah River navigation channel (Figure 2-2). The resulting data were used to create a comprehensive profile of the geologic and hydrogeologic units underlying the navigation channel and to calculate a vertical leakage rate of seawater through the paleochannels and Miocene confining unit to the top of the Floridan aquifer. The 1998 feasibility study concluded that the volume of seawater moving vertically through the overlying stratigraphic units was insignificant compared to the volume of freshwater moving laterally through the Upper Floridan aquifer; therefore, the proposed dredging would have no noticeable effect on the quality of ground water in the Upper Floridan aquifer.

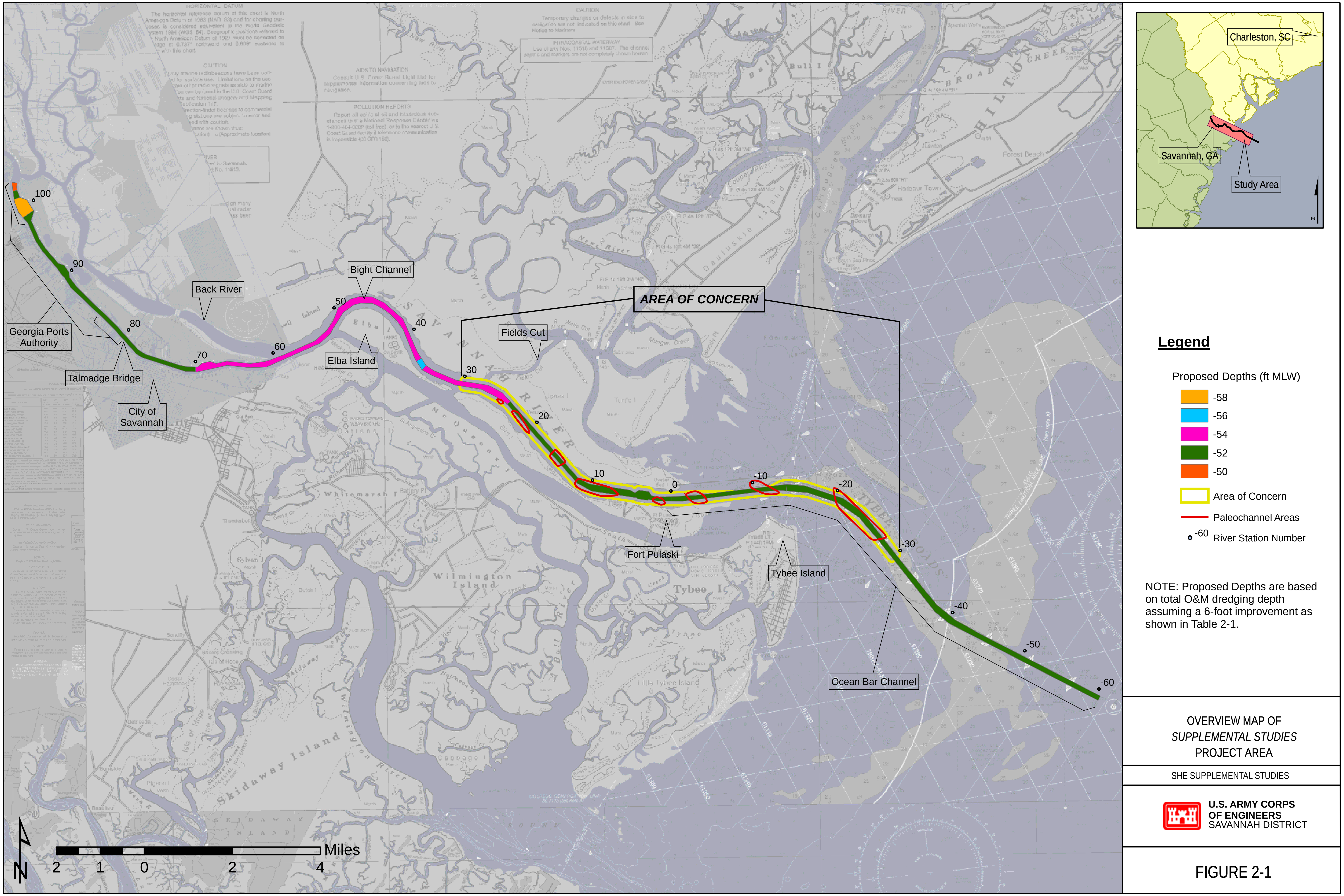


BORINGS AND SUBBOTTOM SURVEY LINES
COMPLETED AS PART OF
1998 *GROUND-WATER IMPACTS* STUDY

SHE SUPPLEMENTAL STUDIES

**U.S. ARMY CORPS
OF ENGINEERS**
SAVANNAH DISTRICT

FIGURE 2-2



NOTE: Proposed Depths are based on total O&M dredging depth assuming a 6-foot improvement as shown in Table 2-1.

OVERVIEW MAP OF
SUPPLEMENTAL STUDIES
PROJECT AREA

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 2-1

3. DESCRIPTION OF THE STUDY AREA

3.1. GEOLOGIC SETTING

Eastern Chatham County is underlain by approximately 2,000 feet of sedimentary Coastal Plain sediments ranging in age from Holocene to Cretaceous (Miller, 1986). From land surface to a depth of about 500 feet, these sediments consist of unconsolidated to somewhat indurated beds of sand and clay of Recent (Holocene) age to indurated limestones of Oligocene and Eocene age (Table 3-1). The Oligocene and Eocene limestones comprise what is commonly referred to as the Upper Floridan aquifer. A regional west-east geologic cross-section (Figure 3-1) published by Clarke et al. (1990) illustrates the attitude and thickness of the Upper Floridan aquifer and overlying strata from updip in Bulloch County to downdip in eastern Chatham County.

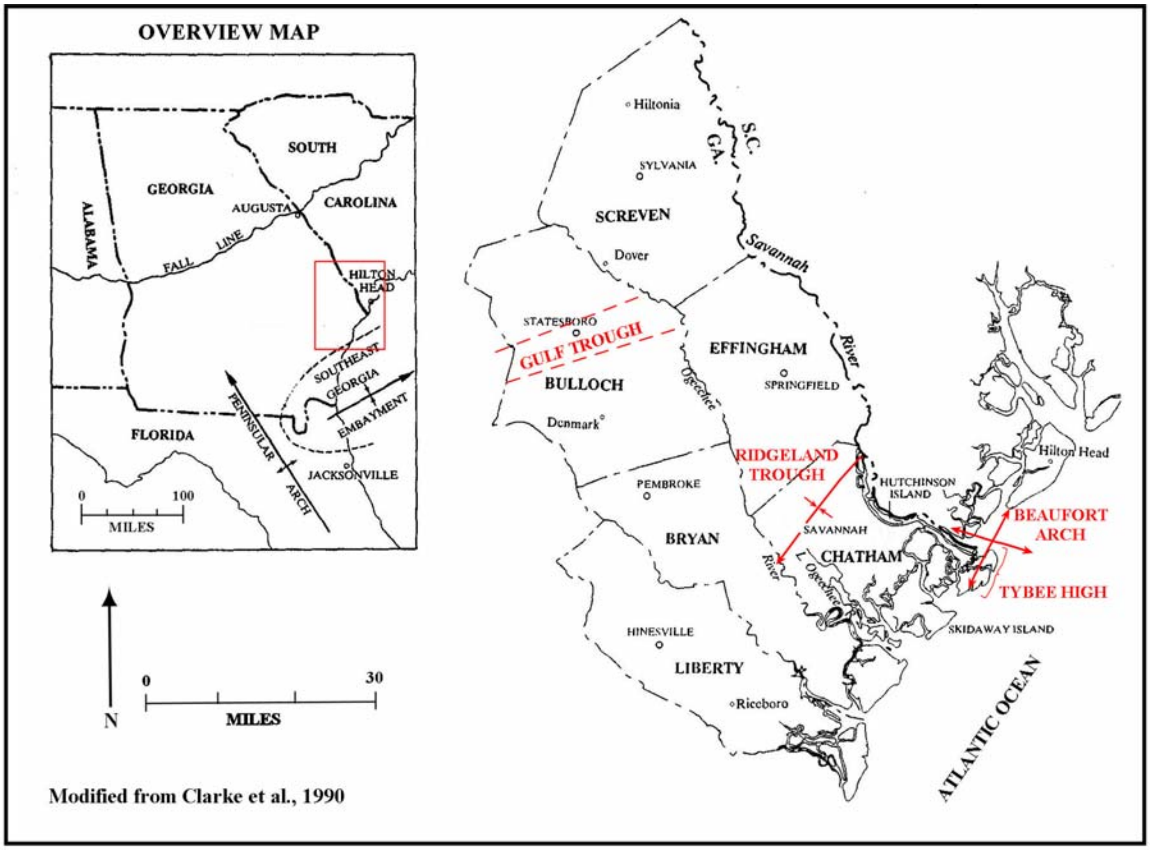
Table 3-1. Geologic and Hydrogeologic Units in Eastern Chatham County

Age	Geologic Unit[1]		General Lithology	Hydrogeologic Unit[2]
Pleistocene-Recent	Satilla Formation		Fluvial sands, silts, and clays	Surficial Aquifer
Upper Miocene	Hawthorne Group	Ebenezer Formation (Miocene Unit A)	Green-colored clays, silts, clayey silts, and sandy or silty clays	Upper Confining Unit
Middle Miocene		Coosawhatchie Formation (Miocene Unit B)	Green-colored clays, silts, clayey silts, and sandy or silty clays	Upper Confining Unit
Late Oligocene		Tiger Leap Formation	Buff-colored, porous limestone with foraminifera	Upper Floridan Aquifer
Early Oligocene	Lazaretto Creek Formation		Buff-colored, porous limestone with foraminifera	Upper Floridan Aquifer
Late Eocene	Ocala Limestone		Massively bedded, fossiliferous limestone	Upper Floridan Aquifer

[1] Modified from Weems and Edwards, 2001

[2] Clarke et al., 1990

In general, Tertiary strata in Chatham County dip 10 to 15 feet per mile to the south-southwest. However, the dips are locally controlled by structural “highs” and “lows” as illustrated in Figure 3-2. Prominent structures include the Beaufort arch, a domal structure near Beaufort, South Carolina (Siple, 1960), the Tybee high, an anticlinal structure with a northwest-southeast trending axis near the mouth of the Savannah River (Furlow, 1969), and the Ridgeland trough, a structural low with a northeast-trending axis extending northeastward through northern Chatham County, Georgia into Jasper County, South Carolina (Heron and Johnson, 1966).



Modified from Clarke et al., 1990

Figure 3-2. Structural features in the Chatham County area.

Within the study area, the elevation of the top of the Oligocene unit, the uppermost unit of the Upper Floridan aquifer, ranges from roughly –95 feet MLW near the Tybee high to approximately –200 feet MLW near downtown Savannah. The top of the Miocene unit occurs at an average of –45 feet MLW and is generally level within the study area, and unit thickness ranges from less than 30 feet near the Tybee high to 160 feet near downtown Savannah. The GIS analyses presented in Figures 3-3a and 3-3b show locations where the Miocene unit is exposed in the bottom of the navigation channel through time based on historic bathymetric data. Notice that 1998 marks the first time that dredging activities exposed large stretches of Miocene along the Bight Channel (Elba Island) and near Kings Island Turning Basin.

In this study, the Tybee high is the structural feature of most importance, namely where the tops of the Miocene confining unit and the Oligocene unit are nearest land surface. Over the crest of the Tybee high, the elevations of the top of the Oligocene unit range from –95 feet MLW beneath Tybee Island to –115 feet MLW at the channel at Fields Cut, and the Miocene is generally exposed in the bottom of the navigation channel (Figure 3-3b). Proposed dredging operations associated with the Savannah Harbor Expansion Project would lower the channel depth to as much as –58 feet MLW. In the harbor vicinity, this stratigraphic horizon is composed of Pleistocene-Recent and Miocene sediments (Figure 3-4).

3.2. HYDROGEOLOGIC SETTING

The Floridan aquifer system underlies parts of Alabama, Georgia, South Carolina, and Florida and supplies approximately 50 percent of the ground water in Georgia (Kressler et al., 2001). Formerly known as the principal artesian system, the aquifer system is divided into two major aquifers: the Upper Floridan and Lower Floridan. Within Chatham County and the study area, the Upper Floridan aquifer is the primary source of ground water. Recharge to the confined aquifer system occurs to the northwest and west of the study area, and precipitation generally does not influence water levels within the study area. Instead, water levels in the Savannah area show direct response to pumping (Clarke et al., 1990).

Prior to development, the flow system was considered steady state, i.e. recharge was equal to natural discharge (artesian springs, streams, etc.), and water levels showed little fluctuation from year to year. However, development within the coastal region and the associated increased ground-water withdrawal rates has unbalanced the recharge and discharge rates. This increased pumping has lowered water levels, induced additional recharge and reduced natural discharge, and increased total flow through the system (Krause and Randolph, 1989).

The long-term pumping of the Upper Floridan aquifer in the Savannah area and surrounding coastal areas has lowered ground-water levels and reversed the seaward hydraulic gradient that existed before development (Garza and Krause, 1996; Krause and Randolph, 1989) as shown in Figure 3-5. The increased withdrawal of water from the Upper Floridan aquifer has resulted in radial flow directed toward the center of pumping and a cone of depression beneath Savannah. Prior to development, heads in the Upper Floridan aquifer ranged from 20 to 150 feet above sea level in southeast Georgia and from 30 to 50 feet above sea level in Chatham County (Krause and Randolph, 1989). In contrast, in May of 1998 Peck et al. (1999) reported a maximum head of 60 feet above sea level occurring south of Brunswick and maximum drawdown occurring near the city of Savannah, where heads ranged from -10 feet to -100 feet below mean sea level (Figure 3-6).

This reversal in hydraulic gradient has resulted in lateral encroachment of seawater and downward vertical intrusion of salt water through the confining unit. The lateral encroachment of seawater is evidenced two ways. First, lateral encroachment is expressed by the westward movement of the freshwater / salt-water interface toward the center of pumping (Savannah) (Figure 3-5). Second, lateral encroachment is seen at Port Royal Sound where the confining unit is completely absent and the aquifer is directly overlain by seawater. Here, seawater enters the aquifer and moves southward (laterally) toward the center of pumping. The plumes associated with this lateral encroachment have been well documented as elevated chloride concentrations in Floridan wells at the north end of Hilton Head Island, South Carolina (Smith, 1988; Ransom et al., 2006).

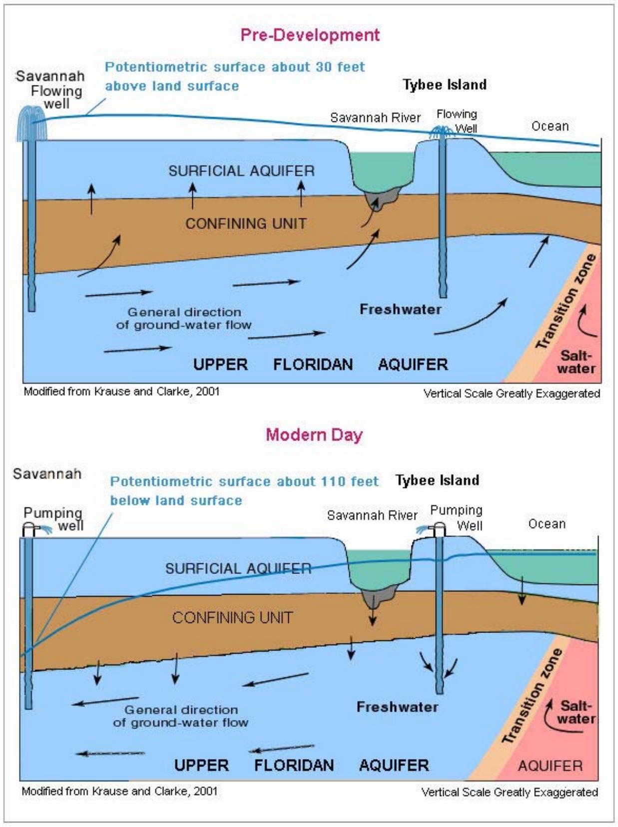


Figure 3-5. Schematic view of pre-development and modern day ground-water flow in the Savannah area.

The sustained pumping in the Savannah area has also resulted in a downward hydraulic gradient and induced significant head differences between the surficial aquifer and the confined Upper Floridan aquifer, with head differences ranging from –60 to –120 feet in Chatham County (Clarke et al., 1990). Additionally, the Savannah District (1998) and Clarke et al. (1999) documented downward hydraulic gradients through the upper confining unit at four nested well locations in the Savannah area (SHE-9, SHE-10, Fort Pulaski, and Tybee Island). The results from these reports indicated that downward leakage of water through the confining unit contributes a significant amount of water to the flow system in the study area; in fact, the leakage through the upper confining unit has been estimated to represent nearly half the water budget for the Savannah area, or 40 million gallons per day (MGD) (Garza and Krause, 1996). This study examines the impact of the proposed dredging on the rate of this vertical intrusion, which consists of both fresh and salt water, and the resulting ground-water impacts in the Upper Floridan aquifer.

3.3. GEOLOGIC AND HYDROGEOLOGIC UNITS

The stratigraphic intervals and general hydrogeologic framework of the Floridan aquifer and overlying geologic units were first described in the late 1950's and early 1960's by Herrick (1961), Siple (1960), Counts and Donsky (1963), and McCollum and Counts (1964), and numerous reports since have further detailed the lithologic and hydrologic properties (Clarke et al., 1990; Clarke, 2003; Weems and Edwards, 2001). The nomenclature and, in some cases, age of the various stratigraphic units vary from report to report according to location and data available. For the purposes of this study, geologic units are referred to according to nomenclature designated by Weems and Edwards (2001), and hydrogeologic units are referenced according to the framework set forth in Clarke et al. (1990) (Table 3-1).

The Upper Floridan aquifer system stretches from coastal South Carolina to northern Florida and includes Chatham County and Savannah Harbor. This study focused on the hydrogeology of sediments underlying the present navigation channel, specifically the upper 150 to 200 feet, which encompasses the Oligocene, Miocene, and Pleistocene-Recent units. In the Savannah Harbor area, the geologic formations can be grouped into three broadly defined hydrogeologic units: the Upper Floridan aquifer, the Miocene confining unit, and the surficial aquifer (Table 3-1). Past reports include descriptions of the upper and lower Brunswick aquifers, Miocene-aged aquifers that are productive in the Glynn County area and as far north as Bryan County (Krause and Clarke, 2001). In the past, the northern extent of these aquifers was determined using electrical logs, gamma logs, and well cuttings (Clarke et al., 1990), and it was surmised that these aquifers extended to the Savannah area. More recently, however, Clarke (2003) and Weems and Edwards (2001) reported that the upper and lower Brunswick aquifers are discontinuous or absent in Chatham County. In addition, the Savannah District collected numerous continuous core samples to the top of the Oligocene unit, and none of these cores indicated the presence of such units underlying the navigation channel. As such, their descriptions were not included in this report.

3.3.1. Upper Floridan Aquifer

In the coastal area, the Upper Floridan aquifer consists of limestone of Late Eocene and Oligocene age and is characterized as vuggy and highly fossiliferous. The Late Eocene (Ocala Limestone) unit consists of massively bedded, fossiliferous limestone and dolomite that contains bryzoans, foraminifera, and mollusk shells. The Oligocene unit unconformably overlies the Late Eocene unit and consists of buff-colored, porous limestone with foraminifera, zones of micrite, and nonparticulate phosphate. The Oligocene unit is distinguished from the Late Eocene unit by its lack of bryozoans and its abundance of miliolid foraminifera (Clarke et al., 1990).

The elevation of the top of the Upper Floridan aquifer (Oligocene) is approximately –200 feet MLW under the city of Savannah, and the contact gently slopes upward to the east toward Tybee Island. Over the crest of the Tybee high, the top of the Upper Floridan aquifer is closer to land surface and is typically around –100 feet MLW in elevation. In the study area, the Upper Floridan aquifer is 150 to 250 feet thick, and the uppermost two zones, zone 1 and zone 2, are the most productive (McCollum and Counts, 1964; Krause and Randolph, 1989). Zone 1 and zone 2, approximately 44 feet and 35 feet thick, respectively (Clarke et al., 1990), combine to supply more than seventy percent of the water pumped from open holes tapping the entire aquifer (Krause and Randolph, 1989). Pumping reached a maximum of 88 MGD in 1990 (Fanning, 1999) and has since slightly declined due to a reduction in industrial pumping. In the year 2000, Chatham County withdrew approximately 72 MGD from the Upper Floridan aquifer (Fanning, 2002).

Transmissivity of the Upper Floridan aquifer is highly variable in the coastal area, and in the area between Port Royal Sound, South Carolina and Savannah, the transmissivity varies from 27,000 ft^2/d to 80,000 ft^2/d (Counts and Donsky, 1963; Hayes, 1979; Spigner and Ransom, 1979). The transmissivity in the Savannah area is low in comparison with other areas along the coast (27,000 ft^2/d to 33,000 ft^2/d).

The low transmissivity has resulted in a substantially deeper cone of depression as compared with other major pumping centers with similar withdrawal rates (Clarke et al., 1990).

3.3.2. Miocene Confining Unit

Strata of Miocene age in the coastal area have been differentiated into the Ebenezer Formation (upper Miocene), the Coosawhatchie Formation (middle Miocene), and the Marks Head and Parachula Formations (lower Miocene); three depositional sequences of similar lithology each bounded by unconformable contacts (McCollum and Herrick, 1964; Weems and Edwards, 2001). Hydrogeologists refer to the units collectively as the “confining bed” or “confining unit” overlying the Upper Floridan aquifer. In the Savannah area, the Miocene sediments unconformably overlie limestone of Oligocene age, a lithologically and geophysically distinctive contact.

The confining unit is a series of lithologically complex sequences of predominately clastic sediments containing low-permeability clays, silts, clayey silts and sands, and clayey or silty sands. Each sequence comprises a geologic unit that consists of a basal carbonate layer, a middle clay layer, and an upper sand layer and is bounded above and below by an unconformity. These units were each defined by persistent geophysical markers designated as A, B, and C and are basal contacts for each of the Miocene units. Clarke and others (1990) felt these three units best fit the stratigraphic framework of McCollum and Herrick (1964), whereby units A, B, and C correlate to upper, middle, and lower Miocene, respectively.

As illustrated on geologic cross-sections in reports by Counts and Donsky (1963), Hayes (1979), and Spigner and Ransom (1979), the Miocene confining unit both thins and lies progressively nearer land surface in the area from eastern Chatham County, Georgia into southern Jasper County, South Carolina and the Beaufort arch area in coastal Beaufort County, South Carolina. In the project area, Miocene units A and B occur, and Miocene unit C is generally absent or eroded such that only the basal carbonate layer remains and is indistinguishable from the basal contact of unit B. In the study area, Miocene units A and B consist of green-colored, silty clay and clayey or silty sands underlain by a basal dense, phosphatic limestone or dolomite. Underneath the navigation channel, the basal contacts range in thickness from less than 1 foot to 10 feet thick and the overall thickness of the confining unit (units A, B, and C) ranges from about 30 feet thick near the Tybee high to over 150 feet thick near downtown Savannah.

Thin beds of fine-grained sands typically occur between two high gamma activity signatures within the Hawthorne Group (Table 3-1). In some areas, these zones are sufficiently permeable to yield significant quantities of water to wells and, thus, can be classified as aquifers. This “Hawthorne aquifer” (Hayes, 1979) is separated from the Upper Floridan aquifer by a phosphatic sandstone with high natural gamma activity. The USGS referred to the same stratigraphic interval in the Savannah area as the "upper Brunswick aquifer" (Clarke et al., 1990). In the project area, however, no permeable sands occur within the Miocene that could be considered aquifers. In addition, a water-use inventory failed to identify any Miocene (Hawthorne) wells in the area within several miles on either side of the Savannah River, as wells in the Savannah area generally tap either the underlying Upper Floridan aquifer or the overlying basal Pleistocene sands (surficial aquifer).

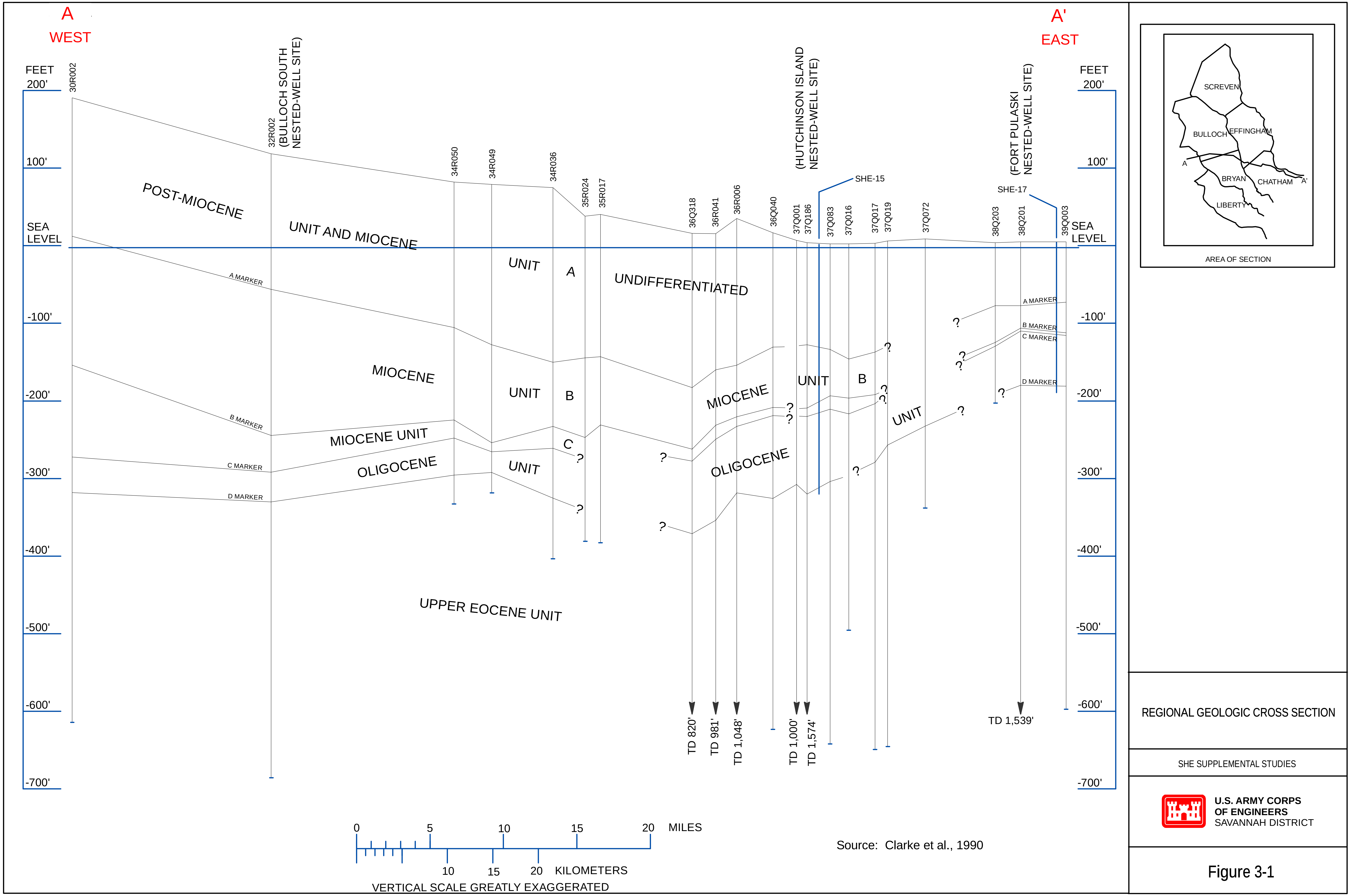
3.3.3. Pleistocene-Recent Unit

Herrick (1965) and Furlow (1969) first described the Pleistocene deposits in the Savannah area, and detailed lithology and geometry of the Pleistocene to Recent sediments were compiled as part of subsequent ground-water studies of the Floridan aquifer system, including those conducted by the Savannah District. The Pleistocene-Recent unit overlies the Miocene unit in the Savannah area, and the contact is marked by an erosional unconformity, which is sharp in some areas but gradational in others. The shallow sands and clays that occur from land surface to a depth of typically 60 to 75 feet, but locally as much as 130 feet, comprise the Pleistocene-Recent unit (Counts and Donsky, 1963 and Furlow, 1969).

Pleistocene to Recent sediments in the Savannah area consist of phosphatic, micaceous, and clayey sand of Pliocene age; arkosic sand and gravel containing discontinuous clay beds of Pleistocene age; and mud, sand, and gravel of Holocene age (Clark et al., 1990). According to Miller (1986), post-Miocene sediments generally can be divided into a basal sequence of marginal to shallow marine beds overlain by a series of sandy, marine terrace deposits that are in turn capped by a thin layer of fluvial sand or residuum, or both. Although the geometry and lithologies of these Pleistocene-Recent sediments are geologically complex, with typically lenticular bodies of sand or clay, aquifer sands near the base of the Pleistocene are laterally persistent although not necessarily continuous throughout the coastal region.

Within the study area, the Pleistocene to Recent sediments generally range in thickness from about 50 to 70 feet. Along the present day navigation channel, the Pleistocene-Recent sediments range from 0 to 30 feet thick and are predominantly composed of clays and silts. Depositional environments of the Pleistocene-Recent unit within the Savannah River corridor include off-channel deposits of sands and clays and in-channel deposits of fluvial sands, silts, and clays (paleochannels).

The Pleistocene sands, also known as the surficial aquifer, collectively constitute one of the most important sources of water for irrigation purposes in southeast Georgia. Ground water within the surficial aquifer occurs under both unconfined (water table) and confined (artesian) conditions in the coastal zone. In places, a basal Pleistocene sand, typically about 15 to as much as about 40 ft thick, is separated from an upper fine-grained sand by a low-permeability dark-gray clay. These sands are recharged by local rainfall, and ground water moves laterally with typically very low hydraulic gradients toward local streams and tidal water bodies. In the Savannah area, daily combined withdrawals from the upper and lower water-bearing zones range from 120,000 to 855,000 gallons per day (Clarke et al., 1990).



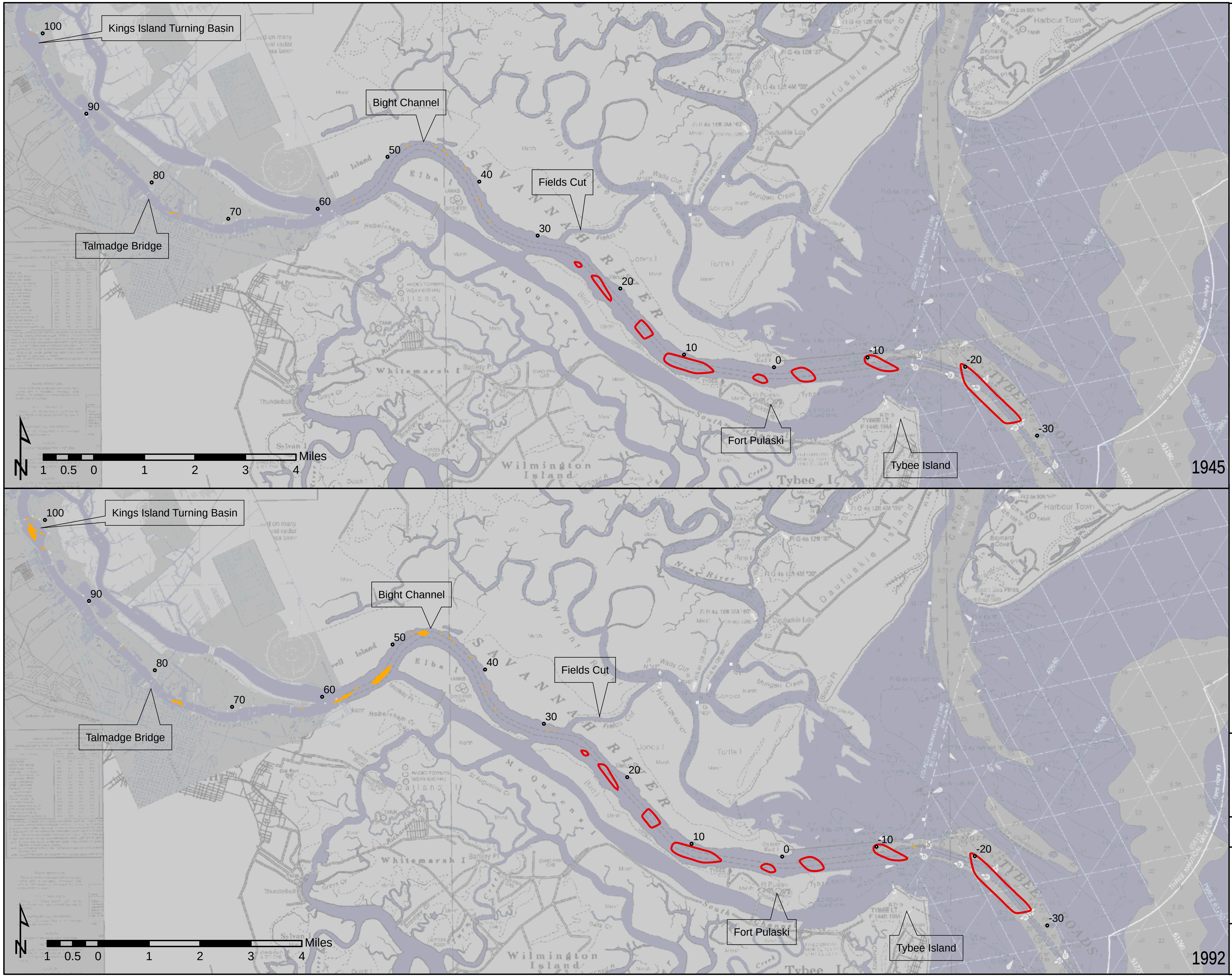
Source: Clarke et al., 1990

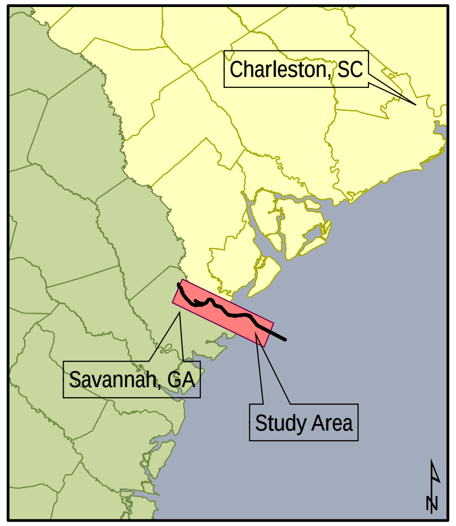
REGIONAL GEOLOGIC CROSS SECTION

SHE SUPPLEMENTAL STUDIES

**U.S. ARMY CORPS
OF ENGINEERS**
SAVANNAH DISTRICT

Figure 3-1





Legend

🟧 Miocene Exposed

— Paleochannel Areas

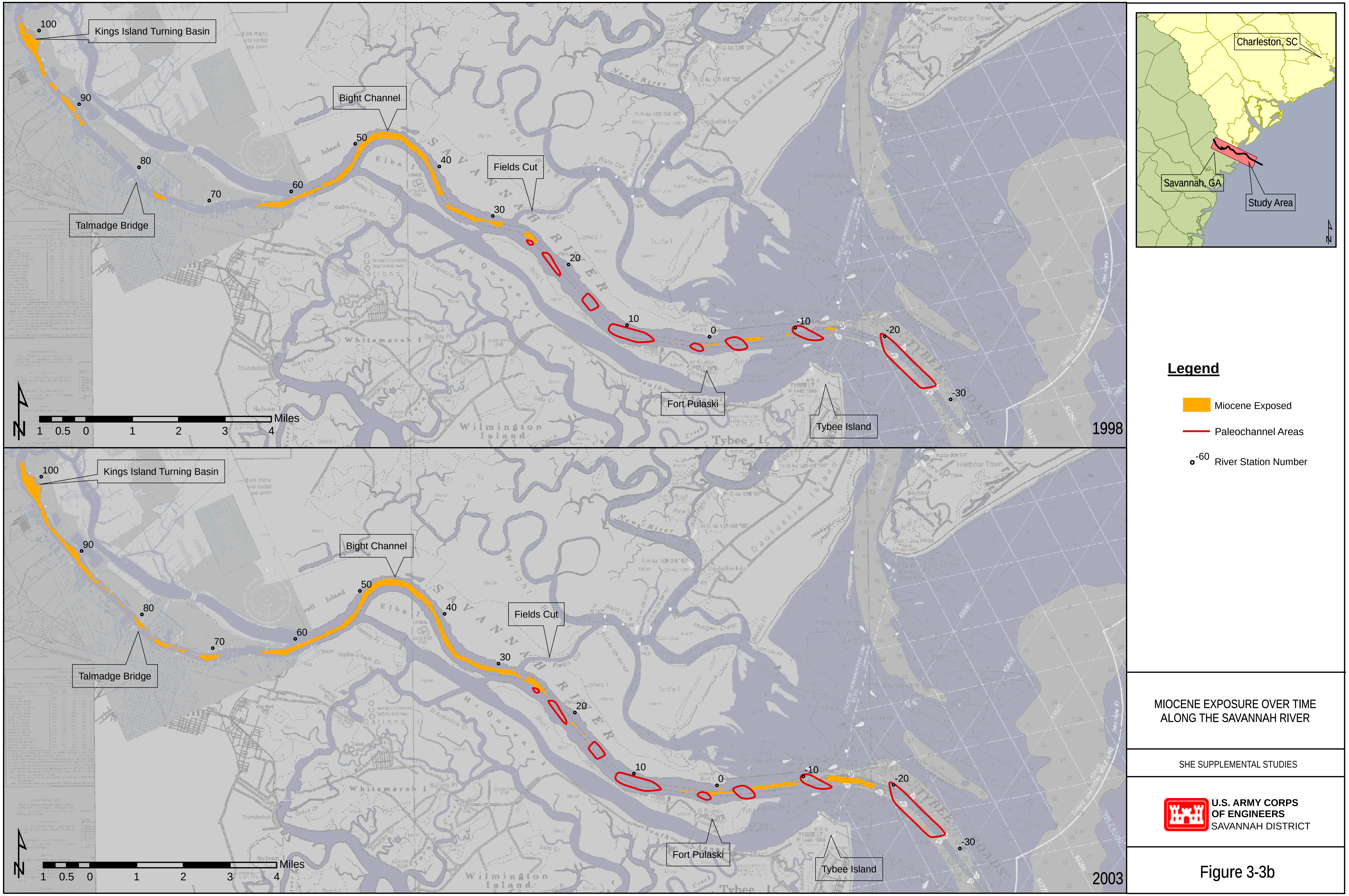
○ -60 River Station Number

MIOCENE EXPOSURE OVER TIME
ALONG THE SAVANNAH RIVER

SHE SUPPLEMENTAL STUDIES

**U.S. ARMY CORPS
OF ENGINEERS**
SAVANNAH DISTRICT

Figure 3-3a

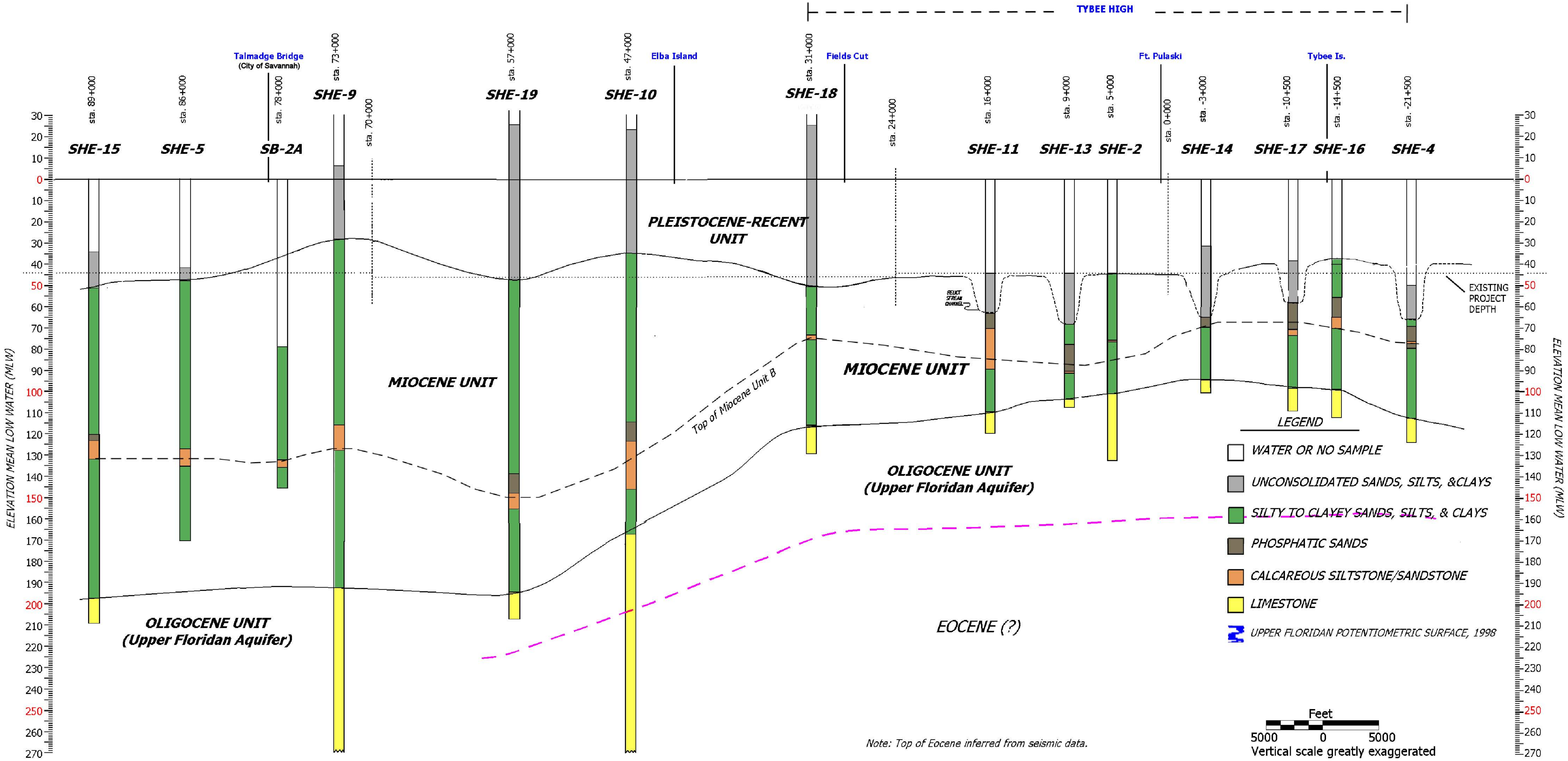


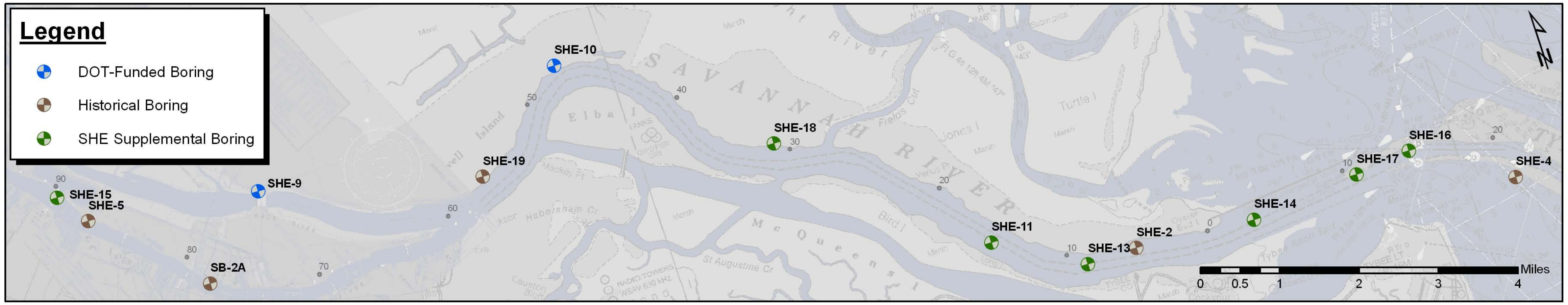
MIOCENE EXPOSURE OVER TIME
ALONG THE SAVANNAH RIVER

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

Figure 3-3b



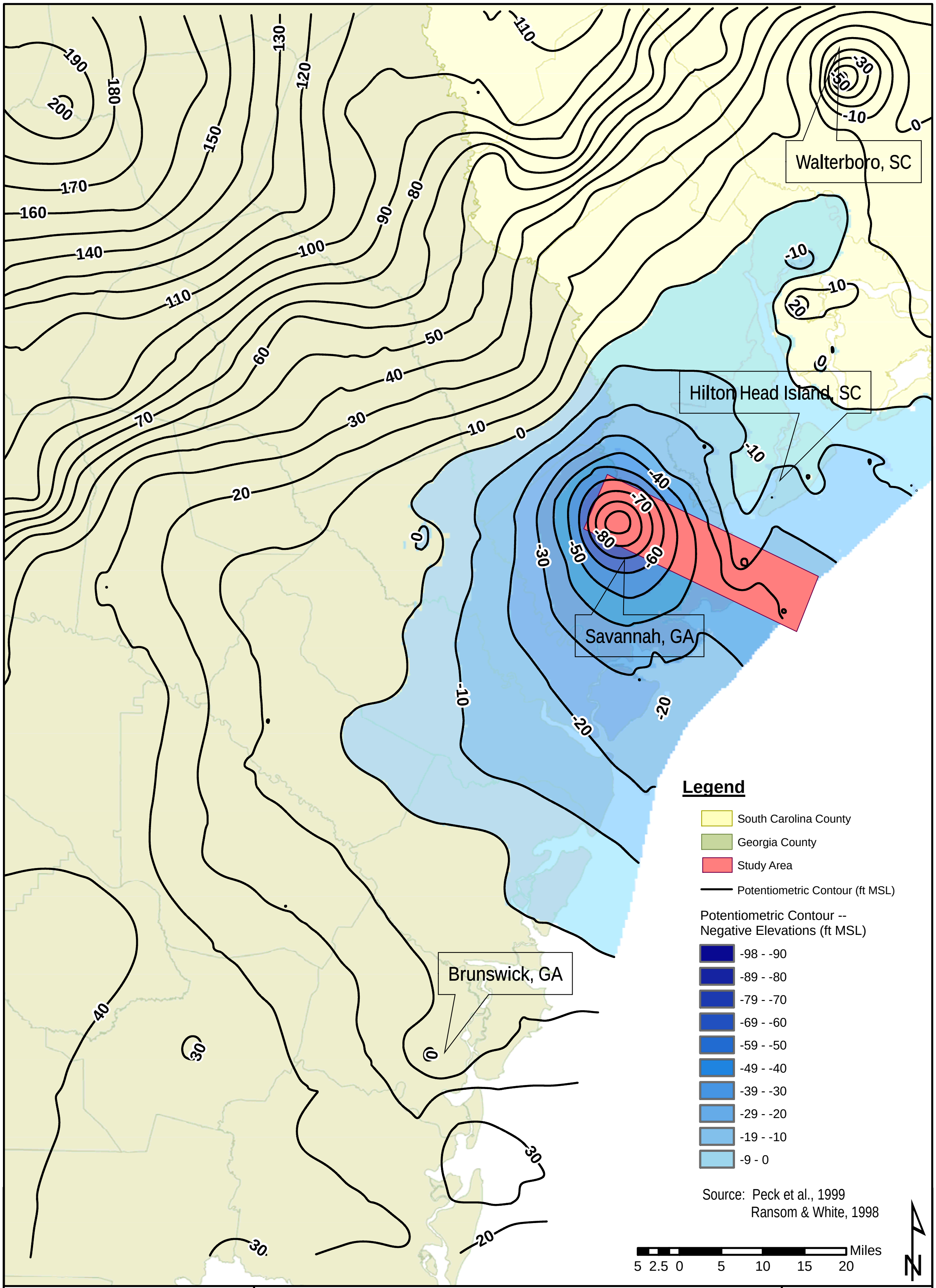


GEOLOGIC CROSS SECTION
OF STUDY AREA

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 3-4



Source: Peck et al., 1999
Ransom & White, 1998

**U.S. ARMY CORPS
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SAVANNAH DISTRICT

POTENTIOMETRIC SURFACE
OF THE UPPER FLORIDAN AQUIFER
IN THE COASTAL AREA, 1998

SHE SUPPLEMENTAL STUDIES

Figure 3-6

4. STUDY METHODS

The methods employed in this study were intended to build and expand on the information from previous studies, particularly the internal studies done by the Savannah District (USACE, 1998) and USGS Bulletin 113 by Clarke et al. (1990). The Savannah District used input from various agencies including the USGS, GAEPD, SCDHEC, SEG, and Georgia Ports Authority to develop a scope of work for the supplemental studies. The study was implemented according to six tasks (Table 4-1), each of which is summarized below.

Table 4-1. Tasks Comprising Supplemental Studies

Task	Subject	Description
1	Subbottom Seismic Survey	Conduct additional subbottom seismic surveying with particular emphasis to better define paleochannel geometry and Upper Floridan confining unit thickness. All seismic data will be acquired in digital format to facilitate analysis and storage in the GIS.
2	Marine Drilling	Conduct additional marine continuous core borings to further characterize in-filled sediments of paleochannels and Miocene confining unit below paleochannels.
3	Land Drilling	Conduct additional continuous core borings on land adjacent to navigation channel to top of Upper Floridan aquifer at three strategic locations where geologic or hydrogeologic data is sparse.
4	GIS	Combine existing geologic, hydrogeologic, seismic, and engineering data from previous studies into the harbor-wide GIS being constructed for Savannah Harbor. Add future supplemental data to the GIS to allow enhanced analysis and visualization.
5	3-D Numerical Hydraulic Model	Develop 3-D coupled flow and transport model of the hydrologic system focused on the navigation channel, and use model to compare before and after dredging results as related to projected chloride changes in the Upper Floridan aquifer.
6	Aquitard Test Feasibility	Conduct trial step-drawdown pumping test on two recently installed Upper Floridan wells located adjacent to river channel to determine feasibility of hydraulic testing of confining unit. If results indicate hydraulic testing of confining unit is feasible, estimate design parameters and assumptions for full aquitard testing.

Ocean Surveys, Incorporated (OSI), acting as a contractor to the Savannah District, performed a supplemental subbottom geophysical survey to fulfill requirements outlined in Task 1. The survey served as an addition to the extensive work completed in 1997, in which relict paleochannels and the underlying stratigraphy were defined along the centerline of the navigation channel. OSI conducted the supplemental survey along the sides of the navigation channel between river stations +30+000 to –30+000, where the majority of paleochannels cut across the navigation channel, in an effort to better determine the orientation of the paleochannels and the thicknesses of the underlying units.

During the period 9 December 2003 to 6 May 2004, seven marine continuous core borings (SHE-11 through SHE-17) were drilled adjacent to the navigation channel, six of which were drilled in known paleochannels (Figure 4-1), to fulfill the requirements outlined in Task 2. The cores were drilled to the top of the Upper Floridan aquifer to further define the stratigraphy underlying Savannah harbor. Each core was drilled using freshwater and analyzed for porewater geochemistry, geophysical markers, grain size, porosity, and vertical hydraulic conductivity.

Similar to Task 2, Task 3 entailed drilling two additional land borings (SHE-18 and SHE-19) in an effort to complete the geologic transect along the entire length of the navigation channel. The borings were strategically drilled in areas where geologic or hydrogeologic data was sparse, and core samples were analyzed for porewater geochemistry, geophysical markers, grain size, porosity, and vertical hydraulic conductivity. In addition, the data from the borings will be used to install two sets of multi-level wells near existing Upper Floridan wells. Although right-of-entry issues have delayed well installation, the multi-level wells will be installed within the surficial aquifer and the Miocene confining unit and will be used to collect hydraulic head and ground-water data at discrete depth intervals over long periods of time.

Task 4 concerned the development of a comprehensive harbor-wide Geographic Information System (GIS). Specifically, the task aimed to compile existing geologic, hydrogeologic, seismic, and engineering data from available historical reports published by the Savannah District, USGS, GAEPD, SCDHEC, or otherwise into a comprehensive GIS for enhanced analysis and visualization.

Task 5 entailed developing a three-dimensional (3-D) numerical hydraulic coupled flow and transport model of the hydrologic system in the immediate vicinity of the navigation channel. The Savannah District issued a contract to CDM to perform this task. The model incorporated hydraulic properties, confining unit thickness, and historic and present pumping rates to determine a range of plausible aquifer responses to deepening the navigation channel. Simulations were run according to a no dredging scenario and a worst-case dredging scenario, where “worst-case” refers to a maximum project depth of -48 feet MLW and the associated overdredging allowances. The outputs were compared to evaluate the potential effects of dredging on water quality in the Upper Floridan aquifer.

Task 6 was intended to be a trial pumping test on two existing Upper Floridan wells in order to determine the feasibility of performing an aquitard test on the confining unit. Prior to conducting this task, several model simulations were performed to evaluate the potential response in the Surficial aquifer and Miocene confining unit to a long-term pumping test conducted with a well in the Upper Floridan aquifer. Further details on the simulated pump tests are included in Section 4.5.

4.1. DRILLING

During the period 9 December 2003 to 27 August 2004, the Savannah District drilled nine additional borings along the present navigation channel to complete the work outlined in the supplemental studies work plan, and those boring locations are presented in Figure 4-1. Seven of the nine borings were marine borings drilled using the Savannah District’s self-elevating barge, and the remaining two borings were drilled on land in close proximity to the Savannah River. Eight of the nine borings completed were located between approximate river stations 30+000 and –30+000, roughly between the Intra-Coastal Waterway (ICW) at Fields Cut and the area immediately offshore from Tybee Island, where the confining unit is thinned and paleochannels are known to cut across the navigation channel. An additional boring (SHE-15) was drilled near river station 89+000, about two miles upriver from the Talmadge Bridge and near the center of the cone of depression.

All borings were completed using traditional mud-rotary drilling with wire-line coring, with the exception of SHE-12 and part of SHE-19. The upper portions of these holes were advanced using splitspoon techniques in an effort to improve recovery of the Pleistocene-Recent material, which is generally more heterogeneous and unconsolidated in nature than the Miocene confining unit material. An attempt was made to obtain continuous samples from river bottom (or land surface) to maximum hole depth, and core recovery was generally good, greater than 75% for all borings, with only occasional core losses due to soft unconsolidated sediments being washed away during coring. Cores were described and classified, and samples were collected and analyzed for porewater geochemistry, hydraulic conductivity, and triaxial shear properties. All borings were drilled from river bottom (or land surface) to the top of the Upper Floridan aquifer with the exception of SHE-12, which served as a test hole for locating boring SHE-13.

4.1.1. Marine Borings

The majority of marine borings were located between river stations +16+000 and –14+000, where paleochannels are known to cut across the navigation channel and the confining unit is closest to land surface (river bottom). Six of the seven marine borings were drilled within known paleochannels, and the remaining boring (SHE-16) was drilled outside any known paleochannel to serve as a control and comparison tool for porewater geochemistry and permeability samples. Several precautions were taken in order to prevent salt-water contamination of the porewater geochemistry samples. Before coring commenced, 6” steel casing was firmly seated in the river bottom. The salt water was then flushed out of the casing and replaced with freshwater that was stored in enclosed tanks on the drilling barge. In order to ensure the casing sealed out salt water, the conductivity, temperature, pH, and salinity were monitored using a Horiba U-22 water quality monitoring system. The water quality probe was used throughout the entire drilling process to ensure non in-situ salt water did not enter the core hole.

4.1.2. Land Borings

Two land borings were drilled adjacent to the navigation channel at strategic locations where geologic or hydrologic data was sparse. The locations of borings SHE-19 and SHE-18 corresponded to river stations +57+000 and +31+000, respectively. Land borings were drilled similarly to marine borings, and although salt-water contamination was not a concern, water quality was monitored throughout the drilling process with the Horiba U-22 water quality monitoring system.

4.2. POREWATER PROFILES

Since the 1880's, increasing withdrawals of water from the Upper Floridan aquifer have caused a cone of depression to form in the Savannah area and lowered the water level in the aquifer to as much as 100 feet below sea level (Peck et al., 1999). The net effect of this lowering of water level has reversed the natural pre-development flow of ground water from the aquifer upward through the confining layer to a downward flow of water from above through the confining layer and toward the center of the area of pumping in Savannah. This downward flow accounts for a significant portion of the water budget contained within the cone of depression, and, since much of the area within the drawdown cone of depression is overlain by salt water, chloride levels in the Upper Floridan aquifer in the Savannah area are expected to increase. The porewater data collected for this study provided a means to better characterize the Miocene confining unit in terms of downward hydraulic gradient, intrusion rates, and effects of thinning the material due to dredging or paleochannel incisions.

In recent years, studies on low-permeability clayey aquitards (i.e. confining layers) have increased greatly due to the effects they have on the movement of contaminants in hydrogeologic systems. More specifically, several studies have addressed the use of porewater salinity data from aquitards to better understand the relationship between aquitards and adjoining aquifers in salt-water intrusion scenarios (Husain et al., 1998 and Lenahan et al., 2004). Van der Kamp (2001) stresses the importance of using solute-transport observations in conjunction with permeability measurements to increase confidence in the characterization of aquitards.

Ransom et al. (2006) first identified porewater salinity profiles as a helpful tool in assessing salt-water intrusion in the Savannah-Hilton Head coastal area. In 2001, funded by SCDHEC as part of the Sound Science Initiative, a porewater profile was constructed from both Geoprobe screen point ground-water samples and rotosonic core samples taken at a site located in Chatham County near Bull River. As part of the supplemental studies, the Savannah District utilized the methods set forth by Dr. James Landmeyer (USGS) and Mr. Camille Ransom (SCDHEC) to collect porewater geochemical data to measure the extent to which salt water (i.e. chloride) has penetrated the confining unit along the navigation channel.

4.2.1. Sampling

For each boring, samples of porewater, water contained within the pore spaces of a geologic material, were collected at regular intervals from, at minimum, the top of the confining unit to the top of the Upper Floridan aquifer. Several sampling methods, each of which is described below, were employed to collect in-situ porewater at discrete depths throughout the confining unit. The porewater samples were then analyzed for concentration of several dissolved ions including chloride. The resulting concentrations were then plotted according to the depth at which they were collected, yielding profiles of chloride concentration within the confining unit versus elevation for each boring location.

4.2.1.1. Sample Integrity

Several steps were taken in order to ensure that the cores were not contaminated and were truly “undisturbed.” As mentioned in Section 4.1.1, the drilling fluid was monitored throughout the drilling process to insure that salt water did not contaminate the drilling fluid in marine borings. When possible, porewater was extracted immediately following each core run in order to minimize evaporation of porewater within the core. Additionally, a procedure was performed during the drilling at SHE-9 to insure that drilling fluid did not permeate the entire cross section of any given core. Micron-sized polystyrene spheres that contain a fluorescent dye (Polysciences, Inc.) were added to drill mud during mixing at a final concentration of near 10^6 to 10^7 miocrospheres/mL of mud. After drilling was completed, an epifluorescent microscope at the USGS Science Center in Columbia, South Carolina was used to check for the presence of microspheres in a given cross section of core.

The core material from a particular depth was split into two pieces. Following a transect from the exterior of the core to the interior, approximately 1 mg of sediment was removed every 5 mm. The sediment was added to 9 mLs of distilled water and then shaken, and approximately 1 mL of the supernatant was placed on a nucleopore membrane. The membrane was then placed on a standard microscope slide, and the density of microspheres was recorded using an epifluorescent microscope. No penetration of microspheres into the undisturbed core material recovered was observed.

4.2.1.2. Core Sampling

The Miocene confining unit typically contains a significant amount of fine sand, yet still contains enough clay to maintain cohesiveness and medium to high porosities. As a result, the Miocene material cores well and proved to be ideal for obtaining porewater samples. A typical ten-foot core run yields at least eight feet of recovery, and the core is well consolidated and virtually undisturbed (Figure 4-2). Likewise, a typical porewater sample yields over 2mLs of fluid.

Figure 4-2. Core sample of Miocene confining unit (left) and underlying Oligocene limestone (right).

The Savannah District employed a method developed by Dr. James Landmeyer of the USGS to collect porewater samples from Miocene cores. After cores were extracted from the core barrel, measured, and described, a 0.5 to 0.7 foot interval of core was removed from the 8 to 10 foot section. The outside of the core was then cut away to ensure no drilling fluid contaminated the water sample. The remaining core sample, typically 40 to 50 grams in weight, was then loaded into a specially designed piston and cylinder chamber. The stainless steel chamber was constructed using three main components, a base with a small sampling port, a hollow cylinder that fit securely on the base, and a solid cylindrical piston that fit snugly into the hollow cylinder. In addition, a series of Teflon, polypropylene, stainless steel, and cellulose filter paper were placed in the bottom of the chamber to prevent the core sample from clogging the sample port in the base. The core sample was loaded into the hollow cylinder, and then solid discs of polypropylene and Teflon were placed on top of the sample to form a tight seal. The solid piston was then inserted into the hollow cylinder (Figure 4-3). The loaded chamber, or “bomb,” was then placed in a Carver manual lab press equipped with a scale gauge. A 10mL syringe was then placed in the sampling port, and up to 3000 psi of pressure was applied. As the piston compressed the core sample, porewater was forced into the sample syringe. The sample, typically 2 to 4mLs, was then placed into a 5mL airtight scintillation vial and stored at room temperature until analyzed.

Figure 4-3. Porewater sampling chamber or "bomb."

4.2.1.3. Geoprobe® Sampling

The Miocene confining unit is well consolidated and cohesive; whereas, the surficial Pleistocene-Recent sediments typically consist of coarser grained, loose sands and silts. As a result, core recovery is usually poor, and core samples retained are disturbed and unconsolidated. Chloride penetration through these sediments is still of interest; however, and an alternative sampling technique was utilized at the land boring locations (SHE-18, SHE-19, SHE-9, and SHE-10) to obtain in-situ porewater samples. Using a Geoprobe direct-push rig, screen point samples were taken to obtain water from ground surface to the top of the Miocene confining unit. The screen point ground-water sampling system, used in conjunction with the Geoprobe, is a protected screen sampler that enables the user to collect representative ground-water samples from a discrete interval as small as a few inches or as much as three feet. In any case, the smallest screen interval possible was used to obtain the necessary volume of water. A small check valve was inserted in Teflon tubing, and the tubing was then inserted inside the drill rods down to the screened interval to obtain a sample. The tubing was removed from the drill rods and the water sample was transferred to 5mL scintillation vials and stored at room temperature until analyzed.

4.2.2. Analysis

A field screening method was used prior to sending porewater samples to the laboratory for quantitative analysis. After extracting porewater from a given sample, a portable refractometer was used to measure bulk salinity (Figure 4-4). Based on the results, the screening interval could be refined or additional samples could be squeezed to verify or invalidate anomalous results.

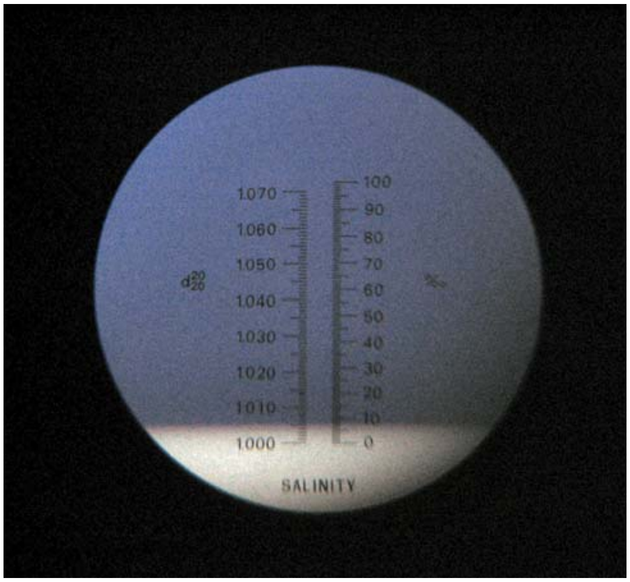


Figure 4-4. View of refractometer shadow line and corresponding salinity value in parts per thousand.

Upon drilling completion of each boring, porewater samples were securely packed and delivered by car to the USGS South Carolina District Office in Columbia. Dr. James Landmeyer of the USGS analyzed each sample for chloride, bromide, and sulfate using established ion chromatograph methods, specifically US Environmental Protection Agency (EPA) Method 300.0 (Dionex, 2003).

4.3. GEOPHYSICAL SURVEY

Past subbottom geophysical surveys revealed the existence of buried relict stream channels (paleochannels) underlying the present day navigation channel. The survey performed as part of the scope of work for this report was designed to complement and expand upon subbottom data gathered in 1997. Specifically, the survey aimed to identify and profile all significant paleochannels underlying the navigation channel from river stations +30+000 to –30+000, where the confining unit is thinned and the aquifer is closest to ground surface. The data collected also provided a means for locating several of the marine borings completed as part of this study.

4.3.1. Location

During the period 11-17 February 2004, OSI performed a subbottom geophysical survey in the Savannah Harbor bar channel and entrance channel. Initially, data was acquired along each edge of the navigation channel from river station +30+000 to –30+000. Following a brief review of the survey data, representatives from OSI and the Savannah District established supplemental track lines in areas where prominent paleochannels occurred. The supplemental tracklines were oriented both parallel and perpendicular to the course of the present day navigation channel in an effort to better determine the orientation and attitude of the paleochannels. In total, the survey incorporated approximately 60 miles of tracklines and greater than 50 survey lines. Figure 4-5 shows the locations of the tracklines.

4.3.2. Field Survey

4.3.2.1. Equipment

OSI performed the subbottom survey using a 26-foot survey vessel equipped with an array of geophysical survey and support equipment. A Real Time Kinematic Differential Global Positioning System (RTK DGPS) was installed on the vessel and interfaced with a radio link to a shoreside DGPS base station and onboard computer, which allowed the field team (OSI and Savannah District representatives) to navigate precisely along pre-determined tracklines and correct for tidal variations in real-time.

OSI employed a suite of geophysical equipment to conduct the subbottom survey, including a modified version of Coastal Oceanograhic's HYPACK® MAX PC-based navigation and data-logging software package, an Innerspace Model 448 digital depth sounder, and an OSI 300-joule high resolution "boomer" subbottom profiling system. For further details and specifications, see Appendix A.

4.3.2.2. Data Processing

OSI generated a survey trackline plot and all-inclusive daily field log detailing survey lines investigated and their associated data file names immediately upon conclusion of the field survey. Subbottom profile data were then extensively reviewed and interpreted with the primary task of identifying the prominent relict channel features within the study area (river stations +30+000 to –30+000). The reconstructed survey tracklines, identified subbottom reflector "picks," and contoured hydrographic data are all incorporated in the final report furnished by OSI, which is included as Appendix A.

4.4. THREE-DIMENSIONAL GROUND-WATER MODEL

As part of the scope of work for this study, CDM developed a comprehensive three-dimensional (3-D) numerical hydraulic coupled flow and transport model of the hydrologic system in the immediate vicinity of the navigation channel. The model incorporated hydraulic properties, confining unit thickness, and historic and present pumping rates to determine a range of plausible aquifer responses to dredging. The model was run according to several scenarios, including no future dredging, dredging with a 6-foot improvement plus an additional 3-foot removal of confining material, and varying the hydraulic conductivity of the confining layer. The model assumed an additional three feet of confining material was removed in order to account for any additional material that may be disturbed by the dredge cutter-head during the deepening process. While the cutter-head would not necessarily remove the additional material, any disturbance would alter the hydraulic properties of the material. For that reason, the model properties assumed the three additional feet were completely removed to insure the simulation results represented a conservative response. The model structure and simulations are summarized below, and a complete report is included as Appendix B.

4.4.1. Model Background

Siple (1957) first observed and reported seawater encroachment in coastal South Carolina. Over the past fifty years, the hydrogeology and ground-water flow system of the coastal area and Savannah have been studied extensively, and numerous papers have presented ground-water flow models (Bush, 1988; Clarke and Krause 2000; Garza and Krause, 1996; Krause and Randolph, 1989; Smith, 1988; Smith, 1994). Early ground-water flow models by Bush (1988) and Smith (1994) used a version of the USGS Saturated-Unsaturated Transport (SUTRA) model code to investigate the potential for lateral salt-water encroachment into the Upper Floridan aquifer. The models simulated ground-water flow and solute transport in 2-D vertical sections under various pumping schemes and predicted movement of the freshwater/salt-water transition zone in the Upper Floridan aquifer beneath Port Royal Sound near Hilton Head Island, South Carolina.

Krause and Randolph (1989) developed a Regional Aquifer-System Analysis (RASA) model that simulated 3-D ground-water flow using MODFLOW. The RASA model results provided a comprehensive picture of the steady-state ground-water flow regime in the coastal area and served as a basis for three more site-specific models: the Glynn model (Randolph and Krause, 1990), the coastal model (Randolph et al., 1991) and the Savannah model (Garza and Krause, 1996).

As part of the ongoing Sound Science Initiative, the USGS is updating the RASA MODFLOW model and applying a 3-D version of SUTRA to simulate both ground-water flow and density-dependent solute transport in coastal Georgia and adjacent parts of South Carolina and Florida. The model results will be used to evaluate regional ground-water management issues, salt-water intrusion, and seawater encroachment in coastal Georgia.

The USGS regional ground-water flow model does not contain sufficient detail to evaluate potential changes in ground-water heads, gradients, and migration of saline water due explicitly to dredging of the Savannah River navigation channel. Therefore, for this study, CDM developed a fully 3-D, finite element ground-water flow and salt-water intrusion model with a higher level of discretization in the Savannah area to specifically evaluate the potential effects of dredging on water quality in the Upper Floridan aquifer.

The early models, the RASA model, and its offspring models simulated ground-water flow influenced by pumping in Savannah and indicated fairly high vertical downward flows (leakage) through the upper confining unit to the Upper Floridan aquifer, but none of these models addressed vertical salt-water intrusion. Of these models, only Smith (1988) and Bush (1988) used SUTRA 2D to specifically simulate solute transport of chlorides; however, the simulations addressed only lateral seawater encroachment in two dimensions. The RASA model and its successors simulated regional ground-water flow in three dimensions but did not address seawater encroachment or salt-water intrusion. The proposed dredging, however, would not directly affect the rate of lateral seawater encroachment from the Atlantic Ocean or the regional ground-water flow regime. Instead, the removal of confining material along the navigation channel would affect the rate of downward leakage of water through the confining unit. As such, the CDM model focuses only on the vertical leakage mechanism and the effects of confining layer thickness and vertical hydraulic conductivity on water quality in the Upper Floridan aquifer in the Savannah area.

4.4.2. Study Approach

CDM adopted a five-step approach to develop the ground-water model: data review and analysis, development of ground-water flow and salt-water intrusion model, model refinement, model calibration, and model application.

CDM conducted a review of existing data and reports on aquifer studies and investigations for the proposed Savannah Harbor Expansion (SHE) project, including the studies published by the Savannah District. CDM then developed a ground-water flow model with salt-water intrusion simulation capabilities based on the existing USGS MODFLOW regional ground-water flow model. A finite element modeling code with a flexible grid structure was used so that the SHE model would have a sufficient level of detail along the Savannah River to evaluate the impact of the proposed dredging program. The model was specifically developed to simulate only intrusion of salt water from the Savannah River in the harbor area, with the focus on the stretch of river where dredging is proposed.

Following development of the model, CDM refined the model to accurately represent current flow conditions along the Savannah River navigation channel. The refinement involved increasing the discretization of the finite element grid along the Savannah River in the project area, improving the representation of the Miocene confining unit based on USACE boring and seismic data, and improving the channel and offshore bathymetry based on detailed USACE survey data and data available from the National Oceanographic and Atmospheric Association (NOAA). In order to verify the model, CDM tested the ability of the model to represent both steady state and transient ground-water head and flow conditions. Additionally, CDM tested the ability of the model to simulate saline water migration through the Miocene confining unit as measured in the USACE porewater profiles.

Once the model was tested and shown to be able to adequately reproduce observed ground-water heads, gradients, and chloride concentrations, it was applied to evaluate the potential impacts of the proposed dredging. The model was used to simulate the rate of migration of saline water from the Savannah River through the Miocene confining unit into the underlying Upper Floridan aquifer under a variety of input parameter assumptions. Chloride sources located outside the Savannah River channel (offshore, salt marshes, etc.) were not included in the simulations to ensure that simulation results represented the explicit effects of dredging on chloride concentration distributions in the Upper Floridan aquifer.

4.4.3. Model Structure

4.4.3.1. Model Codes

The modeling software utilized in this study included DYNFLOW (single phase ground-water flow), DYNTRACK (solute transport) and DYNCFT (dual-phase, density dependent ground-water flow). DYNFLOW is a fully three-dimensional, finite element ground-water flow model. CDM engineering staff has developed, tested, and documented DYNFLOW over the past 25 years, and the model is commonly used for both site-specific remedial design investigations and large-scale basin modeling projects. DYNFLOW uses a grid built with a large number of tetrahedral elements. These elements are triangular in plan view and allow for a wide flexibility in grid variation over the area of study. An identical grid is used for each level of the model, but the thickness of each model layer (the vertical distance between levels in the model) can vary at each point in the grid. In addition, two-dimensional elements can be inserted into the basic 3-D grid to simulate thin features such as faults. One-dimensional elements can be used to simulate the performance of wells that are perforated in several model layers. DYNFLOW has been applied to over 200 ground-water modeling studies in the United States and has been reviewed and tested by the International Groundwater Modeling Center (IGWMC) (van der Heijde, 1985, 1999).

CDM utilized DYNTRACK as the solute transport code, which was developed over the past 15 years by CDM engineering staff. DYNTRACK uses the random-walk technique to solve the advection-dispersion ground-water flow equation. In DYNTRACK, a solute source can be represented as an instantaneous input of solute mass (represented by a fixed number of particles), as a continuous source on which particles are input at a constant rate, or as a specified concentration at a node. The concentration within a particular zone of interest is represented by the total number of particles that are present within the zone multiplied by their associated solute mass then divided by the volume of water within the zone. DYNTRACK has also been reviewed and tested by the IGWMC (CDM, 2005; van der Heijde, 1985).

DYNCFT, a coupled flow and transport model, was used to fully simulate variable density effects on ground-water flow. DYNCFT combines the ground-water flow capabilities of DYNFLOW with the contaminant transport capabilities of DYNTRACK. Coupling flow and transport computations allows the effect on ground-water flow of fluid density gradients associated with solute concentration gradients to be incorporated into model simulations (i.e. density-dependent flow). In the SHE model, DYNCFT was applied to simulate the density-dependent flow component of saline water from the Savannah River navigation channel.

4.4.3.2. Model Domain and Finite Element Grid

The domain or geographic extent of the SHE project ground-water model was based on the USGS regional ground-water flow model. The SHE model domain covered approximately 42,250 square miles and was discretized into 16,362 triangular elements defined by 8,257 nodes at the vertices of the triangles (Figure 4-6). In order to represent the proposed dredging, discretization was finest in the area of the Savannah River to ensure the chloride source area (i.e. the river) was sufficiently defined. Node spacing was on the order of 125 feet within the river, which allowed any given transect across the width of the river to contain four nodes. The node spacing increased outside of the Savannah River area to typically 4.5 to 5 miles for inland nodes, and offshore nodal spacing is approximately 10.5 to 11 miles. Figure 4-7 shows a portion of the grid with detailed discretization near the city of Savannah.

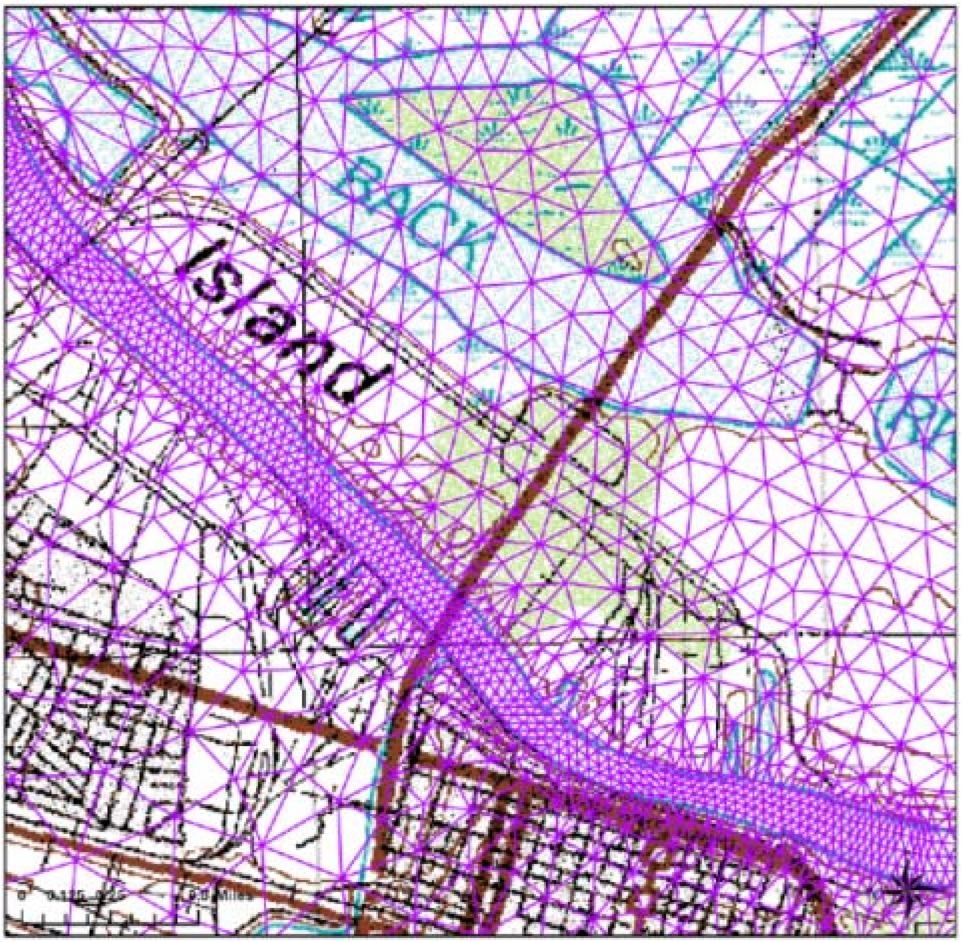


Figure 4-7. Detailed view of finite element grid in the Savannah area.

4.4.3.3. Boundary Conditions

The boundary conditions assigned in the SHE model are based on the USGS regional ground-water flow model and modified to fit the finite-element model structure. Fixed head and no flow boundaries were used as the major types of ground-water flow boundary conditions, and fixed concentration boundary conditions were used for the seawater transport computations. Chloride concentrations in the Savannah River were obtained from the surface water modeling conducted by Tetra Tech NUS, Inc. (Tetra Tech) for the SHE project. Salinity values for both existing and post-dredging conditions were obtained from preliminary surface water model simulations and represent simulated average annual concentrations of river water at the bottom of the river. Salinity was converted to chloride concentration by multiplying the salinity values by 0.37, a reasonable value for seawater. Chloride input concentrations ranged from a high of about 10,000 mg/L near the mouth of the river to below 3 mg/L in downtown Savannah. Both ground-water flow and transport boundary conditions are summarized in Table 4-2. See Appendix B, Section 2.4 for further discussion regarding boundary conditions.

Table 4-2. Boundary Conditions Assigned for Ground-water Model

Boundary Description	Type of Boundary Condition
Savannah River	Fixed Head = 0 for flow boundary; Constant Concentration for chloride seawater migration simulations (transport)
Upstream Savannah River	Rising Water
Ocean	Fixed Head
East (Ocean)	No Flow
Southeast (Ocean)	No Flow
Southwest	Fixed Head
Southern	Fixed Head
Northwest	No Flow
Northeast	No Flow
Water Table	Fixed Head
Base	No Flow

4.4.3.4. Stratigraphy/Layering

The conceptual layout of the aquifer and confining units was based on the USGS regional model. The units and their properties were defined according to the regional stratigraphic framework set forth by the USGS; however, not all the hydrogeologic units, namely the Miocene aquifers, are present in the project area. As such, the model utilized the generalized units in distal areas around the Savannah River, but in the immediate vicinity of the navigation channel, the model used the refined, site-specific stratigraphy shown in Table 3-1. To accommodate this refinement and to provide sufficient vertical discretization for chloride migration simulation beneath the river, the seven hydrogeologic units used in the model were divided into 12 levels and 11 layers, where levels are the planes containing nodes that bound the area contained within the layers. Table 4-3 below lists the seven basic hydrogeologic units, the corresponding layer numbers represented in the model, and their equivalent units underlying the study area.

Table 4-3. Model Hydrogeologic Units and Layers and Their Equivalent Units in Eastern Chatham County

Model Layer	Regional Hydrogeologic Unit	Eastern Chatham County Equivalent Unit
11	Surficial Aquifer	Surficial Aquifer
10 9 8	Miocene Confining Unit	Upper Confining Unit
7	Miocene Aquifer	Not Present in Study Area
6 5	Upper Floridan Confining	Upper Confining Unit
4 3	Upper Floridan Aquifer	Upper Floridan Aquifer
2	Lower Floridan Confining	Lower Confining Unit
1	Lower Floridan Aquifer	Lower Floridan Aquifer

4.4.3.5. Ground-Water Pumping

The ground-water pumping specified in the model was taken directly from data files developed by the USGS for the regional MODFLOW model. Ground-water pumping data are available in two formats: well specific and distributed. The well specific pumping data are based on either individual well or facility permits. Typically, well specific data are available for 100,000 gallons per day permits or larger, and in most cases, the total permit capacity is known but the individual well production is not known. The distributed pumping data refer to the total ground-water pumping estimates for each of the Georgia counties located within the model domain. Additionally, for the historical simulation, ground-water pumping data were obtained from the USGS. Figure 4-8 shows the total ground-water pumping rates applied in the model for the historical period from 1900 to 2000. Note that for projection simulations, the 2000 pumping rate was projected to continue indefinitely into the future.

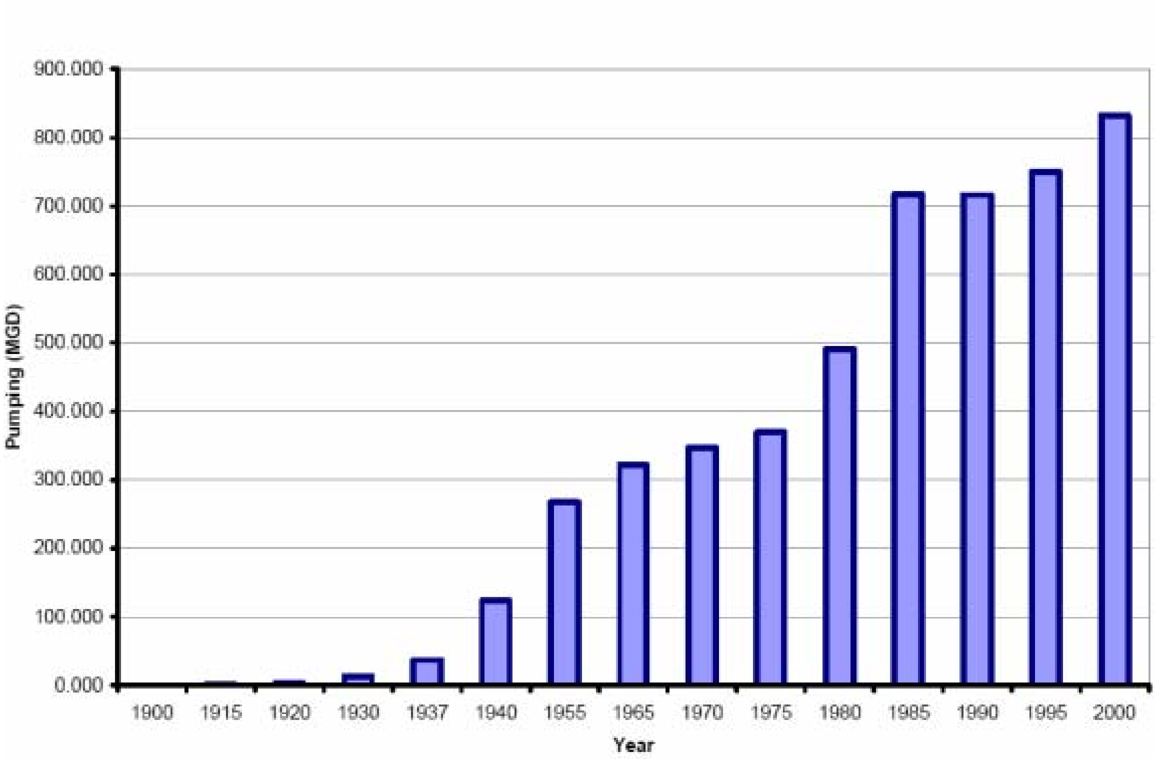


Figure 4-8. Applied ground-water pumping rates for historical simulations (1900-2000) across entire model domain.

4.4.4. Model Calibration

4.4.4.1. Steady-State Calibration

Model calibration is the process of making adjustments to model input parameters until the output from the model reasonably matches a set of measured data and the observed behavior of the ground water flow system. The USGS regional ground-water flow model was calibrated to steady-state year 2000 conditions, and the SHE model was calibrated to the same set of aquifer parameters to represent a best fit in terms of the observed and simulated ground-water heads and gradients. In steady-state calibrations, measured and model-computed heads (water levels) are compared, and the difference between the two, referred to as the residual, is calculated. According to ASTM Standard D 5918-96 *Standard Guide for Calibrating a Ground-Water Flow Model Application*, a calibration is considered adequate when there is no systematic head bias across the model and the standard deviation of residuals is within 10 to 15% of the total measured head range across the model domain.

Figure 4-9 shows that no single area of the model had systematically high or low simulated ground-water heads relative to the measured heads, and the heads closely matched those reproduced by the USGS model. The measured heads in the Floridan aquifer system vary by 100 feet in the Savannah area alone, which is a difficult system to calibrate. However, the calculated standard deviation (11 feet) was significantly lower than 10 percent of the total measured head gradient across the model (200 to 300 feet). Based on this assessment, the SHE model was adequately calibrated to simulate steady state conditions.

4.4.4.2. Transient Testing

In addition to the steady-state calibration check, CDM tested the ability of the model to reproduce both the historical and temporal behavior of ground-water heads and the measured chloride levels in the Miocene confining unit below the Savannah River. Measured ground-water head data is only available for the model area from around the 1980s onward. However, to test the ability of the model to reproduce the measured levels of chloride in the Miocene confining unit, CDM developed a transient simulation starting with pre-development conditions (1900).

The transient testing was performed for the period from 1900 to 2000 using an annual time step. Surficial aquifer heads were kept constant from 1900 to 1960 and then changed every 10 years based on a linear interpolation between the 1900 and 2000 values. Pumping was varied every 5 to 10 years depending on the availability of data, and chloride concentrations in the Savannah River were kept constant using the chloride distribution set forth by the Tetra Tech surface water model simulations.

The model effectively reproduced the long-term behavior observed in the ground-water heads in the Upper Floridan aquifer as shown in CDM Figures 2-26 and 2-27 in Appendix B. The model accurately simulated the heads as well as the general trends in heads, even though annual variations in pumping could not be simulated due to a lack of data.

In addition to testing the ability of the model to reproduce historical and temporal heads, the ability of the model to reproduce the measured values of chloride in the Miocene confining unit was also assessed. The simulated results represent the chloride concentrations resulting from the migration of saline water from the Savannah River over the 100-year (1900-2000) transient simulation period. CDM Figures 2-28 through 2-37 in Appendix B compare measured porewater chloride concentration profiles to simulated chloride concentration profiles. The simulated profiles generally resulted in deeper penetration of saline water than observed and higher chloride concentrations than measured porewater values. Furthermore, the transient test also indicated that the simulated penetration depths and chloride concentrations are most sensitive to the vertical hydraulic conductivity of the Miocene confining unit.

The calibrated value of vertical hydraulic conductivity (1.5 x 10^{-4} ft/day) for the Miocene confining unit is considered to represent the mid-range of reasonable values; however, given that the simulated results overestimated the rate of salt-water intrusion, this value is perhaps higher (more transmissive) than actual field conditions. A second set of simulations using a lower vertical hydraulic conductivity (1.5 x 10^{-5} ft/day) was also tested, and the simulated results slightly underestimated the rate of salt-water penetration. Therefore, the true system response lies somewhere between the two simulations. The model simulation runs that used the higher value (1.5 x 10^{-4} ft/day) ensured that the model results represented a conservative evaluation of possible dredging effects on the salt-water intrusion rate through the confining unit.

4.4.5. Model Simulations

4.4.5.1. Input Parameters

As mentioned above, the model application used two values of vertical hydraulic conductivity for the Miocene confining unit: the calibrated value, which represents the mid-range of reasonable values, and a lower value. In doing so, the two sets of results bound true conditions. Table 4-4 shows the range of vertical hydraulic conductivity for the Miocene confining units in the project area. The lower value of vertical hydraulic conductivity results in chloride profiles at the SHE borehole locations that were in some ways more consistent with the measured values. However, the simulation produced heads in the cone of depression in the Upper Floridan aquifer that were approximately 25 feet too low when compared to field data. Conversely, the calibrated value of hydraulic conductivity produced accurate head distribution within the cone of depression, but the model results overestimated the rate of penetration when compared to the porewater sample data. Results of the sensitivity simulation are provided in Appendix B. With little data available, conservative storativity and specific yield values were used. Values of 0.00001 for storativity and 0.1 for specific yield were applied to all layers and hydrologic units in the model.

Table 4-4. Ground-Water Model Hydraulic Conductivity Input and Sensitivity Analysis Parameters

Sensitivity Parameters		Calibration Statistics		Upper Floridan Heads at Hutchinson Island Well (37Q185)	
Unit	Vertical Hydraulic Conductivity (ft/day)	Mean Difference (ft)	Standard Deviation (ft)	Simulated (ft MLW)	Observed Mean Year 2000 (ft MLW)
Miocene Confining Unit	1.50E-5	-5.5	12.4	-123.5	-93.8
	1.50E-4 (Calibrated)	-1.121	10.86	-97.6	

It should be noted that simulations of future conditions become less certain the farther one gets away from the calibrated data set and selected input parameters, and future pumping rates and boundary conditions will change over time. The projection simulations done for this study assume a continuation of current conditions for the next 200 years, making results beyond the 20-year time horizon less and less certain.

For this study, simulations were run forward in time with a 1-year time-step for a period of 200 years. The results were used to evaluate the potential impact of dredging on ground-water flow and chloride concentrations in the Miocene confining layer and eventually chloride concentrations in the Upper Floridan aquifer.

Upon breakthrough, the salt water leaking downward through the Miocene confining layer will be diluted into the fresh-water Upper Floridan aquifer. However, assuming mixing of the salt water throughout the full thickness of the Upper Floridan aquifer would result in very low concentrations and would not be a conservative assumption. Therefore, an aquifer thickness of 50 to 60 feet was used to calculate the final concentration of chlorides in the Upper Floridan aquifer. The chosen aquifer thickness limited the chloride mixing to the upper, more conductive portion of the aquifer, resulting in higher and thus more conservative estimates of chloride concentration. The predictive simulations used the following input parameters:

<u>Initial ground-water heads</u>: The year 2000 steady state ground-water levels were used as the starting condition for the simulations.

<u>Ground-water pumping:</u> Future ground-water pumping was kept constant at year 2000 levels. Regulatory officials from both South Carolina and Georgia agree that future pumping from the Upper Floridan aquifer must decrease in order to limit the impacts of salt-water intrusion in the coastal area. A recently-released GAEPD document entitled *Coastal Georgia Water and Waste Water Permitting Plan for Managing Salt-Water Intrusion* (2006) indicates that Georgia will reduce withdrawals from the Upper Floridan aquifer by 5 MGD by the end of 2008; therefore, keeping the pumping rate constant provided a conservative assessment of future ground-water production in the area.

<u>Chloride concentrations in the Miocene:</u> The simulated 2000 distribution of chlorides in the Miocene unit (Figure 4-10) was used as the initial condition. Note that these figures represented significant penetration of chlorides into the Miocene confining units as of “today” (i.e. the start of the projection simulation). The starting chloride concentrations were generally an overestimate of chloride penetration, as discussed above, and, therefore, represented a conservative starting assumption.

Savannah River salinity: As discussed in Section 4.4.3.3, the Savannah River nodes were assigned a constant chloride concentration. The chloride concentrations used for the dredging simulations were obtained from the Tetra Tech surface water model and were higher than the no dredging scenario. For the dredging scenario, the higher values were applied at the beginning of the simulation (year 2000).

Miocene thickness and dredged depths: The dredging depths used in the model represent the “6-foot” improvement option at full maintenance depth plus three additional feet. The removal of three additional feet accounts for any additional material that may be disturbed by the dredge cutter-head. A disturbance would alter the hydraulic properties of the material; therefore, to insure model results represented a conservative response, the model properties assumed the three additional feet were completely removed.

Transport parameters: Table 4-5 shows the transport parameters utilized in the simulations. The applied values have generally provided reasonable dispersion results in other modeling studies and are not based on field data. Advective transport dominated choride transport in the SHE model; therefore, variation of the dispersion transport parameters did not significantly affect results.

Table 4-5. Transport Modeling Input Parameters

Parameter	Value
Longitudinal Dispersivity	30 feet
Transverse Dispersivity	3 feet
Upper Floridan Vertical Dispersion Anisotropy	0.1 (dimensionless)
Effective Porosity	0.1 (dimensionless)
Retardation	1 = no retardation (dimensionless)

Salt-water density: The ratio of salt-water density to freshwater density was varied linearly from 1.0 for zero chloride concentration to 1.013 for a chloride concentration of 10,000 mg/L.

4.4.5.2. Conservative Assumptions

The model simulations intended to provide a bracketed range of results to evaluate the probable range of impacts following dredging activities. In order to accomplish this objective, several conservative assumptions were used in the input parameters as described above in Section 4.4.5.1. In summary, the conservative assumptions applied to the model simulations were:

- Pumping rates from the Upper Floridan aquifer in the Savannah area were assumed to remain as they are at present although withdrawal rates are expected to decrease in the future.

- The model utilized the simulated present-day chloride distributions in the Miocene confining unit. These values generally overestimated penetration concentrations when compared with measured porewater values.

- The model was sensitive to the porosity of the confining unit, with lower values increasing the rate of movement of salt downward. This was tested, but with little field data to adequately defend a "calibrated" value, a low end value (0.1) was selected to be conservative.

- Paleochannel in-fill material was assumed to have hydraulic properties comparable to that of surficial aquifer sands, although actual core permeability results indicate the paleochannels contain a significant amount of material that is less permeable.

- Three additional feet of confining layer material were assumed to have been removed throughout the project area to allow for possible disturbance by the cutter-head during dredging activities.

- Historical simulations were run using current-day navigation channel geometry and depths.

4.5. SIMULATED PUMPING TEST

CDM conducted several simulations to evaluate the potential response in the surficial aquifer and Miocene confining unit to a long-term pumping test conducted with a well in the Upper Floridan aquifer. The intent of the simulations was to evaluate the feasibility of performing full aquitard testing of the confining unit.

CDM simulated a pump test within the framework of the flow model described in Section 4.4 and applied the calibrated mid-range value of vertical hydraulic conductivity ($1.5x10^{-4}$ ft/day).

The pumping well used in the simulation was located on the north end of Tybee Island at the approximate location of the Tybee Island Test Well Cluster. Three different pumping rates, 500, 1,000 and 2,000 gallons per minute (gpm), were evaluated, and the simulations were run for a period of one year. The simulated response in observations wells at distances of 750, 1,100 and 2,400 feet was recorded.

4.6. MISCELLANEOUS

4.6.1. Gamma Logging

Distinctive, characteristic natural gamma peaks occur within the Miocene sediments throughout coastal Georgia and South Carolina, and gamma logging has long been acknowledged as a useful tool for correlating strata between borings (McCollum and Counts, 1964; Weems and Edwards, 2001). As part of this study, natural gamma logs were obtained from all borings to aid in correlating and defining stratigraphic units within the project area. Specifically, two known gamma markers occur in the project area within the Miocene unit (known as “A” and “B”). These markers are found in stratigraphic layers that contain high natural gamma radiation. They are associated with highly phosphatic carbonate beds and are generally found a few feet above the unconformities separating Miocene units A and B, and Miocene unit B and the Oligocene unit (Clarke et al., 1990).

A natural gamma probe and digital controller manufactured by Mount Sopris Instrument Company was employed to conduct all gamma logging. The probe, connected to a cable and a winch, measured natural gamma of the soil, and the data was detected, shaped, and transmitted up the cable line to the controller. The controller, an MGX II Console, then converted the data to a digital output and transmitted it to a laptop computer to provide a real-time continuous log as the probe was winched up or down the borehole.

4.6.2. Electrical Conductivity Logging

Soil conductivity is useful to help classify soils and qualitatively assess the amount of salt water present in pore spaces. Finer grained soils typically exhibit higher conductivities, while sand and gravels are characterized by distinctly lower conductivities. Soil conductivity logs were acquired at boring locations SHE-9, SHE-10, SHE-18, and SHE-19, and the results were checked for correlation with both boring logs and porewater chloride profiles. A Direct Image Electrical Conductivity (EC) System with a Wenner array in conjunction with a Geoprobe direct-push rig was used to obtain the logs. The EC probe measured approximately 15 inches long and contained four electrodes. The probe was installed on the end of drill rods and advanced into the subsurface using the percussion hammer and hydraulic slides from the Geoprobe (Butler et al., 1999). A current was applied to the two outside electrodes and voltage was measured on the two inside electrodes (Christy et al., 1994). The measurement was conveyed to a laptop computer via a pre-strung coaxial cable to provide a real-time continuous log as the probe advanced.

4.6.3. Ground-Water Gradient Data

The cone of depression in the Savannah area has induced a downward flow gradient, and while the gradient between the surficial aquifer and the Upper Floridan is well known, little is known about the corresponding downward gradient within the Miocene confining layer. The 1998 *Ground-Water Impacts* study (USACE, 1998) presented the first measured evidence of a downward vertical hydraulic gradient through the Miocene confining layer in the Savannah area. As part of the supplemental studies, additional measurements were taken in an array of wells along the Savannah River from upstream near the center of the cone of depression to downstream on the north end of Tybee Island. Heads were measured using a water-level indicator or, where available, vibrating wire pressure transducers installed at various levels within the Miocene confining layer (SHE-9 and SHE-10). Gradients were then calculated based on the elevations of the water levels and screen intervals and the height difference between the measurement points.

4.6.4. Soils Laboratory Data

Sixty-five undisturbed core samples collected from December 2003 to August 2004 were submitted to the USACE Engineering and Materials Unit and analyzed to determine laboratory permeability and hydraulic conductivity as well as grain size distribution and other geotechnical parameters. In addition, two undisturbed core samples were submitted and analyzed for triaxial shear properties.

After cores were extracted from the core barrel, measured, and described, a 0.5 to 1.0 foot interval of core was removed from the 8 to 10 foot section. The samples were wrapped in plastic cling wrap, aluminum foil, and a covering of duct tape to prevent moisture loss, and, in addition, some samples were placed into rigid plastic tubing and sealed for added protection. The cores were refrigerated until completion of the boring, at which time they were packed in a foam-padded box and delivered by car to the USACE Engineering Materials Unit in Atlanta, Georgia. Overall, every effort was made to preserve the samples intact with minimal disturbance. Regardless of the received condition, some sample specimens required slight remolding in preparation of testing. Any specimen remolding was conducted with all efforts directed at preserving the as-received moisture condition and density prior to engineering properties testing.

Twenty-four samples collected from November 2001 to June 2002 (borings SHE-9 and SHE-10) were submitted to DLZ Engineering Laboratory. Sample preservation and laboratory analyses were performed according to similar protocol as described above, and the sample results are included in the section below along with the results from samples submitted to the USACE Engineering Materials Unit.

4.6.4.1. Permeability, Porosity, and Hydraulic Conductivity

The hydraulic conductivity (K) of the geologic units overlying the aquifer, the Pleistocene-Recent unit and the Miocene unit, are of particular interest in this study. Specifically, the values determined by the lab analyses were applied to calculations and model simulations that evaluated the potential downward migration of seawater through the Miocene confining unit into the Upper Floridan aquifer.

Samples were tested for hydraulic conductivity using ASTM Method D5084. Various base and head platens were utilized during sample preparation to best match the diameter of each sample. All permeability specimens were properly back-pressure saturated and verified to meet the required minimum B value of 95% prior to conducting permeation. Porosity (n) was calculated using standard dry unit weight and specific gravity determination techniques and the relationship $n = e/(1+e)$, where e is the void ratio of the sample. The hydraulic conductivity was measured using a Mercury U-tube Manometer and the resultant values were reported at a target hydraulic gradient value of about 20.

4.6.4.2. Triaxial Compression

The strength of geological materials is generally expressed as the maximum resistance to deformation or fracture by applied shear or compressive stress. The strength characteristics of geological materials depend to an important degree on their previous history and on the conditions under which they will be stressed. Consequently, laboratory tests are designed to simulate the conditions under which the material will be stressed in the field. For this study, samples were analyzed for triaxial shear properties in order to better characterize the strength and deformation-specific properties of the Miocene confining unit under in-situ conditions.

Triaxial testing was conducted using ASTM Method D4767 Consolidated Undrained Triaxial Compression test with pore pressure measurements. The loading for specimens was selected at 0.5 and 1.0 tons per square foot (tsf) for each of the two sample locations. Specimens were prepared by carefully trimming them from the as-received samples to an approximate diameter of 1.4 inches and a height of 3 inches. Some sample specimens required slight remolding in preparation of testing, particularly for sample hole SHE-17 at depth 79.0 to 80.0, which was classified as clayey sand.

4.6.4.3. Unified Soil Classification

Core samples were classified according to the Unified Soil Classification system using grain-size analyses and Atterberg Limits results. Samples that were suspected to contain organic material were subjected to an oven-dried liquid limit testing method to verify the classification description. When oven-dried liquid limit results were found to be less than 75% of the results from moist prepared liquid limit samples, the soil was classified as an organic silt or organic clay. Some soil classification results were also visually identified when both the grain-size and Atterberg Limits tests were not performed. These sample classifications are identified as “Visual.”

4.7. GEOGRAPHIC INFORMATION SYSTEM (GIS)

A geologic and hydrogeologic GIS was developed as part of this supplemental study in order to enhance visualization and analysis of both historical and newly collected data. Ultimately, the resulting maps and products included in this report will be incorporated into the larger harbor-wide GIS. ArcGIS 9 was used as the framework for the GIS. Data was compiled and entered into a Microsoft Access 2000 database, which, in turn, was linked and integrated with the GIS as a geodatabase. ArcInfo Desktop version 9 with Spatial Analyst and 3-D Analyst extensions was used to process and analyze the data. ArcMap version 9, a two-dimensional visualization tool, was used to produce maps and figures.

X, Y, Z data files containing locations and elevations of critical geologic contacts or features along the Savannah River were used to define raster surfaces. The data was used to define several base surfaces including the study area, the river bottom, and the stratigraphy of major geologic formations. The base surfaces were then used to create several calculated surfaces, which are discussed in the Section 5.7 of this report. The processes used to create them are detailed in Appendix C.

4.7.1. Data Sources

4.7.1.1. Geologic Data

As part of the objectives outlined in the supplemental studies, historical boring logs were compiled, digitized, and added to the GIS. Coordinates for each boring were converted to NAD83, Georgia State Plane Coordinate System, East Zone. The boring locations and corresponding digitized boring logs were plotted in the GIS to provide a clickable resource for quick reference. In addition, major formation elevations were identified for each boring log and entered into an integrated database, which served as the basis for creating various surfaces of the lithologic units underlying the navigation channel for both the ground-water model and GIS analyses. Over 400 boring logs and their interpretations were processed and mapped as part of this study.

The Savannah District compiled permeability and hydraulic conductivity, porewater, gamma, and soil conductivity data collected as part of the 1998 feasibility study as well as the data collected as part of the supplemental studies into a geodatabase that was integrated with the GIS. The tabular data was plotted according to location and elevation from which it was collected. In addition, where available, plotted data curves and lab reports including grain-size analyses and soil classifications were scanned, and the resulting image files were linked to the data location to allow quick access to the data source.

4.7.1.2. Hydrogeologic Data

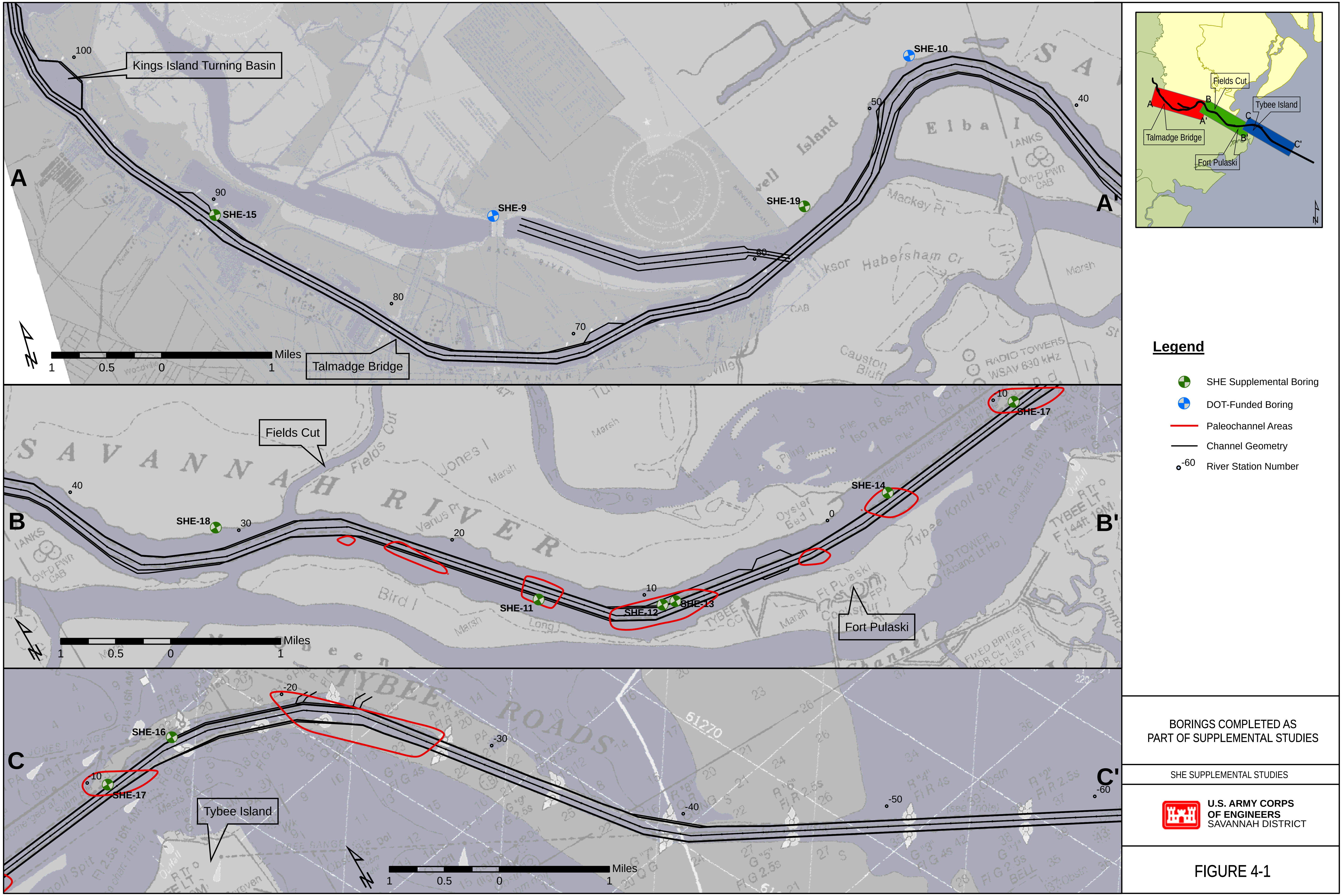
Drawdown data of the Upper Floridan aquifer (Peck et al., 1999) was obtained from the USGS and incorporated into the GIS. The potentiometric contours generated by the well data cover the cone of depression around Savannah and coastal Georgia and limited areas of South Carolina and Florida. In order to illustrate a more complete view of the potentiometric heads in the Upper Floridan, SCDHEC data (Ransom and White, 1998) was included in the potentiometric surface calculation as well.

4.7.1.3. Seismic Data

As detailed in Section 4.3, all seismic data collected as part of the supplemental studies was acquired in digital format to facilitate its inclusion in the GIS. OSI also provided all subbottom interpretation data in Microsoft Excel "pick files," X, Y, Z formatted data that included coordinates and elevations of each reflector along each survey trackline. The data was loaded into the geodatabase and used to create detailed surfaces of not only the major lithologic contacts but also of each major paleochannel as it intersected the navigation channel. Additionally, the tracklines were plotted and embedded with hyperlinks to image files of each interpreted cross section that included color-coded interpretations of each reflector.

4.7.1.4. Historical Dredging Records

Historical dredging records were incorporated into the GIS to assess the location and amount of confining material removed through time. Internal historical documents including annual surveys, congressional authorizations, status reports, exam studies, and design memoranda were reviewed for information regarding channel depth and geometry. The resulting authorized depths and widths were used to interpolate coordinates and incorporated into the GIS. Whenever available, digitized bottom survey data (1986 and 2003) and geometry design files superseded information gathered from congressional authorizations or other text-based sources.

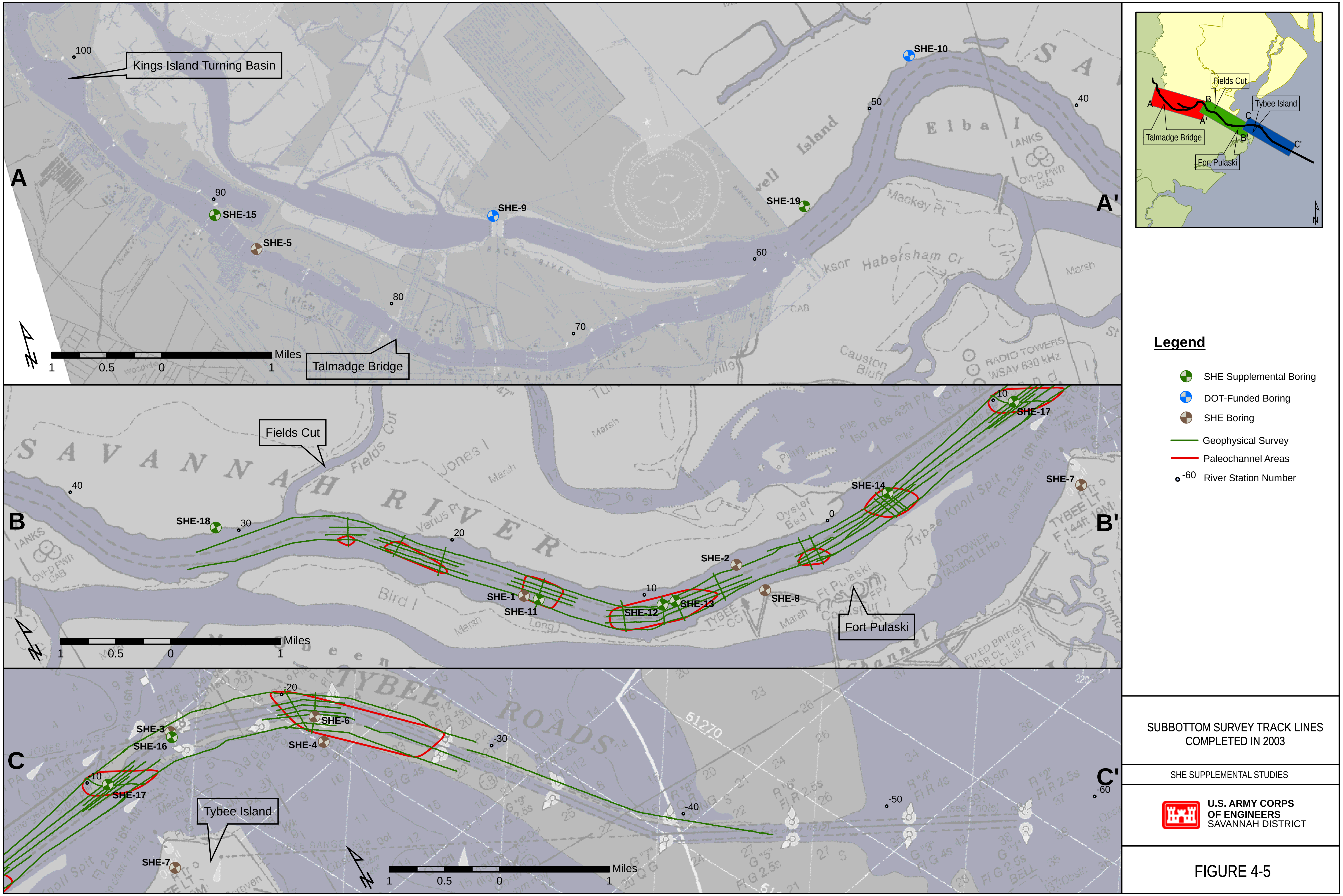


BORINGS COMPLETED AS
PART OF SUPPLEMENTAL STUDIES

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 4-1

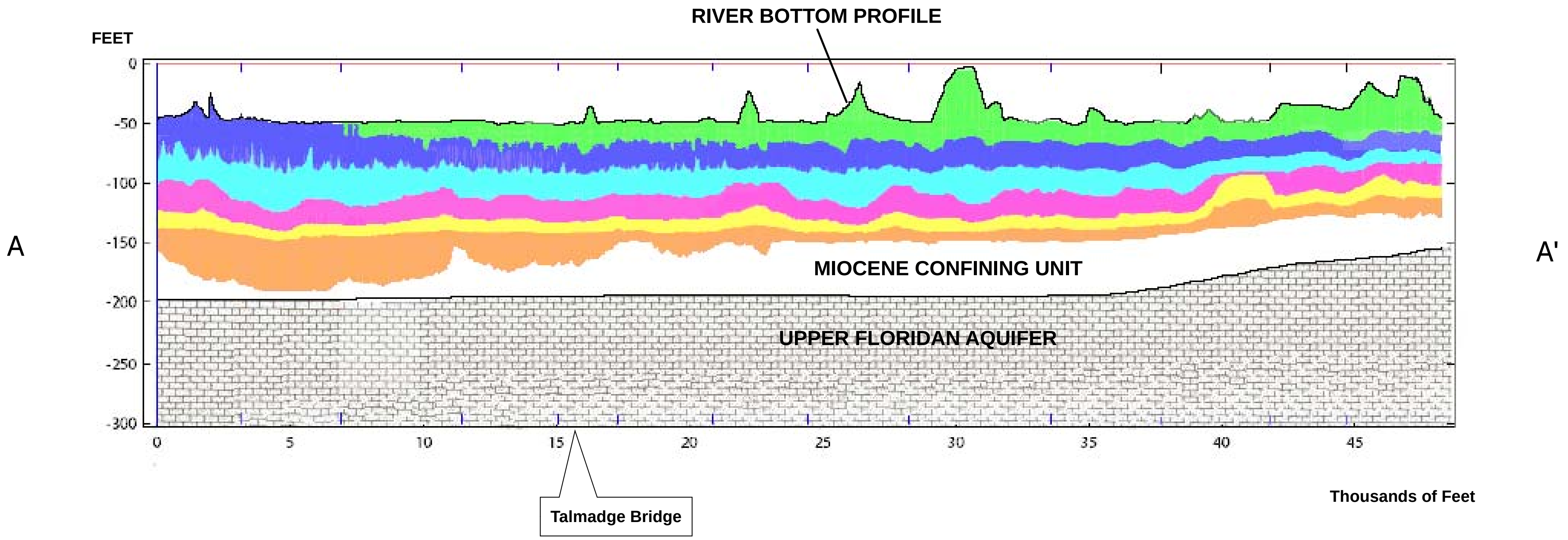


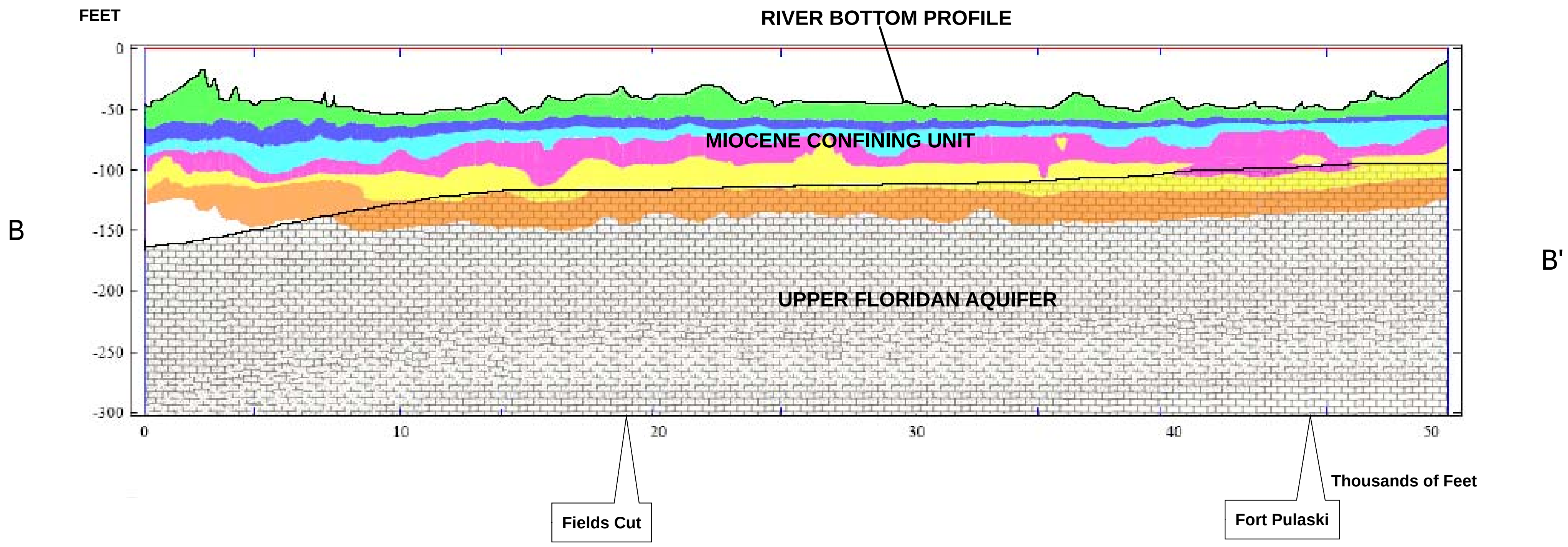
SUBBOTTOM SURVEY TRACK LINES
COMPLETED IN 2003

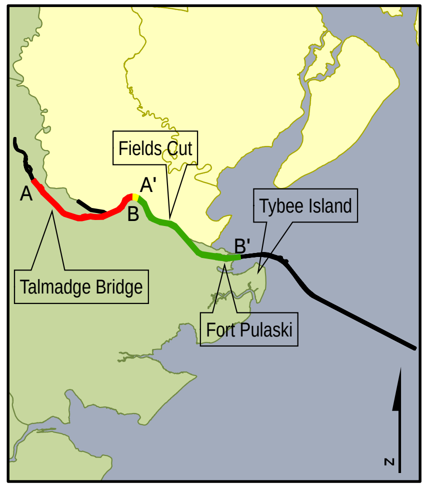
SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 4-5







Legend

Cl (mg/L)

- 🟧 25 - 250
- 🟨 250 - 500
- 🟪 500 - 1000
- 🟦 1000 - 2500
- 🟦 2500 - 5000
- 🟩 5000 - 10000

- ▦ Limestone
- □ Silty to Clayey Sands, Silts, & Clays

CROSS SECTIONS OF SIMULATED CURRENT CHLORIDE DISTRIBUTIONS ALONG THE SAVANNAH RIVER

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS OF ENGINEERS
SAVANNAH DISTRICT

Source: CDM

FIGURE 4-11

5. STUDY RESULTS AND DISCUSSION

The study results and discussion presented below encompass data collected not only as part of this supplemental report but also from the initial 1998 *Ground-Water Impacts* study (USACE, 1998). Where appropriate, historical data was used to complement or verify findings associated with new data collected.

5.1. DRILLING

Core borings completed as part of the supplemental studies indicated presence of the lithological sequence typical of that associated with historical data, and contact elevations of geologic units encountered correlated well with those determined from historical borings. In general, the sediments underlying the navigation channel are laterally continuous sequences of heterogeneous Pleistocene to Recent sediments underlain by relatively homogenous Miocene units A and B (Table 3-1). The characteristic green-colored sediments of the Miocene units are underlain by Oligocene-aged porous limestone. Appendix D contains boring logs for borings completed as part of the supplemental studies.

Pleistocene to Recent sediments encountered consisted of poorly graded sands (SP), silty sands (SM), silt (ML), clayey silt (MH), low plasticity clays (CL), and high plasticity clays (CH). These sediments were typically tan to gray with occasional small gravel and organic debris. In some cases, particularly in marine borings located within paleochannels, the Pleistocene to Recent sediments contained green-colored fine-grained sediment, which is most likely Miocene-aged material that has been reworked or transported by historical channels.

The Pleistocene to Recent sediments varied in thickness depending upon whether or not the boring was located within a paleochannel. In borings located outside paleochannels, the lower boundary of the Pleistocene to Recent sediments generally ranged from –40 to –50 MLW (Figure 5-1). In contrast, borings located within the relict channels indicated Pleistocene to Recent sediments were present to lower elevations where the paleochannel had cut down into the underlying Miocene unit. In these borings, the elevation of the Pleistocene to Recent/Miocene contact varied from –58 (SHE-17) to –71 MLW (SHE-12). Historically, the contact was observed as deep as –73 MLW at boring SH-318 (Figure 5-1).

Miocene sediments typically consisted of dark to light olive green silty sands (SM), clayey sands (SC), silt (ML), clayey silt (MH), and low plasticity clay (CL) and contained characteristic seams of calcareous clays, silts, and sands and limestone. Frequent thin partings of very fine micaceous sand and silt were found in cores throughout the Miocene sediments, as were trace fossils of burrows. No fractures were observed in any of the borings.

Miocene unit A, as described by Clarke et al. (1990), consisted of compacted, sometimes dense, clayey silt or sand, or silty, sandy clay and an abundance of small brown fish scales described by Huddlestun (1988). Thicknesses ranged from 20 to 30 feet thick in borings outside paleochannels near the Tybee high (river stations 30+000 to –30+000). Historical borings indicate that the thickness progressively increases upriver, and the maximum thickness observed was 76 feet at SHE-15, upriver of the Talmadge Bridge (Figure 5-1). In all borings, the lowest approximately 10 feet contained a characteristic highly phosphatic zone (Tybee Phosphorite member of the Coosawhatchie Formation). The phosphatic zone was underlain by calcareous clay, sandstone, or dolomitic limestone that ranged in thickness from several tenths of a foot to 2.5 feet thick and was moderately hard to hard. The dark green to black phosphate-rich zone and the cream colored, hard to brittle calcareous clay/limestone seams were distinctly evident in each boring, as was the distinction between the lower carbonate of unit A and the mixed olive green clay, silt and sand material above. However, no distinction was apparent between a “middle clay and upper sand” as described by Clarke and others (1990) in any of the borings.

Miocene unit B typically consisted of 25 to 40 feet of materials similar to the A unit. The highest elevation of the top of unit B in the core borings occurred over the Tybee high at -70 MLW in boring SHE-14, and historical boring SHE-3 showed the contact at –67 MLW (Figure 5-1). Miocene unit A and unit B soils were found to be very similar, but a few noticeable distinctions were noted. In hand sample, unit B materials appeared to contain a lower percentage of sand and a higher percentage of clay than unit A sediments, and phosphatic sand occurred not only in the bottom few feet of the unit similar to unit A, but also in the top few feet as well (SHE-4, SHE-9). Unit B material tended to become more dense and indurated with depth and often exhibited mottled light green to green bioturbated zones. As in unit A, the “lower carbonate, middle clay and upper sand” sequence was not apparent within unit B.

Bartholomew et al. (2000) observed fractures in Eocene and Pliocene to Holocene (but not specifically Miocene) sediments at outcrops from northwest of Charleston, South Carolina to Sapelo Island, Georgia that were associated with horizontal stresses produced by the Charleston earthquake of 1886. As noted above, no fractures were observed in Miocene-aged material during drilling activities conducted as part of this study or the 1998 report. Although nearly all core borings drilled for this or previous projects in the Savannah Harbor area have been near-vertical borings, no historical boring logs (out of approximately 300) indicated the presence of fractures within the Miocene.

The Oligocene unit, considered in this study to be the first occurrence of continuous limestone below Miocene unit B and the top of the Upper Floridan aquifer, was typically characterized by a light gray to white, highly fossiliferous limestone. The first few feet of the limestone was generally dense, moderately hard to hard, pitted, vuggy, somewhat phosphatic, and in several borings, very sandy. The contact between the limestone and the olive green Miocene unit B material immediately above was very distinct, with the first few tenths of a foot of limestone consisting of a very weathered, hard, gray to black cap. However, occasionally it was characterized by a transitional zone of a mixture of re-worked limestone and Miocene material or with Miocene material filling voids or burrows in the limestone. The highest occurrence of the top of the Oligocene limestone in the core borings was –94 MLW at SHE-14 (Figure 5-1).

5.2. POREWATER PROFILES

Porewater samples were first collected as part of the Savannah Harbor Expansion in 2001-2002 at borings SHE-9 and SHE-10. The resulting profiles of chloride concentration versus elevation are included as part of this report along with results from borings completed in 2003 and 2004 (Figure 5-1). All profiles indicated highest chloride concentrations occur nearer ground surface (or river bottom) and show an overall decrease in concentration with increased depth.

5.2.1. Profiles Outside Known Paleochannels

Porewater profiles constructed outside known paleochannel locations included two marine boring locations (SHE-15 and SHE-16) and all land boring locations (SHE-9, SHE-10, SHE-18, and SHE-19). Figure 5-1 and Table 5-1 show chloride concentration versus elevation. The profiles show highest chloride concentrations occur closest to land surface (or river bottom) and decrease with descending elevation. The highest chloride value occurred at boring SHE-16 (12,381 mg/L) at approximately 5 feet below the bottom of the riverbed (-42.0 ft MLW). The next sample, taken 10 feet below the bottom of the river (-46.8 ft MLW), indicated the concentration decreased more than 50 percent to 5,253 mg/L. The remainder of the porewater profile at SHE-16 showed decreasing chloride concentrations to the top of the Oligocene limestone, with no values above 100 mg/L below the Miocene A/B contact. The concentration of chloride in the Miocene porewater sample nearest the top of the aquifer (-99.8 ft MLW) was 16 mg/L. The high values recorded near the top of the boring were expected, as the boring is located in the Atlantic Ocean where the surface water undergoes decreased freshwater mixing from the Savannah River.

Table 5-1. Porewater Data Collected from 2001 to 2004

Boring	Sample	Geologic Unit	Elevation (MLW)	Chloride (mg/L)
SHE-9	P-1	P/R	-1.8	4212
SHE-9	P-2	P/R	-5.8	5421
SHE-9	P-3	P/R	-9.8	4201
SHE-9	P-4	P/R	-13.8	4871
SHE-9	P-5	P/R	-20.1	901
SHE-9	P-7	P/R	-21.8	1212
SHE-9	P-8	P/R	-24.8	1264
SHE-9	P-9	P/R	-29.2	2154
SHE-9	P-10	A	-29.8	1296
SHE-9	P-12	A	-44.4	1523
SHE-9	P-14	A	-52.7	1542
SHE-9	P-16	A	-71.1	910
SHE-9	P-18	A	-87.7	917
SHE-9	P-20	A	-97.8	901
SHE-9	P-22	A	-112.7	967
SHE-9	P-24	A	-115.9	904
SHE-9	P-25	A	-119.3	2189
SHE-9	P-26	A	-128.2	1847
SHE-9	P-27	B	-130.9	910
SHE-9	P-28	B	-149.2	961
SHE-9	P-30	B	-164.7	910
SHE-9	P-32	B	-175.8	480
SHE-9	P-34	B	-184.6	310
SHE-10	10SP1	P/R	13.5	5086
SHE-10	10SP2	P/R	3.5	4374
SHE-10	10SP3	P/R	-6.5	332
SHE-10	P-1	P/R	-10.5	1769
SHE-10	P-2	A	-40.5	820
SHE-10	P-3	A	-50.5	810
SHE-10	P-4	A	-55.5	756
SHE-10	P-6	A	-68.5	782
SHE-10	P-7	A	-76.5	454
SHE-10	P-8	A	-83.5	451
SHE-10	P-9	A	-91.5	220
SHE-10	P-10	A	-98.5	179
SHE-10	P-11	A	-104.5	141
SHE-10	P-12	A	-112.5	130
SHE-10	P-14	A	-128.5	76
SHE-10	10-PW-1	B	-152.5	42
SHE-10	10-PW-2	B	-161.2	34
SHE-11	P-1	CF	-48.1	5196
SHE-11	P-2	CF	-56.1	3573
SHE-11	P-3	CF	-58.6	5218
SHE-11	P-4	A	-66.6	7880
SHE-11	P-5	A	-79.1	1418
SHE-11	P-6	B	-90.6	971
SHE-11	P-7	B	-97.3	936
SHE-11	P-8	B	-100.6	782
SHE-11	P-9	B	-106.3	501
SHE-13	P-1	CF	-50.9	17423
SHE-13	P-2	CF	-52.4	19760
SHE-13	P-3	CF	-56.4	16516
SHE-13	P-4	CF	-62.9	9973
SHE-13	P-5	A	-73.1	7676
SHE-13	P-6	A	-78.7	4485
SHE-13	P-7	A	-82.9	1760
SHE-13	P-8	A	-86.9	1062
SHE-13	P-9	B	-91.9	493
SHE-13	P-10	B	-97.6	281
SHE-13	P-11	B	-104.4	153
SHE-14	P-1	CF	-45.2	14405
SHE-14	P-2	A	-52.9	5199
SHE-14	P-3	A	-56.6	6570
SHE-14	P-4	A	-65.6	14687
SHE-14	P-4a	A	-65.6	15916
SHE-14	P-4c	A	-66.1	13334
SHE-14	P-5	B	-71.6	2710
SHE-14	P-6	B	-76.7	462
SHE-14	P-7	B	-81.6	186
SHE-14	P-8	B	-87.1	257
SHE-14	P-9	B	-92.8	69
SHE-14	P-10	O	-96.1	151
SHE-15	P-1	P/R	-41.3	4296
SHE-15	P-2	P/R	-48.9	3237
SHE-15	P-3	A	-52.5	7209
SHE-15	P-4	A	-53.3	3573
SHE-15	P-5	A	-57.9	1406
SHE-15	P-6	A	-64.3	280
SHE-15	P-7	A	-74.9	130
SHE-15	P-8	A	-89.2	92
SHE-15	P-9	A	-101.8	45
SHE-15	P-10	A	-111.7	192
SHE-15	P-11	A	-114.3	173
SHE-15	P-12	A	-120.8	51
SHE-15	P-12a	A	-120.8	51
SHE-15	P-13	A	-123.6	50
SHE-15	P-14	B	-135.8	16
SHE-15	P-15	B	-145.2	12
SHE-15	P-16	B	-155.0	22
SHE-15	P-17	B	-171.0	11
SHE-15	P-18	B	-180.5	15
SHE-15	P-19	B	-193.6	24

(Continued)

Boring	Sample	Geologic Unit	Elevation (MLW)	Chloride (mg/L)
SHE-16	P-1	A	-41.8	12381
SHE-16	P-2	A	-46.6	5253
SHE-16	P-3	A	-51.6	2810
SHE-16	P-4	A	-56.6	1245
SHE-16	P-5	A	-61.6	630
SHE-16	P-6	A	-69.6	176
SHE-16	P-7	B	-79.6	67
SHE-16	P-8	B	-89.6	24
SHE-16	P-9	B	-97.6	16
SHE-16	P-10	O	-99.6	24
SHE-18	18SP1	P/R	7.0	847
SHE-18	18SP2	P/R	-3.0	3642
SHE-18	18SP3	P/R	-13.0	9065
SHE-18	18SP4	P/R	-23.0	4133
SHE-18	18SP5	P/R	-33.0	5678
SHE-18	18SP6	P/R	-43.0	4297
SHE-18	P-1	A	-49.5	6185
SHE-18	P-2	A	-56.5	3860
SHE-18	P-3	A	-67.5	1601
SHE-18	P-4	A	-72.5	945
SHE-18	P-5	B	-90.7	110
SHE-18	P-6	B	-91.8	42
SHE-18	P-7	B	-96.6	23
SHE-18	P-8	B	-107.0	15
SHE-19	19SP1	P/R	11.0	811
SHE-19	19SP2	P/R	1.0	2390
SHE-19	19SP3	P/R	-9.0	1995
SHE-19	19SP4	P/R	-19.0	6316
SHE-19	19SP5	P/R	-29.0	1145
SHE-19	19SP6	P/R	-39.0	1171
SHE-19	P-1	A	-62.3	554
SHE-19	P-2	A	-68.8	338
SHE-19	P-3	A	-77.5	292
SHE-19	P-4	A	-81.8	209
SHE-19	P-5	A	-91.9	143
SHE-19	P-6	A	-102.0	82
SHE-19	P-7	A	-112.0	58
SHE-19	P-8	A	-121.6	57
SHE-19	P-9	A	-132.1	47
SHE-19	P-10	A	-146.6	26
SHE-19	P-11	B	-163.0	35
SHE-19	P-12	B	-167.5	31
SHE-19	P-13	B	-181.6	19
SHE-19	P-14	B	-193.2	30

P/R = Pleistocene/Recent Unit
CF = Channel Fill
A = Miocene Unit A
B = Miocene Unit B
O = Oligocene

Boring SHE-15, in contrast to SHE-16, was located well upstream near the center of the cone of depression in downtown Savannah (Figure 5-1). The maximum chloride concentration (7,209 mg/L at -52.5 ft MLW) was observed approximately 18 feet below the bottom of the riverbed (-41.3 ft MLW), noting that the top 15 feet of the boring log indicated presence of soft, wet, fat silt, also called “fluff”. Consolidated material, poorly graded sand in this case, was first encountered at –49.3 ft MLW. The remainder of the porewater data from SHE-15 showed a general decrease in chloride concentration with increasing depth, with 24 mg/L recorded closest to the top of the Oligocene unit at –193.6 ft MLW. No values above 50 mg/L were observed below the Miocene A/B contact.

All supplemental land borings were drilled in close proximity to the dredging disposal areas in Jasper County, South Carolina. Borings SHE-9 and SHE-10 were drilled in 2001 and 2002, respectively; whereas, the remainder of all borings were drilled sequentially throughout late 2003 and 2004. SHE-9, located near the tide gate structure, showed the same trend seen in the marine boring profiles outside paleochannels: decreasing chloride concentration with depth. The chloride concentrations fluctuated from 901 to 5,421 mg/L throughout the surficial material and from 310 to 2,189 mg/L in the Miocene confining layer. The profile within the Miocene material generally decreased with depth, with the exception of values from –119 and –128 ft MLW. The punctuated increase in chloride concentration at depth coincides with the Miocene A/B contact and a spike in the resistivity log and the gamma log.

Located across the Savannah River from Elba Island, SHE-10, similar to SHE-9, was drilled earlier than the majority of the borings in 2002. All porewater samples within the Miocene confining unit were taken at the time of drilling with the exception of 10-PW-1 and 10-PW-2 (Table 5-1). These samples were taken in 2005 in an effort to fill in data gaps and complete the profile to the top of the limestone as shown in Figure 5-1. The results show fluctuating chloride values throughout the surficial material, which is most likely related to the elevated chloride content contained in dredge spoils that are piped into the nearby disposal areas over long periods of time. In the Miocene confining layer, the chloride porewater profile showed a steady decrease in concentration from the top to the bottom elevation. Values ranged from 820 mg/L at –40.5 ft MLW to 76 mg/L at –128.5 ft MLW.

It is important to note the chloride concentrations within the Miocene in SHE-9 and to a lesser degree in SHE-10 are significantly higher than samples taken at similar elevations in other boreholes. For example, the SHE-9 sample taken closest to the Miocene/Oligocene contact has a concentration of 310 mg/L, an order of magnitude greater than similar samples in all other borings located outside known paleochannels. Similarly, the results from boring SHE-10 were inflated by approximately one-half an order of magnitude. Figure 5-2 shows a scatter plot of all the porewater data collected as part of the supplemental studies. As depth increases, the majority of the samples are clustered tightly near the low end of the chloride concentration axis. The samples from SHE-9, however, show inflated values throughout the Miocene confining unit and do not fit the trend seen in the remainder of the samples.

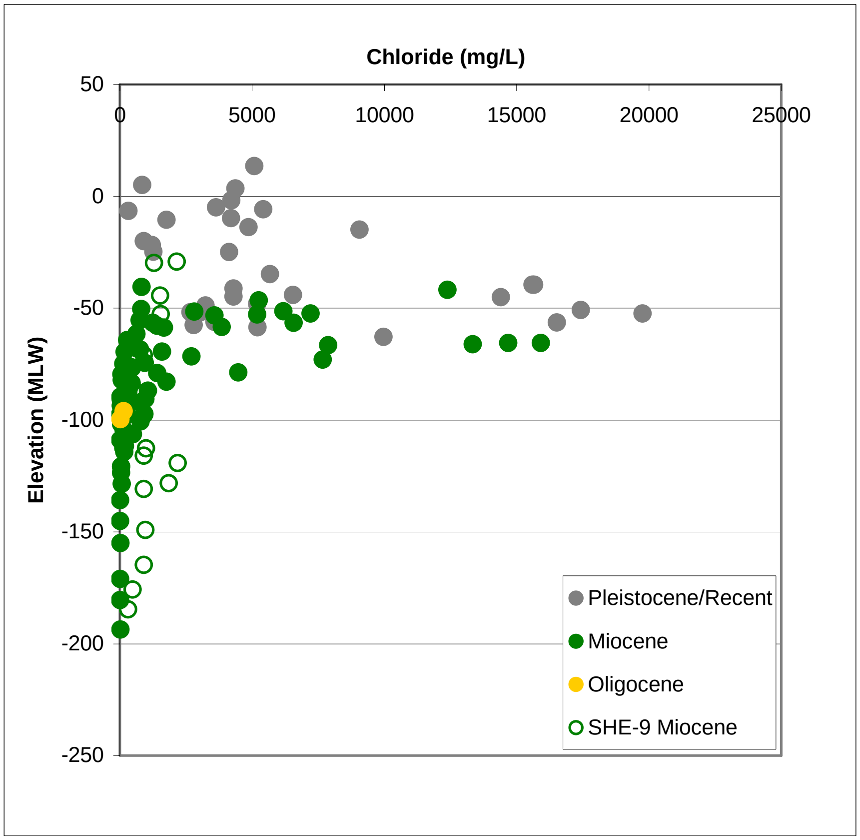


Figure 5-2. Scatter plot of porewater data collected from 2001 to 2004.

This difference is likely attributed to the sample collection technique. Borings SHE-9 and SHE-10 were drilled in 2001 and 2002, and the porewater core samples were not squeezed on site (with the exception of the two deepest samples at SHE-10, as described above). Instead, the core samples were logged, wrapped, sealed, and shipped to the USGS laboratory in Columbia, South Carolina. The cores were refrigerated for an extended period (over 30 days and 5 days, respectively) before being cut and squeezed for porewater. It is likely that evaporation of the porewater falsely inflated the chloride concentrations. Furthermore, it was noted that several samples were not analyzed because “not enough water” could be squeezed from them; whereas, when the cores from borings SHE-11 through SHE-19 were squeezed on site at the time of drilling, every sample yielded at least 2mLs of water.

Land borings SHE-18 and SHE-19 were drilled in 2004, and core porewater samples were collected, logged, and squeezed on site according to the method described in Section 4.2 of this report. The resulting aqueous samples were then stored in airtight scintillation vials and transported to the USGS lab in Columbia, South Carolina for analysis. The chloride profiles indicated the same trends seen throughout other land and marine borings located outside known paleochannels: fluctuation of chloride concentration in surficial sediments underlain by a steady decrease in chloride concentration throughout samples taken from Miocene material. Values ranged from 811 to 9,065 mg/L in the surficial sediments and from 15 to 6,185 mg/L in the Miocene confining layer. No increases in chloride concentration were observed within the Miocene confining layer in either boring SHE-18 or SHE-19.

Porewater chloride profiles constructed from borings outside known paleochannels exhibited similar trends. Data from land borings indicated that chloride values fluctuate throughout the surficial sediments, which is most likely a result of the origin of the materials (dredge spoils). All borings showed a steady decrease in chloride concentration from the top of the Miocene sediments to the bottom with the exception of SHE-9, which showed increased chloride concentration from –119 to –128 ft MLW. SHE-16, a marine boring directly overlain by seawater, showed the maximum chloride concentration seen within the Miocene confining layer (12,381 mg/L), which was observed five feet below the bottom of the navigation channel. The average chloride concentration found within 10 feet of the top of the limestone aquifer was 24 mg/L, excluding SHE-9 (anomalous).

5.2.2. Profiles Within Paleochannels

Four marine borings were drilled (SHE-11, SHE-13, SHE-14, SHE-17) within known paleochannels adjacent to the present day navigation channel (Figure 4-1). All of the borings were overlain by seawater and located within the area of concern, where the confining layer naturally thins and paleochannels have further downcut into the confining material.

Chloride profiles constructed from borings SHE-13 and SHE-17 showed a trend similar to that seen in borings outside paleochannels: a steady decrease in chloride concentration in the confining layer as elevation decreases (Figure 5-1). The maximum value observed at SHE-13 was 19,760 mg/L, which occurred eight feet below the bottom of the river channel in the paleochannel fill material, primarily composed of gray to green fine clayey sand. The paleochannel cut down to –67.1 ft MLW, marking the top of the Miocene confining layer. The first sample taken in the confining material contained a chloride concentration of 7,678 mg/L. The chloride concentrations decreased with elevation to the deepest sample, which was taken two feet above the top of the limestone and measured 153 mg/L chloride concentration.

The paleochannel material at boring SHE-17, located off the north end of Tybee Island, consisted primarily of gray fat silt and was present to a depth of –58.4 ft MLW. Four chloride samples were extracted from paleochannel material, and the maximum concentration was observed one foot below the bottom of the river channel (15,601 mg/L). The shallowest sample taken from Miocene material measured 1,663 mg/L (-58.9 ft MLW). The chloride concentration decreased with depth, and no values above 100 mg/L were observed below the Miocene A/B contact. The deepest sample was extracted less than one foot above the top of the aquifer, and the chloride concentration was 28 mg/L.

The boring log for SHE-11 showed the paleochannel/Miocene contact at a depth of –65.8 ft MLW, and three porewater samples were extracted from the paleochannel material overlying the confining layer. The porewater profile showed an overall decrease in chloride concentration with increasing depth, but the values did not sequentially decrease with depth as seen in other boreholes. Instead, two samples indicated higher chloride concentrations than the preceding samples taken at shallower depths. The chloride concentration found closest to the river bottom was

5,195 mg/L at –48.3 ft MLW. The profile then showed a decrease to 3,573 mg/L (-56.3 ft MLW); however, the next two samples, one of which was extracted from paleochannel material and one of which was extracted from Miocene material, both showed an increase in chloride concentration to 5,128 mg/L (-58.8 ft MLW) and 7,880 mg/L (-66.8 ft MLW), respectively. The sample containing 7,880 mg/L was taken one foot below the paleochannel/confining layer contact. The chloride concentration decreased throughout the remainder of the profile to 501 mg/L at –106.5 ft MLW, five feet above the top of the limestone.

The chloride profile from boring SHE-14 did not follow the trend of decreasing chloride with decreasing elevation. Similar to the profile from SHE-11, the overall concentration from the top to the bottom of the profile decreased; however, the profile showed a spike in concentration near the paleochannel/confining layer contact. A concentration of 14,405 mg/L was measured three feet below the river bottom. The chloride concentration then decreased to 5,199 mg/L (-53.1 ft MLW) before increasing again to a maximum value of 15,916 mg/L at –65.8 ft MLW. The concentration decreased throughout the remainder of the Miocene material to 69 mg/L, one foot above the top of the limestone.

5.2.3. Porewater Profile Summary

The porewater data derived from work completed as part of the supplemental studies indicate that, as expected, seawater is moving downward through the Miocene confining layer toward the Oligocene limestone, and, in some locations, low concentrations of chlorides appear to have migrated entirely through the confining layer and into the limestone. In addition, profiles constructed within known paleochannels differed significantly from those constructed outside paleochannels. In borings drilled outside paleochannels, the corresponding porewater profiles showed decreasing chloride concentration with decreasing elevation in samples throughout confining layer, and concentrations varied depending on the composition of overlying sediments and/or water. Profiles constructed within paleochannels showed punctuated increases in vertical migration of chloride through the paleochannel material, and the spikes in chloride concentration typically occurred at the paleochannel/confining layer contact. Otherwise, the profiles illustrated the same trend seen outside paleochannels: in the confining layer, chloride concentration decreased with decreasing elevation. The punctuated increase of concentration at the base of the paleochannel material and the decreased thickness of the underlying confining layer resulted in higher chloride concentrations near the top of the limestone, with the exception of boring SHE-17.

5.3. GEOPHYSICAL SURVEY

Subbottom profiling records revealed evidence of numerous continuous and semi-continuous subsurface acoustic reflectors that could be confidently mapped, but only those reflectors correlative with the base of identified paleochannel (*RCCF*) features and the underlying sediments were mapped. In almost all cases, recent sediment deposits in the navigation channel were minimal or absent and therefore not mapped. It is believed that natural erosional processes in the river and/or dredging of the current navigation channel have removed the recent deposits.

Several survey tracklines were run directly over boring locations in an effort to “ground truth” the subbottom data set and accurately tie relevant reflectors to specific horizons/stratigraphic units. Subbottom data were reviewed and compared closely with USACE boring logs. Under ideal conditions, the expected resolution of the subbottom profiling system utilized during this investigation is approximately three feet; this margin of error was taken into account when comparing core data with subbottom records. Table 5-2 presents comparisons between contacts documented in the boring logs and acoustic reflectors observed on the subbottom records. Based on these comparisons, an average acoustical velocity of 5,300 feet per second best represented the sediments in the river overlying the Upper Floridan aquifer.

5.3.1. Subbottom Reflectors

Subbottom reflectors could be traced for appreciable distances along survey lines throughout the majority of the area investigated, and subbottom reflectors were correlated with specific horizons/stratigraphic units identified in USACE borings.

Figure 5-3 provides a section of a subbottom "boomer" profile record that exemplifies some of the more prominent reflectors and illustrates an area where a paleochannel incised the Miocene unit and was later filled in with younger sediments.

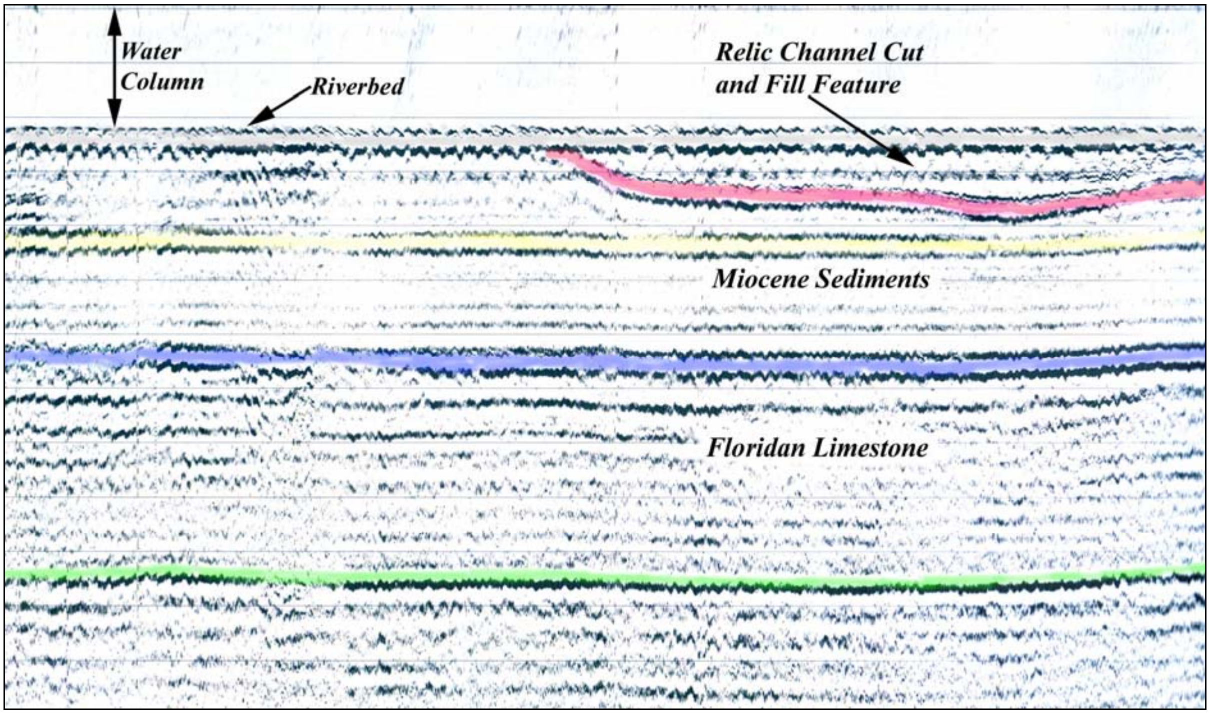


Figure 5-3. Typical subbottom profile with prominent reflectors.

Four prominent subbottom reflectors were identified and color-coded in Figure 5-3. The red and blue reflectors represented the base of the *RCCF* feature and the upper surface of the Upper Floridan aquifer (limestone), respectively. The yellow reflector was representative of the Miocene A/B contact, and the green reflector was believed to correlate with a deep (Eocene) contact within the Upper Floridan aquifer. In several sections of subbottom data, orange was used to differentiate reflectors correlative with the base of a younger *RCCF* feature identified adjacent to or traversing the primary or a red-coded *RCCF* feature (not illustrated in Figure 5-3).

Subbottom penetration was restricted or partially restricted along several segments of the tracklines investigated. In general, this restriction was intermittent and attributed to the presence of trapped gas bubbles within the near-surface sediments.

The gaseous manifestations, interpreted to be a by-product of the breakdown of organics originating in the sediments of paleo-estuarine environments, significantly reduced the level of acoustic signal propagation through the sediment. This reduction in signal propagation adversely affected the ability of the subbottom profiler to identify underlying subsurface acoustic reflectors. Other phenomena that might have been responsible for inhibiting the subbottom profiler from resolving reflectors at depth are changes in sediment type, compaction, lithification, and/or recent dredging/disturbance of the surficial sediments.

5.3.2. Paleochannels

Subbottom profiling data acquired during the current survey confirmed the existence of several *RCCF* features within the Savannah River entrance channel and revealed the presence of several additional *RCCF* features that had not yet been identified during previous investigations of the river. Eight of these features appear to be significant in size and underlie the navigation channel. The remaining *RCCF* features identified between river stations 30+000 and –30+000 were detected along only a single survey line and/or along survey lines located outside the navigation channel. The significant paleochannel features detected during the current investigation are referred to as *RCCF 1-8* and are centered on the following Savannah River stations as shown below in Table 5-2. Depths presented in the following table were based on the interpretation of subbottom profiling records. Considering the resolution of the boomer subbottom profiler and the assumptions made to convert raw subbottom data to depths referenced to the project vertical datum, the accuracy of the interpretation is approximately +/- 10% of the mapped depth of the correlative reflectors. Appendix A contains specific information regarding individual paleochannel features.

As summarized in Table 5-2, the *RCCF 4* feature appears to have incised more deeply into the Miocene confining layer than any of the other features detected in the entrance channel. This feature, detected between Savannah River stations 7+000 and 12+000, also takes up the largest spatial area.

Table 5-2. Paleochannel Locations and Formation Elevations

Feature Designation	Location (River Station)	Elevation of Paleochannel/Miocene Contact at Maximum Incision Depth (ft MLW)	Average Elevation of Miocene/Oligocene Contact (ft MLW)	Minimum Thickness of Miocene Confining Layer (ft)
RCCF 1	22+000	-80	-116	36
RCCF 2	20+000	-64	-116	55
RCCF 3	15+000	-74	-112	42
RCCF 4	9+000	-83	-108	26
RCCF 5	1+500	-70	-107	38
RCCF 6	-3+000	-70	-98	28
RCCF 7	-11+000	-67	-99	34
RCCF 8	-21+000	-73	-110	36

In general, subbottom data suggested that the *RCCF* features identified in the entrance channel are oblique to the present-day course of the river. These findings suggested that historic drainage patterns in the area differed significantly from present-day patterns and/or that survey trackline orientation may have played a role in the ability to detect the *RCCF* features. A large percent of survey tracklines (during the recent and past survey investigations of the river) were oriented parallel to the river's course. Survey tracklines oriented parallel to the river's course are more conducive to detecting features oriented perpendicular or oblique to the river's course. It is possible that *RCCF* features oriented parallel to the river's course and not within the boundaries of the limited cross-river survey tracklines investigated may not have been recognized or their presence may have been masked among other subsurface reflectors identified in the area. However, based on the combined trackline density of all historical surveys, the size and impact of any such feature would be minimal.

5.3.2.1. Correlation with Core Borings

Nine borings were used to verify the elevations of the subbottom reflectors. Of the nine borings, five coincided with survey tracklines, and the remaining four borings were located in the immediate vicinity of a survey trackline. Table 5-3 shows the elevations of contacts according to both the seismic data and USACE boring logs.

The elevations of contacts for both the top of the Miocene and the top of the Oligocene units reported by OSI correlated very well with USACE borings located either directly on a survey trackline or in the immediate vicinity of a trackline as illustrated in Figure 5-4. The elevation differences between the seismic picks and USACE boring logs for the top of the limestone varied from less than one foot at SHE-11 to 3.9 feet at SHE-17. In all cases, the two interpretations differed by less than 10 percent.

Table 5-3. Correlation of OSI Seismic Records with USACE Boring Logs

Location (River Station)	Boring	Seismic Feature	Contact	Seismic Reflector	USACE Boring Log Elevation (ft MLW)	Seismic Record Elevation (ft MLW)	Delta (ft)	Percent Difference
15+895	SHE-1	RCCF 3	Miocene Unit A	Red	-52.7	-51	1.7	3.3
15+895	SHE-1	RCCF 3	Oligocene	Blue	-116.0	-112	4.0	3.5
15+180	SHE-11	RCCF 3	Miocene Unit A	Red	-65.8	-64	1.8	2.8
15+180	SHE-11	RCCF 3	Oligocene	Blue	-111.8	-112	0.2	0.2
9+005	SHE-12	RCCF 4	Miocene Unit A	Red	-71.0	-73	2.0	2.8
8+626	SHE-13	RCCF 4	Miocene Unit A	Red	-67.1	-79	11.9	16.3
8+626	SHE-13	RCCF 4	Oligocene	Blue	-106.6	-109	2.4	2.2
-3+062	SH-327	RCCF 6	Miocene Unit A	Red	-69.2	-69	0.2	0.3
-3+324	SHE-14	RCCF 6	Miocene Unit B	Yellow	-67.9	-62	5.9	9.1
-3+324	SHE-14	RCCF 6	Oligocene	Blue	-94.2	-93	1.2	1.3
-10+675	SHE-17	RCCF 7	Miocene Unit A	Red	-58.4	-62	3.6	6.0
-10+675	SHE-17	RCCF 7	Oligocene	Blue	-98.1	-102	3.9	3.9
-21+922	SHE-4	RCCF 8	Oligocene	Blue	-112.5	-112	0.4	0.4
-21+383	SHE-6	RCCF 8	Miocene Unit A	Red	-70.1	-71	0.9	1.3

The seismic interpretation of the elevation of the top of the Miocene unit correlated well with existing boring log data. The elevations from the two data sets varied from 0.2 feet at SH-327 to 12 feet at boring SHE-13, and all interpretations, with the exception of SHE-13, differed by less than 10 percent. The elevation of the top of the Miocene unit is typically very distinct in both hand sample (boring log) and seismic reflection data. However, where the Miocene unit is overlain by paleochannel material, the distinction is typically less obvious. The paleochannel fill material consists mainly of fine-grained sands and silty sands that often contain reworked Miocene sediments. As a result, the paleochannel material is usually gray to grayish green in color and closely resembles Miocene material. In borings located within paleochannels, the contact was sometimes marked by a thin bed of well-graded sand, but otherwise was indistinguishable. In these cases, the seismic subbottom data proved invaluable to determining the elevation of the Paleochannel/Miocene contact.

5.4. THREE DIMENSIONAL GROUND-WATER MODEL

Ground-water model simulations were evaluated using several sets of results as described below. For each set of results, two different values of vertical hydraulic conductivity for the Miocene (low and mid-range values) were used to bracket the range of potential impacts. “Breakthrough” is said to occur when the simulated chloride concentrations in the top 50 to 60 feet of the Upper Floridan aquifer initially exceeds 250 mg/L. Appendix B contains the complete report and figures furnished by CDM.

It is important to note that all chloride concentrations reported below are based on salt water input exclusively from the river and navigation channel. The concentrations both directly beneath the river and at production wells represent chloride contributions only from within the river and navigation channel and *do not represent total concentrations*. The model did not simulate chloride sources from nearby salt marshes or the Atlantic Ocean so that results would clearly document the effects of dredging and not the overall influence of pumping in the Savannah area. Consequently, simulation results represent the chloride contribution explicitly due to dredging.

5.4.1. Vertical Profiles of Simulated Chloride Concentrations after 200 Years

Figure 5-5 illustrates an example of the simulated chloride concentration as a function of depth in the Miocene confining unit for both no dredging and dredging scenarios in the year 2200. Note that all borehole locations showed a higher chloride concentration at the top of the Miocene for the dredging scenario, which was based on the simulation results from the Tetra Tech surface water model. The increased chloride concentrations at the top of the Miocene generally resulted in higher concentrations at the bottom of the Miocene, and the expected impacts were most sensitive to the pumping gradient and vertical hydraulic conductivity of the Miocene confining unit. The charts labeled “A” show the results based on the calibrated (mid-range) hydraulic conductivity value for the Miocene unit, and charts labeled “B” illustrate the results with the lower hydraulic conductivity value.

The results also indicated that chloride concentrations decreased significantly from the bottom of the Miocene to the top of the Upper Floridan aquifer. This sharp decrease was attributed to the considerable horizontal flow of fresh water within the aquifer mixing with and diluting the relative very low volume of saltwater migrating downward through the confining unit. Overall, the difference in chloride concentration in the Upper Floridan aquifer between the results of the dredging scenario and no dredging scenario were small. Applying the lower hydraulic conductivity value further diminished the difference between the dredging and no dredging scenarios, and at upstream borehole locations where the Miocene confining unit is thicker, little or no breakthrough was observed (year 2200). The simulation results also indicated that total breakthrough did not occur throughout most of the study area, and the system would still be in transition after 200 years.

5.4.2. Time-History of Simulated Chloride Concentrations

5.4.2.1. Underlying Navigation Channel

Figure 5-6 illustrates an example of the simulated chloride concentrations beneath the dredged channel adjacent to each of the SHE borehole locations as a function of time. Both the no dredging and dredging scenarios are presented, and the concentrations shown are computed for the top 50 to 60 feet of the Upper Floridan aquifer. Similar to the previous figures, charts labeled “A” illustrate the results based on the mid-range hydraulic conductivity value for the Miocene unit and charts labeled “B” illustrate the results with the lower hydraulic conductivity value. The actual behavior of the system is expected to fall between the two sets of results.

All the figures represent maximum expected concentrations directly beneath or adjacent to the Savannah River. The concentrations shown are those only resulting from salt water moving through the Miocene confining unit directly below the river and navigation channel, and concentration impacts from all other areas overlain by other salt water sources (i.e. salt marshes, dredge spoils, etc.) are not simulated. Therefore, the predicted concentrations represent only the portion contributed from the navigation channel; they do not represent total expected concentrations.

In the upstream locations where the Miocene confining unit thickens (river stations 89+000 to 47+000), either chloride breakthrough into the Upper Floridan did not occur ("B" charts) or concentrations remained low, typically not exceeding 100 to 200 mg/L ("A" charts). Under all conditions in these locations, the dredging scenario showed no chloride concentration contributions in the Upper Floridan exceeding the EPA drinking water standard (250 mg/L).

In contrast, at locations further downstream (river stations 31+000 to –14+000), the mid-range hydraulic conductivity simulations ("A" charts) showed significantly higher chloride concentrations at the top of Upper Floridan aquifer directly below the river. After 200 years, chloride concentrations ranged from several hundred to greater than 1000 mg/L. For the low hydraulic conductivity simulation ("B" charts), concentrations were either significantly lower (SHE-18 and SHE-11), or simulated initial breakthrough in the Upper Floridan occurred much later than the year 2200.

In general, applying the dredging scenario did not appear to significantly change the timing of chloride breakthrough into the Upper Floridan aquifer. Figure 5-6 and CDM Figures 3-17 to 3-28 in Appendix B show very little separation between the dredging versus no dredging scenarios, which indicates the proposed dredging would not significantly increase the rate of vertical salt-water intrusion into the Upper Floridan aquifer. The maximum amount of time dredging decreased the initial breakthrough was 10 to 15 years at the location in the navigation channel adjacent to SHE-18. The remainder of the locations showed negligible time differences of initial breakthrough between the dredging and no dredging scenarios. The results indicate that, regardless of dredging, as the system approached steady state (total breakthrough), the increased chloride concentration in the downward flux from Savannah River eventually resulted in slightly increased concentrations in the Upper Floridan aquifer.

5.4.2.2. Nearby Production Wells

Simulated chloride concentration time-histories were also generated for nearby Upper Floridan production wells located along or near the river from downtown Savannah to Tybee Island (Figure 5-7). An example of the simulated chloride concentrations is shown in Figure 5-8 for both the no dredging and the dredging scenarios utilizing the mid-range and low hydraulic conductivity values. The mid-range hydraulic conductivity simulations indicated that downward migration of chloride from the river would contribute 10 to 50 mg/L to total chloride concentrations in Savannah area production wells by the year 2200, and the difference between the dredging and no dredging scenarios ranged from negligible to less than 10 mg/L for each well location. These concentrations represent only the contribution from the river and navigation channel and do not represent total concentration in the wells. As such, the added impact from dredging (negligible to less than 10 mg/L) represents a small fraction of the much higher total concentration expected in a given production well. Simulations using the lower value of hydraulic conductivity showed that downward migration of chloride from the river would not contribute to any increase in total chloride concentration at most of the wells by the year 2200.

5.4.3. Simulated Chloride Concentration Distributions in the Upper Floridan Aquifer

Figure 5-9 shows plan view simulated chloride concentrations in the Upper Floridan aquifer for the years 2000, 2050, and 2200 for both dredging and no dredging scenarios. The distributions indicated that chloride plumes tend to move parallel to the river due to the ground-water flow direction induced by heavy pumping near downtown Savannah. Thus, the concentration results discussed above are relevant only for chloride concentrations directly below the river. Simulated impacts north or south of the river dissipated over a relatively short distance.

Simulated chloride concentrations in the Upper Floridan aquifer were significantly higher underlying the downstream reaches of the river; however, simulations using the mid-range value of hydraulic conductivity showed negligible difference between the dredging and no dredging scenarios (Figure 5-9).

5.4.4. Ground-Water Model Analysis and Conclusions

Increased ground-water pumping in Savannah has depressed ground-water heads in the Upper Floridan aquifer and induced downward flow of water from the surficial aquifer and Savannah River through the Miocene confining unit to the Upper Floridan aquifer. The resulting head gradients are the dominant force contributing to downward movement of salt water through the Miocene confining unit.

The expected increase in downward volume of flow of saline water from the area underlying the Savannah River due to dredging is small. The model results indicated that the area affected by dredging accounted for a total downward flow between 50 to 250 gallons per minute depending on the hydraulic conductivity assigned to the Miocene confining unit. Dredging the navigation channel increased the total downward flow between 2 to 7 gallons per minute, or 3 to 4 percent. The contribution is negligible when compared to ground-water production in the Savannah area from the Upper Floridan aquifer, which is on the order of 80 million gallons per day (55,555 gallons per minute).

The 200-year projection simulations were most sensitive to the aquifer thickness and vertical hydraulic conductivity of the Miocene confining unit, and the results showed salt water from the river potentially penetrating the Miocene and reaching the Upper Floridan aquifer. After 200 years, the upstream chloride concentrations in the Upper Floridan aquifer beneath the river were simulated to be approximately 0 mg/L for low-value hydraulic conductivity simulations and up to 100 mg/L for the mid-range hydraulic conductivity simulations. Downstream, where the Miocene is relatively thin, chloride concentrations directly beneath the river approached 500 mg/L after 200 years for the low-value hydraulic conductivity simulations. For the mid-range hydraulic conductivity simulations, total breakthrough occurred after approximately

100 years, and the maximum chloride concentration in the Upper Floridan aquifer occurred in the downstream portion of the project area (1,400 mg/L).

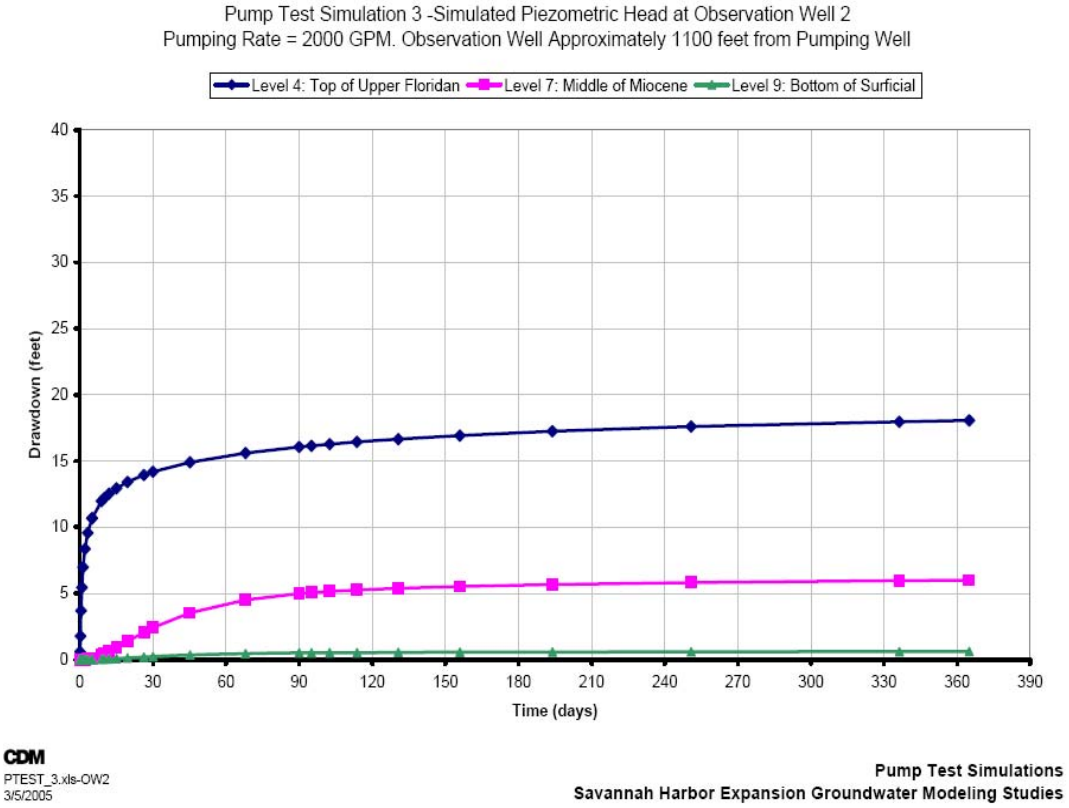
The increased river source concentrations assigned at the bottom of the river, values for which were obtained from the Tetra Tech surface water model, appeared to increase simulated chloride concentrations in the top of the Upper Floridan aquifer. In the upstream reaches of the river, where the surface water model predicted minimum increases in chloride concentrations, the differences in chloride concentrations in the top of the Upper Floridan aquifer between the dredging and no dredging scenarios were minor. Downstream, where higher surface water chloride concentrations were predicted to occur, the corresponding differences in concentrations in the Upper Floridan aquifer directly below the river ranged from 10 to 200 mg/L and were typically observed 50 or more years into the future.

5.5. SIMULATED PUMPING TEST

5.5.1. Effects of Pumping Test on Hydraulic Heads

All simulation results are based on applying the mid-range value of vertical hydraulic conductivity to the Miocene confining layer (1.5×10^{-4} ft/day). At the lowest pumping rate simulated (500 gpm), the simulated drawdown in the surficial aquifer at the pumping well location was less than 0.5 feet after 1 year of pumping. At the observation point located 1,100 feet from the pumping well, the simulated response was less than 0.25 feet in the surficial aquifer and less than 2 feet in the Miocene confining unit. At the observation point located 2,400 feet away negligible response in the surficial aquifer or Miocene confining unit was noted.

At the highest pumping rate simulated (2,000 gpm), the simulated drawdown at the pumping well location was approximately 1 foot in the surficial aquifer and approximately 12 feet in the Miocene confining unit. At the observation point located 1,100 feet from the pumping well, the simulated drawdowns in the surficial aquifer and Miocene confining unit were approximately 0.6 and 6 feet, respectively. Response curves for the simulated pumping rate of 2,000 gpm at the observation point located 1,100 feet away from the pumping well are shown in Figure 5-10. Additional response curves for each scenario are included in Appendix B.


Pump Test Simulation 3 -Simulated Piezometric Head at Observation Well 2
Pumping Rate = 2000 GPM. Observation Well Approximately 1100 feet from Pumping Well

CDM
PTEST_3.xls-OW2
3/5/2005

Pump Test Simulations
Savannah Harbor Expansion Groundwater Modeling Studies

Figure 5-10. Response curves in the Upper Floridan aquifer, Miocene confining unit, and surficial aquifer for a simulated pumping rate of 2000 gallons per minute.

The simulation results are somewhat corroborated by results from a pump test conducted on wells at the Tybee Island Test Well Cluster by Clemson University in 1997. Although a misinterpretation of stratigraphy nullified the intended purpose, the results clearly indicated significant hydraulic separation between the Miocene confining layer and the Upper Floridan aquifer. The pump test was run using a pumping well completed in the uppermost 18 feet of the aquifer and an observation well 20 feet away that was completed in the Miocene confining layer 25 feet above the top of the aquifer. The pumping well was pumped for 72 hours at an average pumping rate of approximately 100 gpm, and the observation well showed no response to pumping from the aquifer.

5.5.2. Implications

Results from the simulated pump tests indicate that response times in the surficial aquifer and Miocene confining unit would be relatively slow with heads gradually decreasing over a period of 30 to 60 days. The slow response times and expected drawdowns of only a few inches would make it difficult to perform a meaningful pump test. The test would have to be at least two months in duration and pump at least 1,000 gpm to develop sufficient data with which to assess the vertical hydraulic conductivity of the Miocene confining unit. In addition, numerous sources of interference including tidal variations, other local pumping wells, and regional pumping would mask the observation data, and further complicate interpreting any results. The small drawdowns at high pumping rates as seen in the simulation results, combined with the amount of background interference in the area of concern, indicated that this task was not practical.

5.6. MISCELLANEOUS

5.6.1. Gamma Logs

The gamma logs obtained from core borings as part of the supplemental studies were almost without exception uniquely characteristic of their associated strata (Figure 5-11). Specifically, the shapes of the gamma signatures for the two marker beds, Miocene A and B, differ significantly. The upper marker associated with the bottom of unit A (i.e. contact between unit A and unit B) was typically represented by a thick, multi-lobed, somewhat blunt peak. The lower marker associated with the bottom of unit B (i.e. contact between unit B and Oligocene unit) was characteristically a single, thin, very sharp peak. Typically, the peaks were located slightly above their corresponding contacts (SHE-19); however, in some borings, one or both gamma peaks bracketed the contact (SHE-18). The gamma log from boring SHE-13 represented the only exception. No upper marker was observed, which may indicate that the contact has been eroded by the overlying paleochannel. In addition, the peak representing the lower marker was significantly smaller in magnitude than peaks observed in adjacent boreholes. With the exception of SHE-13, the gamma markers were particularly useful in determining the elevation of the contact between unit A and B when the associated phosphatic carbonate zone was not readily recognizable or missing in core samples.

5.6.2. Electrical Conductivity Logs

Soil conductivity varied according to soil type and salinity of the porewater fluid. Conductivity logs recorded at borings SHE-9, SHE-10, SHE-18, and SHE-19 showed higher conductivities in finer grained soils and lower conductivities in sandier soils. The resulting conductivity logs were used to verify depths of soils recorded on boring logs. The conductivity logs showed large scale curve shifts in addition to the peaks and valleys associated with soil type. These shifts indicate an overall increase or decrease in the salinity of the porewater fluid and correlated very well with chloride values derived from porewater sampling (Figure 5-12).

5.6.3. Ground-Water Gradient Data

Water levels recorded in well clusters on the north end of Tybee Island and at Fort Pulaski indicated that pumping the Upper Floridan aquifer has not only reduced heads in the aquifer, but also that the head differences have propagated through the overlying confining layer.

Data collected from additional wells along the Savannah Harbor navigation channel give a more complete picture of the vertical hydraulic gradient changes that occur from the surficial aquifer to the Upper Floridan aquifer over the distance from Tybee Island to downtown Savannah. Table 5-4 shows the hydraulic heads measured in wells set at various depths in the surficial aquifer, Miocene confining layer, and Upper Floridan aquifer. At several locations, the results indicated that the vertical hydraulic gradient across the entire confining layer is less than that of some intervals within the confining layer. These intervals within the confining layer, some of which exhibit gradients 2 to 3 times the average gradient of the entire confining layer, suggest that somewhat lower permeability zones exist within the confining layer.

Table 5-4. Measured Hydraulic Heads in Savannah Area Wells

Well	Date	Harbor Area	Approx River Station	Hydrogeologic Unit	Measuring Point Elevation	Head Elevation	Hydraulic Gradient	
							Interval	Overall
SHE-MW-1	3/5/2005	Tybee	-10+000	S	2.0	**2.32**		
(39Q029)							-0.04	
Tybee-3	3/5/2005		-10+000	M	-61.0	**0.11**		-0.22
(39Q026)								
							-0.47	
Tybee-2	3/5/2005		-10+000	F	-108.0	**-21.24**		
(39Q025)								
SHE-MW-3	3/5/2005	Ft. Pulaski	4+000	S	-9.0	**-0.01**		
(38Q208)							-0.03	
SHE-MW-4	3/5/2005		4+000	M	-85.0	**-2.07**		-0.25
(38Q209)							-0.75	
USNPS	3/5/2005		4+000	F	-103.0	**-23.13**		
(38Q002)								
SHE-10A	4/30/2005	Elba Island	48+000	S	-24.0	**4.10**		
							-0.04	
SHE-10B	4/30/2005		48+000	U	-56.5	**2.80**		
							-0.22	
SHE-10C	4/30/2005		48+000	M	-96.5	**-6.10**		-0.26
							-0.24	
SHE-10D	4/30/2005		48+000	L	-151.5	**-19.50**		
							-0.14	
SHE-10	4/30/2005		48+000	F	-165.8	**-33.10**		
SHE-9A	4/30/2005	Tide Gate	75+000	S	2.7	**2.70**		
							-0.09	
SHE-9B	4/30/2005		75+000	U	-87.7	**-5.60**		
							-0.36	-0.33
SHE-9C	4/30/2005		75+000	L	-152.4	**-28.80**		
							-0.30	
SHE-9D	4/30/2005		75+000	F	-191.8	**-60.90**		
GGS-A	1/5/2005	Hutchinson	90+000	S	-0.65	**-0.65**		
(37Q185)								-0.40
GGS	1/5/2005		90+000	F	-200.0	**-80.55**		
(37Q185)								

S = Surficial Aquifer
U = Upper Confining
M = Middle Confining
L = Lower Confining
F = Upper Floridan Aquifer
* Head derived from elevation of river according to tide table

Note: Confining layer head elevations at SHE-9 and SHE-10 derived from vibrating wire pressure transducers.

5.6.4. Soils Laboratory Data

Eighty-nine undisturbed core samples from ten borings were analyzed to determine grain size distribution, Atterberg Limits, porosity, and vertical hydraulic conductivity. The laboratory results for hydraulic conductivity, grain size distribution, and porosity are summarized in Table 5-5, and the complete laboratory report, including plasticity data, is attached as Appendix E.

5.6.4.1. Grain Size Distribution and Porosity

Samples were collected at regular intervals, usually five feet, throughout each of the ten borings. Samples were primarily collected from the Miocene confining material, and, when core recovery allowed, samples were collected from paleochannel in-fill material as well.

As illustrated in Table 5-5, the laboratory results for both paleochannel and Miocene sediments indicated high total fines content. The average fines content for paleochannel fill sediments was reported at 69.0 percent, and the average fines content for the Miocene sediments was 52.5 percent. More than 80% of the 67 samples tested contained high liquid limit (LL) plastic fines, and more than 80% of the samples had resultant saturations above 95%. Some of the samples that were not tested for liquid limit determination are believed to contain similar high liquid limit plastic fines characteristics. The laboratory data reported high porosities for both the paleochannel material and the Miocene units, which is typical of geologic materials containing high clay content. The average porosity of the relict channel fill samples was reported as 0.626, and the average porosity of the Miocene samples was reported as 0.593.

5.6.4.2. Permeability and Hydraulic Conductivity

Geologic materials with over 15 percent clay and nearly 30 percent total fines (material passing a number 200 sieve) typically contain correspondingly low permeabilities and hydraulic conductivities (Freeze and Cherry, 1979), as confirmed by the laboratory analyses performed on samples as part of this study (Table 5-5). The hydraulic conductivity for Miocene sediments ranged from 1.12 x 10^{-4} cm/sec in boring SHE-14 to 1.18 x 10^{-8} cm/sec in boring SHE-19 (3.17 x 10^{-1} to 3.34 x 10^{-5} ft/day, respectively). The average vertical hydraulic conductivity for all Miocene samples (units A and B) tested was 2.13 x 10^{-6} cm/sec (6.04 x 10^{-3} ft/day), which was very similar to results reported in the 1998 *Ground-Water Impacts* report (USACE, 1998). The median for all Miocene samples tested was 1.41x10^{-7} cm/sec (3.98x10^{-4} ft/day). As for the relict channel fill samples, the hydraulic conductivity ranged from 2.78 x 10^{-6} cm/sec in boring SHE-13 to 4.33 x 10^{-8} cm/sec in boring SHE-11 (7.88 x 10^{-3} to 1.23 x 10^{-4} ft/day, respectively). The average vertical hydraulic conductivity of the relict channel samples was reported at 3.72 x 10^{-7} cm/sec (1.05 x 10^{-3} ft/day), and the median value was 6.38 x 10^{-8} cm/sec (1.81 x 10^{-4} ft/day).

Table 5-5. Summary of Soils Laboratory Results from 2001 to 2004

					Grain Size Distribution					
Boring	Sample	Elevation	Geologic Unit	USCS Class	% Gravel	% Sand	% Fines	Porosity	Hydraulic Conductivity $k_{20^\circ C}$ (cm/sec)	Hydraulic Conductivity $k_{20^\circ C}$ (ft/day)
SHE-11	K-1	-30.3	CF	CH	0.0	12.3	87.7	0.692	4.79E-08	1.36E-04
SHE-11	K-2	-57.8	CF	CH	0.0	10.8	89.2	0.691	4.33E-08	1.23E-04
SHE-11	K-3	-60.3	CF	CH*	0.0	4.8	95.2	0.728	5.40E-08	1.53E-04
SHE-13	K-1	-51.6	CF	SC	0.0	81.2	18.8	0.412	2.78E-06	7.88E-03
SHE-13	K-2	-57.4	CF	CH*	0.0	47.4	52.6	0.633	1.46E-07	4.14E-04
SHE-14	K-1	-44.9	CF	CH*	0.0	3.2	96.8	0.662	7.90E-08	2.24E-04
SHE-17	K-1	-40.0	CF	CL	0.0	49.9	50.1	0.582	6.99E-08	1.98E-04
SHE-17	K-2	-44.7	CF	CH*	0.0	40.4	59.6	0.577	6.38E-08	1.81E-04
SHE-17	K-3	-52.3	CF	CH	0.0	28.6	71.4	0.655	6.18E-08	1.75E-04
Mean Values for Channel Fill Material:					**0.0**	**31.0**	**69.0**	**0.626**	**3.72E-07**	**1.05E-03**
SHE-9	K-1	-50.8	A	MH	0.3	13.0	86.7	0.683	1.80E-06	5.10E-03
SHE-9	K-2	-61.5	A	MH	0.0	35.3	64.7	0.711	3.10E-07	8.79E-04
SHE-9	K-3	-80.7	A	SM	0.0	65.2	34.8	0.587	1.50E-06	4.25E-03
SHE-9	K-4	-101.1	A	MH	13.6	22.6	63.8	0.660	4.80E-08	1.36E-04
SHE-9	K-5	-112.2	A	CH	1.3	30.0	68.7	0.664	9.40E-08	2.66E-04
SHE-10	HC-1	-55.1	A	SM	0.1	72.5	27.4	0.629	1.70E-07	4.82E-04
SHE-10	HC-2	-62.4	A	MH	0.0	23.9	76.1	0.747	1.10E-07	3.12E-04
SHE-10	HC-3	-69.5	A	MH	0.8	49.0	50.2	0.709	1.10E-06	3.12E-03
SHE-10	HC-4	-83.9	A	MH	0.0	18.3	81.7	0.688	5.50E-07	1.56E-03
SHE-10	HC-5	-92.5	A	MH	0.0	14.8	85.2	0.718	2.90E-07	8.22E-04
SHE-10	HC-6	-98.6	A	MH	0.0	33.8	66.2	0.709	1.70E-07	4.82E-04
SHE-10	HC-7	-104.5	A	SC	0.0	62.5	37.5	0.581	4.50E-07	1.28E-03

					Grain Size Distribution				Hydraulic Conductivity	Hydraulic Conductivity
Boring	Sample	Elevation	Geologic Unit	USCS Class	% Gravel	% Sand	% Fines	Porosity	$k_{20^\circ C}$ (cm/sec)	$k_{20^\circ C}$ (ft/day)
SHE-10	HC-8	-112.0	A	SM	0.0	53.3	46.7	0.774	7.10E-07	2.01E-03
SHE-10	HC-9	-119.5	A	SM	0.0	84.7	15.3	0.504	2.40E-07	6.80E-04
SHE-10	HC-10	-128.5	A	SM	0.0	65.8	34.2	0.456	1.50E-06	4.25E-03
SHE-10	HC-11	-137.5	A	SM	0.0	72.5	27.5	0.464	3.20E-05	9.07E-02
SHE-10	HC-12	-144.4	A	SM	0.0	81.1	18.9	0.458	2.20E-07	6.24E-04
SHE-11	K-4	-70.1	A	SC-H	0.0	80.7	19.3	0.507	2.53E-07	7.17E-04
SHE-11	K-5	-79.6	A	MH	0.0	40.7	59.3	0.507	6.44E-08	1.83E-04
SHE-13	K-5	-74.3	A	CH*	0.0	3.8	96.2	0.662	1.69E-07	4.79E-04
SHE-13	K-6	-79.9	A	CH*	0.0	1.7	98.3	0.688	9.92E-08	2.81E-04
SHE-13	K-7	-83.9	A	MH	0.0	22.8	77.2	0.633	7.32E-08	2.07E-04
SHE-13	K-8	-88.1	A	MH*	0.0	34.3	65.7	0.629	8.81E-08	2.50E-04
SHE-14	K-2	-51.9	A	CH*	0.0	10.8	89.2	0.646	7.39E-08	2.09E-04
SHE-14	K-3	-56.3	A	CH*	0.0	2.1	97.9	0.650	1.58E-07	4.48E-04
SHE-14	K-4	-65.3	A	SP-SM	0.0	94.1	5.9	0.404	1.12E-04	3.17E-01
SHE-15	K-1	-55.0	A	MH	0.0	19.2	80.8	0.712	1.48E-07	4.20E-04
SHE-15	K-2	-63.3	A	MH*	0.0	27.8	72.2	0.636	4.74E-08	1.34E-04
SHE-15	K-3	-72.3	A	CH*	0.0	27.4	72.6	0.671	1.46E-07	4.14E-04
SHE-15	K-4	-83.0	A	SC*	0.0	68.2	31.8	0.572	3.34E-07	9.47E-04
SHE-15	K-5	-95.3	A	OH	0.0	5.3	94.7	0.647	2.44E-07	6.92E-04
SHE-15	K-6	-113.1	A	OH*	0.0	0.4	99.6	0.744	1.84E-08	5.22E-05
SHE-16	K-1	-42.8	A	SC-H	0.0	68	32.0	0.529	6.28E-07	1.78E-03
SHE-16	K-2	-53.8	A	SC*	0.0	83.6	16.4	0.469	7.09E-07	2.01E-03
SHE-17	K-4	-59.2	A	SC-H	0.0	78.6	21.4	0.478	1.04E-06	2.95E-03
SHE-17	K-5	-68.8	A	SP-SM	0.0	88.2	11.8	0.499	2.29E-07	6.49E-04
SHE-18	K-1	-64.5	A	OH	0.0	2.1	97.9	0.817	2.12E-07	6.01E-04
SHE-18	K-2	-70.2	A	SM*	0.0	79.8	20.2	0.494	9.95E-08	2.82E-04
SHE-19	K-1	86.2	A	CH	0.0	48.6	51.4	0.498	3.27E-06	9.27E-03
SHE-19	K-2	96.7	A	MH	0.0	4.4	95.6	0.599	2.61E-06	7.40E-03
SHE-19	K-3	118.5	A	SC-H	0.0	61.6	38.4	0.585	1.41E-07	4.00E-04
SHE-19	K-4	131.8	A	MH*	0.0	48.2	51.8	0.592	6.28E-08	1.78E-04
SHE-19	K-5	142	A	MH	0.0	12.7	87.3	0.638	3.10E-08	8.79E-05
SHE-19	K-6	152.5	A	MH*	0.0	8.5	91.5	0.671	2.58E-08	7.31E-05
SHE-19	K-7	162.3	A	OH	0.0	0.3	99.7	0.761	1.18E-08	3.34E-05
SHE-19	K-8	167.1	A	OH*	0.0	29.7	70.3	0.796	3.15E-08	8.93E-05
Mean Values for Miocene Unit A:					**0.4**	**40.3**	**59.4**	**0.619**	**3.57E-06**	**1.01E-02**
SHE-9	K-6	-129.4	B	SC	0.0	70.0	30.0	0.465	2.80E-07	7.94E-04
SHE-9	K-7	-148.4	B	SM	0.0	73.2	26.8	0.520	1.30E-07	3.69E-04
SHE-9	K-8	-164.2	B	SM	0.0	71.9	28.1	0.540	1.70E-07	4.82E-04
SHE-9	K-9	-175.3	B	SM	0.0	65.7	34.3	0.564	1.40E-07	3.97E-04
SHE-9	K-10	-188.5	B	SM	0.1	68.1	31.8	0.540	2.80E-07	7.94E-04
SHE-10	HC-13	-150.9	B	SM	0.0	77.3	22.7	0.469	2.50E-07	7.09E-04
SHE-10	HC-14	-160.9	B	SM	0.0	66.7	33.2	0.488	1.50E-06	4.25E-03
SHE-11	K-6	-91.1	B	CH*	0.0	0.0	100.0	0.489	6.12E-08	1.73E-04
SHE-11	K-7	-98.8	B	SM*	0.0	79.4	20.6	0.543	9.48E-08	2.69E-04

Boring	Sample	Elevation	Geologic Unit	USCS Class	Grain Size Distribution			Porosity	Hydraulic Conductivity $k_{20°C}$ (cm/sec)	Hydraulic Conductivity $k_{20°C}$ (ft/day)
					% Gravel	% Sand	% Fines			
SHE-11	K-8	-101.1	B	SM-H	0.4	86.0	13.6	0.508	2.37E-07	6.72E-04
SHE-11	K-9	-106.8	B	SM-H	0.0	51.9	48.1	0.663	3.92E-08	1.11E-04
SHE-13	K-9	-93.1	B	MH	0.0	19.2	80.8	0.686	5.44E-08	1.54E-04
SHE-13	K-10	-98.8	B	MH*	0.0	11.0	89.0	0.716	4.88E-08	1.38E-04
SHE-13	K-11	-105.6	B	SM-H	0.0	61.5	38.5	0.612	1.32E-07	3.74E-04
SHE-14	K-5	-71.3	B	MH*	0.0	22.9	77.1	0.582	3.40E-08	9.64E-05
SHE-14	K-6	-76.3	B	SM-H	0.0	51.1	48.9	0.590	1.05E-07	2.98E-04
SHE-14	K-7	-81.3	B	MH	0.0	40.0	60.0	0.634	5.69E-07	1.61E-03
SHE-14	K-8	-86.8	B	SM*	0.0	56.9	43.1	0.593	5.77E-08	1.64E-04
SHE-14	K-9	-92.5	B	SM*	0.0	68.1	31.9	0.616	1.13E-07	3.20E-04
SHE-15	K-7	-135.3	B	SC-H	0.0	68.4	31.6	0.511	6.55E-08	1.86E-04
SHE-15	K-8	-144.7	B	SM-H	0.0	81.9	18.1	0.433	5.74E-07	1.63E-03
SHE-15	K-9	-155.3	B	MH*	0.0	45.3	54.7	0.607	6.64E-08	1.88E-04
SHE-15	K-10	-171.0	B	SM-H	0.0	59.5	40.5	0.586	4.96E-08	1.41E-04
SHE-15	K-11	-181.3	B	SM*	0.0	50.1	49.9	0.611	6.33E-08	1.79E-04
SHE-15	K-12	-193.9	B	SM-H	0.0	66.5	33.5	0.567	4.95E-07	1.40E-03
SHE-16	K-3	-70.1	B	CH*	0.0	43.2	56.8	0.546	2.07E-08	5.87E-05
SHE-16	K-4	-80.1	B	SC-H	0.0	56.0	44.0	0.550	7.26E-08	2.06E-04
SHE-16	K-5	-91.8	B	SM-H	0.0	53.5	46.5	0.579	2.98E-08	8.45E-05
SHE-17	K-6	-86.7	B	MH	0.0	45.4	54.6	0.521	4.87E-08	1.38E-04
SHE-18	K-3	-93.9	B	SM-H	0.0	65.5	34.5	0.603	1.62E-07	4.59E-04
SHE-18	K-4	-106.3	B	SM*	0.0	75.4	24.6	0.541	5.09E-08	1.44E-04
SHE-19	K-9	188.8	B	SM-H	0.0	68.9	31.1	0.430	9.60E-08	2.72E-04
SHE-19	K-10	202.1	B	SM-H	0.0	57.4	42.6	0.565	1.58E-08	4.48E-05
SHE-19	K-11	213.7	B	SM-H	0.0	54.5	45.5	0.478	5.39E-08	1.53E-04
Mean Values for Miocene Unit B:					**0.0**	**56.8**	**43.1**	**0.557**	**1.81E-07**	**5.14E-04**
Mean Values for Miocene Confining Unit:					**0.2**	**47.3**	**52.5**	**0.593**	**2.13E-06**	**6.04E-03**

CF = Channel Fill
A = Miocene Unit A
B = Miocene Unit B
* = Soils visually classified

In all cases, an arithmetic mean was used to compute average values because arithmetic means tend to emphasize the higher values of a given data set, which when applied in a model or calculations, represents a conservative assumption.

The average value of hydraulic conductivity measured from paleochannel material was less than that observed in the Miocene sediments, and the minimum value observed in paleochannel material was within the same order of magnitude as the minimum values observed in samples collected from the Miocene units. Furthermore, the maximum value observed in relict channel samples was two orders of magnitude less than that observed in Miocene samples (Table 5-5). Therefore, the vertical hydraulic conductivity results of the paleochannel material indicate that, although the paleochannel sediments are variable in lithology, zones within them contain significant amounts low-permeability material. It should be noted that samples collected from paleochannel material are biased to the materials that contain higher percentage of clays, as these are the more cohesive samples that remain intact during coring and can be considered truly “undisturbed.” Every attempt was made to sample a representative horizon, and boring logs indicate that while the channel fill sediments did include some sandy soils, they were predominantly fine-grained. The sandier sediments observed in the paleochannel sediments undoubtedly have higher hydraulic conductivities, but they are difficult or impossible to sample without disturbing their structural integrity. Regardless, in the vertical direction, the zones with lower hydraulic conductivity dominate downward flow.

Historical values of hydraulic conductivity of the Miocene units did not vary significantly from values indicated by samples collected as part of this study. Vertical hydraulic conductivities for Chatham County from one core sample in Miocene A and 18 samples in Miocene B discussed in Clarke and others (1990), including work done by Furlow (1969), indicated a value of 4.0×10^{-4} ft/day for Miocene A and a range of 1.3×10^{-2} to 5.3×10^{-5} ft/day for Miocene B.

An alternative statistical method was employed to further investigate the vertical hydraulic conductivity of the Miocene confining unit in the study area. Davis (1969) and Domenico and Schwartz (1998) both report that a log-transformed data analysis is often a more practical approach to viewing hydraulic conductivity data sets and may approximate the log-normal distribution. Figure 5-13 shows the frequency distribution of the log-transformed hydraulic conductivity samples from the Miocene confining unit. The distribution of the log-transformed values is approximately normally distributed with a standard deviation of 0.67 and a median of –3.4. The calibrated hydraulic conductivity from the ground-water model corresponds to a logarithmic value of –3.82, which falls well within the standard deviation of the frequency distribution.

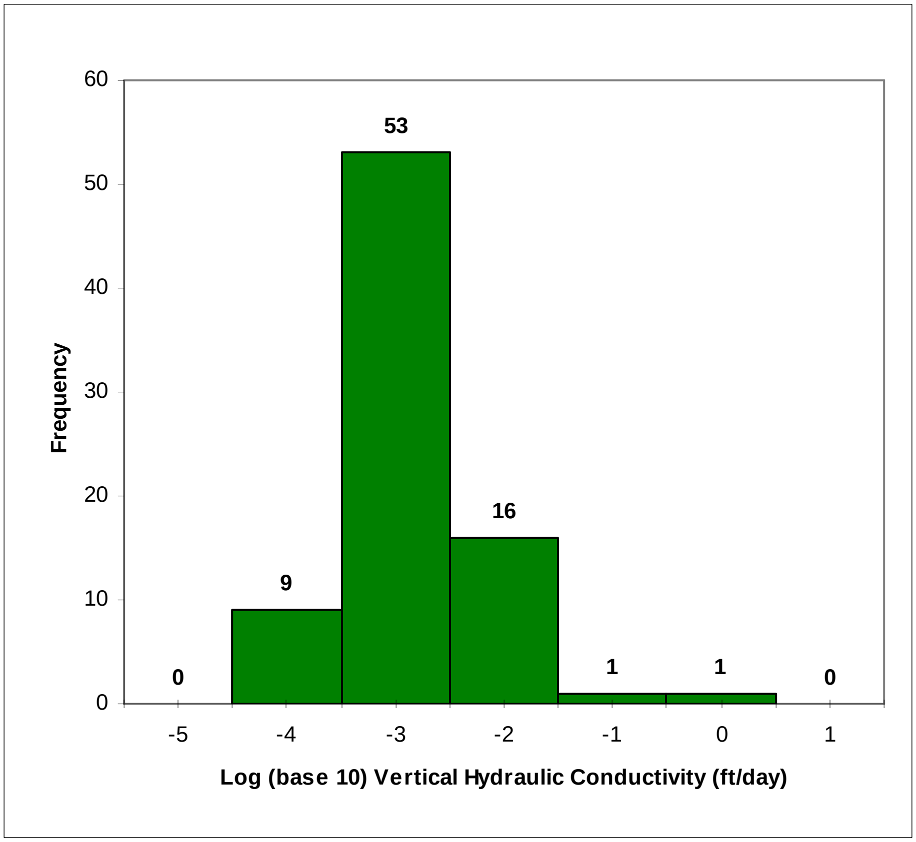


Figure 5-12. Frequency distribution of logarithmic (base 10) vertical hydraulic conductivity of the Miocene confining unit in the Savannah River area.

5.6.4.3. *Triaxial Compression*

In order to evaluate the possibility of open fractures existing in the confining layer underlying the navigation channel, the in-situ conditions under which the material is found must be considered. Two samples were submitted for triaxial compression testing to identify the strength and deformation-specific properties of such material given its inherent physical characteristics and in-situ conditions.

The samples submitted for triaxial testing had similar physical properties (grain-size, plasticity, void ratio, density, and saturation) as the core samples submitted for general grain-size and permeability analyses (Appendix E). The soil classifications of the triaxial samples ranged from a fat clay (k6/282) with 29% sand to a clayey sand high LL (k6/283) with 22% plastic fines. Most samples contained occasional seams of silts and fine sands.

The results of the triaxial tests were used to determine the total stress parameter of "cohesion," which is customary in fine-grained soils. Generally, a fat clay and a clayey sand high LL have a saturated cohesion of 0.12 tsf (230 psf). The saturated cohesion values of the samples collected as part of this study were determined to be 0.56 tsf (1,120 psf) for the fat clay sample and 1.85 tsf (3,700 psf) for the clayey sand high LL sample.

Total stress parameters of soils also include the effect of pore pressure on the materials. Pore pressure effects were significant as evidenced by the test results (Appendix E) and are expected to be significant under in-situ conditions due to the confinement of soil layers and the appreciable amounts of saturated high LL plastic fines. The sample results from this study indicated high cohesion values and a high degree of saturation of in-situ soils that are indicative of materials that tend to deform easily.

5.6.5. Other Considerations

In the study area, the top of the Miocene occurs at approximately –40 feet MLW. Consequently, the confining unit occurs under fully saturated conditions and considerable lithostatic pressure; two conditions that do not favor development of joints or fractures (Carver, 2000). Although no cone penetrometer testing (CPT) was done specifically for this project, extensive CPT testing has been done for geotechnical considerations at various locations along the Savannah river front. These CPT tests typically penetrate into the Miocene confining layer and are used to aid in the design of pile foundations for structures.

As the CPT probe is advanced into the soil, the probe measures an array of geotechnical parameters within the soil strata encountered, including sleeve friction, tip resistance, and pore pressure. It is common knowledge in the Savannah area geotechnical community that a distinctive in-situ pore pressure response is recorded when the CPT probe encounters the Miocene confining layer, namely a sudden high pore pressure kick that does not dissipate as the probe is advanced into the layer.

This response in the confining layer indicates that the pore pressure induced by the CPT probe as it is pushed is well-confined and has no avenue for the pore pressure to escape or dissipate as it would in a more granular, less tight soil such as sand.

The high pore pressure signature of the Miocene confining layer is not characteristic of materials that contain a significant amount of fractures or joints. If fractures existed in the confining layer, the high pore pressure response that is typical of Miocene sediments would not occur. Instead, the pore pressure measurements would be lower, as fractures allow avenues for pore pressure to escape and dissipate.

Furthermore, the historical decrease in aquifer pressure (piezometric head) has further increased net vertical and confining (lateral) pressure in the confining layer. Davis and others (1963, 1976) measured land subsidence in the Savannah area with several precise leveling surveys from 1918 to 1975 and found approximately 0.5 feet of subsidence had occurred in the Savannah area. The reports concluded that declining heads in the Upper Floridan aquifer had caused compaction of the Miocene confining unit, which, in turn, resulted in land subsidence. The compaction of the confining unit would tend to decrease the hydraulic conductivity and any secondary permeability caused by fracturing or jointing, which would further limit the possibility of open fractures occurring in the confining material underlying the navigation channel.

5.7. GIS

The GIS served not only as a repository for organizing and viewing raw data, but also as a helpful tool for enhanced visualization and advanced analysis of the compiled data sources. The analyses completed provided a comprehensive view of the navigation channel to aid in visualizing major changes to the Savannah River through time. Selected analyses and figures completed as part of the supplemental studies are summarized below, and detailed calculations and flow charts illustrating the calculation steps for all surfaces are included as Appendix C.

5.7.1. Calculated Surfaces

5.7.1.1. Miocene Removed from Dredging and Paleochannel Erosion

The total thickness of feet of Miocene material removed (Figure 5-14) was calculated using the 2003 Annual Survey surface (which included supplemental data for Kings Island Turning Basin) and the Undisturbed Miocene with Paleochannels raster. It is important to note that the undisturbed surfaces were constructed by projecting the natural surface of the Miocene based on older marine borings and land borings, and the undisturbed surface was projected in the paleochannel areas to calculate the amount of material removed due to paleochannel incisions. The GIS analysis indicated that approximately 5 feet of confining material has been removed along the majority of length of the navigation channel as a result of dredging activities. The amount of material removed from natural paleochannel incisions is illustrated as well. As expected, natural erosion from paleochannels has removed the largest thickness of material, which in some places is up to 30 feet (Figure 5-14).

5.7.1.2. Miocene (Current)

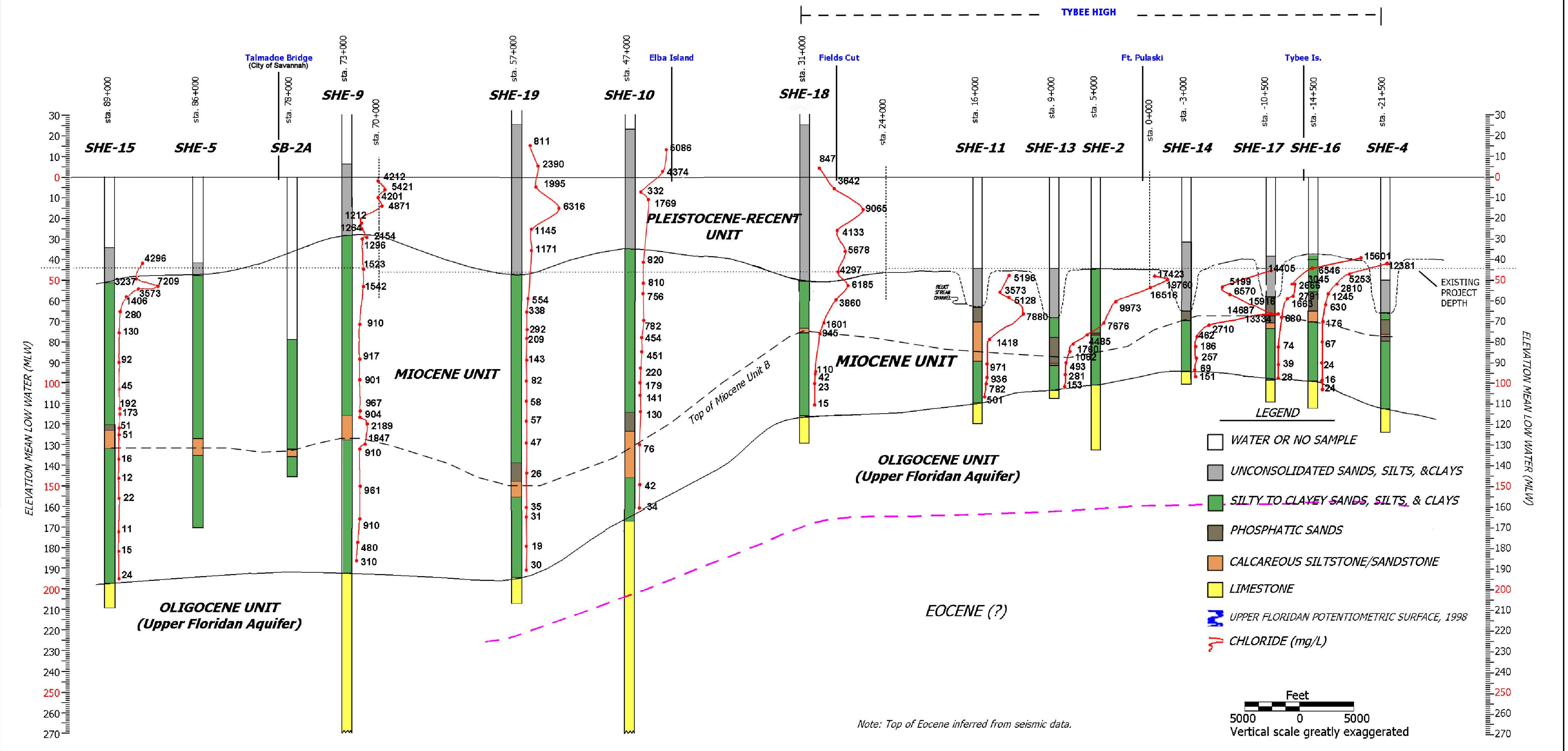
A number of calculations were involved to create a refined surface representing the surface elevation of the Miocene. Boring log data, geophysical data, and bathymetry data were all combined to form a refined surface, which is shown in Figure 5-15. The elevation of the top of the Miocene ranged from –29 feet MLW near the Bight Channel to –80 feet MLW underlying the paleochannel centered at river station 9+000 (*RCCF 4*). The analysis indicated that the average elevation of the top of the Miocene along the majority of the river was between –45 to –50 feet MLW.

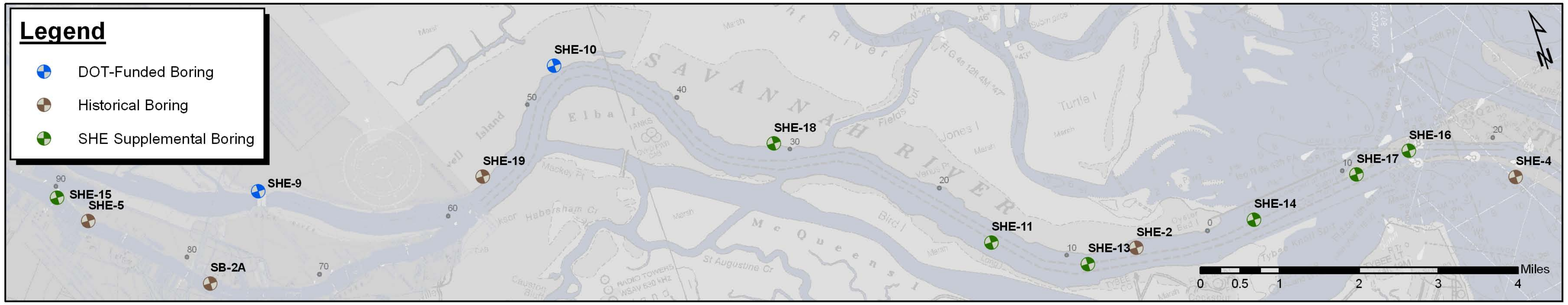
5.7.1.3. Current Miocene Thickness

The Limestone surface was subtracted from the Current Miocene surface in order to determine the thickness of the confining unit. The returned raster values indicated thickness of Miocene material in feet underlying the navigation channel (Figure 5-16). The surface indicated that the Miocene confining unit is most thin where paleochannels have incised the contact. A minimum thickness of 23 feet was calculated underlying the paleochannel centered on river station 9+000 (RCCF 4), which correlates well with the seismic data interpretation (26 feet). The analysis showed a maximum thickness of 160 feet upstream near Kings Island Turning Basin.

5.7.1.4. Projected Miocene Thickness

The Undisturbed Miocene surface and the proposed dredging depths were combined to project the thickness of the Miocene based on a “6-foot improvement” as illustrated in Figure 5-17. The “6-foot improvement” incorporates the total maintenance dredge depths plus an additional 3 feet of material to account for any potential disturbance by the dredge cutter-head. The projected minimum thickness (23 feet) of the Miocene confining layer did not change, as the paleochannel material overlying this area would be dredged, but the underlying Miocene material would not be disturbed. The minimum thickness of confining material outside the paleochannel areas was projected as 38 feet near river station –5+000.



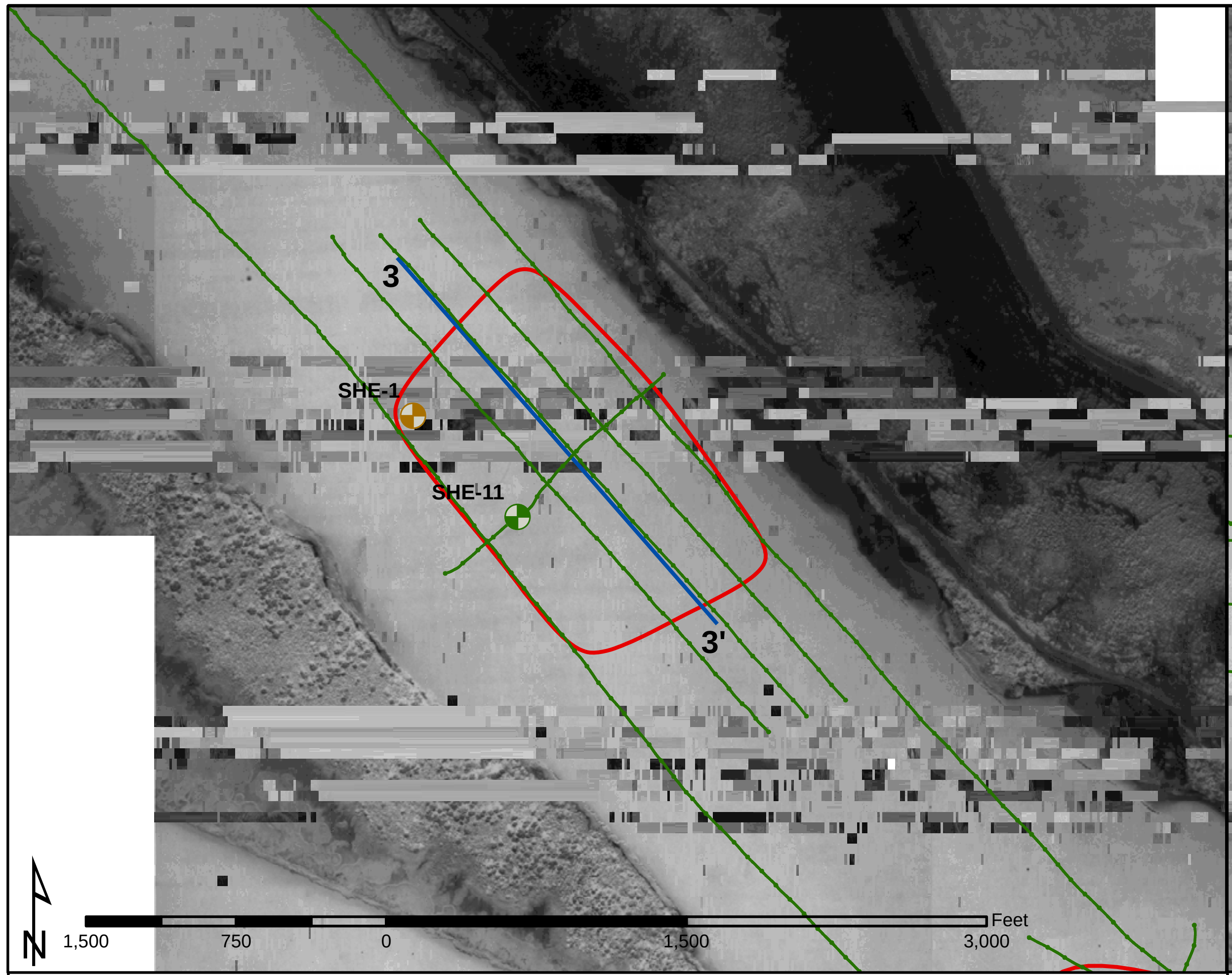


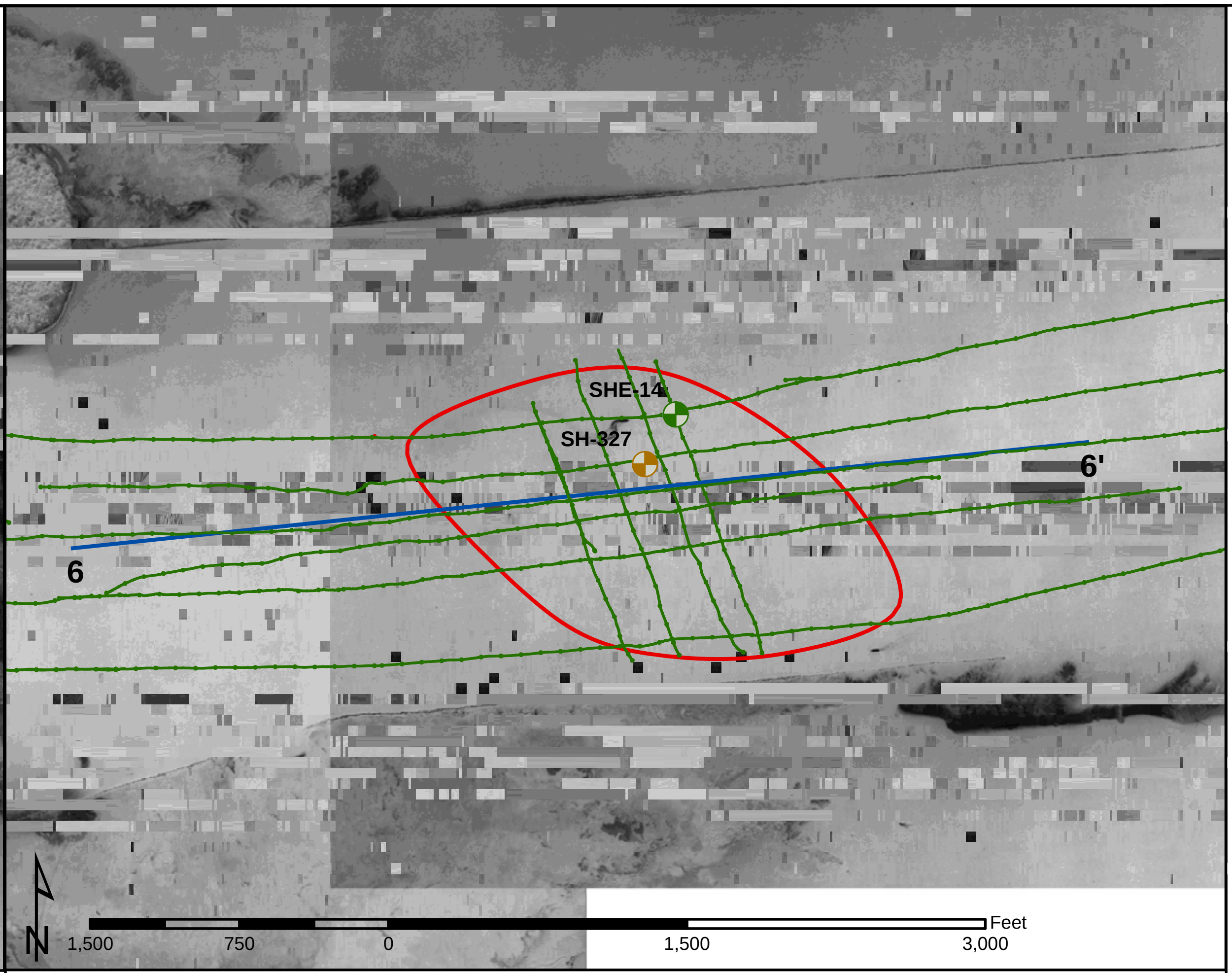
GEOLOGIC CROSS SECTION
OF STUDY AREA SHOWING
CHLORIDE POREWATER PROFILES

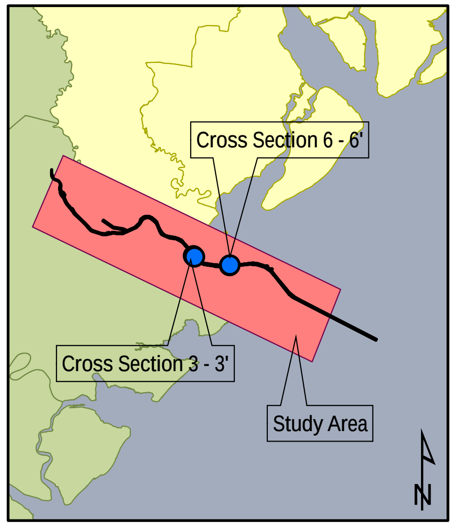
SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-1

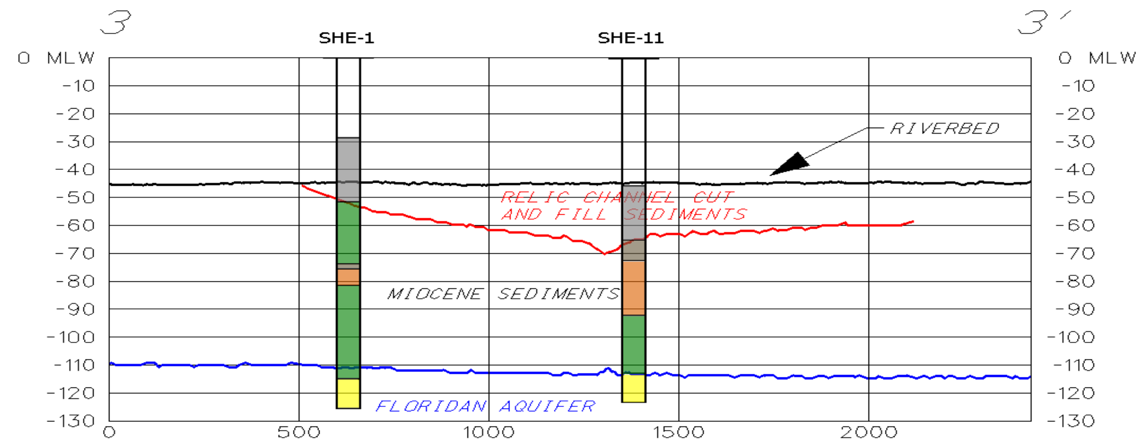


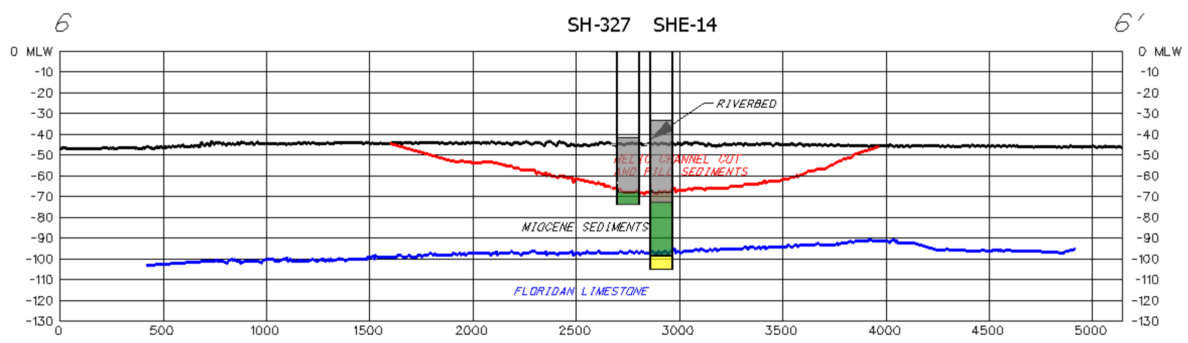




Legend

●	Savannah Harbor Boring
●	SHE Supplemental Boring
—	Geophysical Survey
—	Cross Section
—	Paleochannel Areas





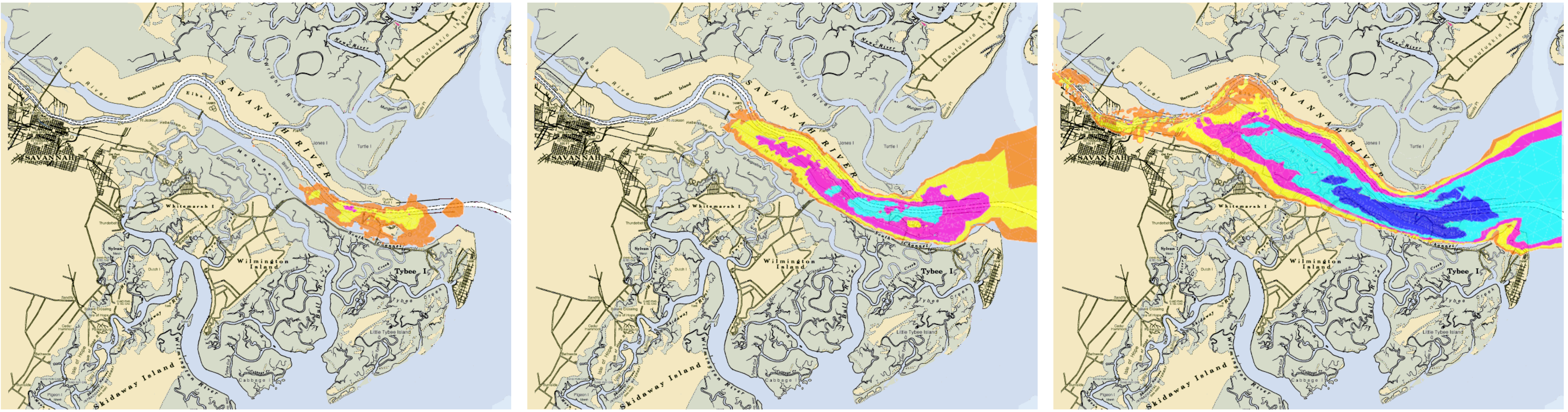
CROSS SECTIONS SHOWING
PALEOCHANNEL ORIENTATIONS AND
CONTACT CORRELATION WITH BORINGS

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

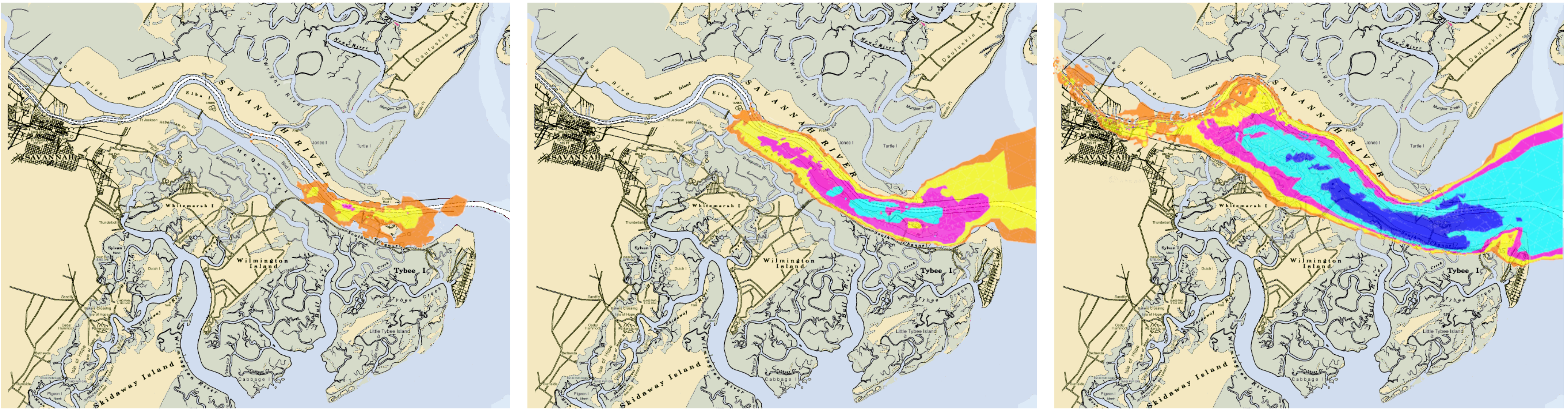
FIGURE 5-4

No Dredging

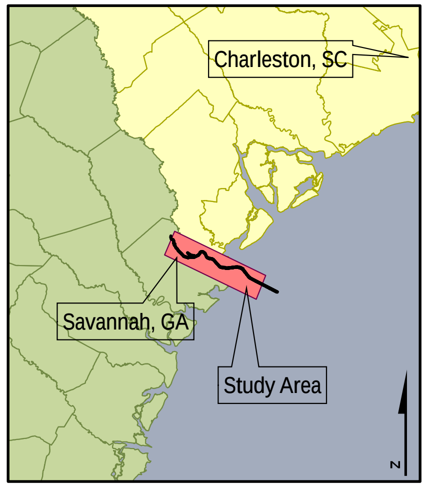


2000 2050 2200

Dredging



2000 2050 2200



Cl (mg/L)
- 🟧 100 - 200
- 🟨 200 - 500
- 🟪 500 - 1000
- 🟦 1000 - 2000
- 🟦 2000 - 5000

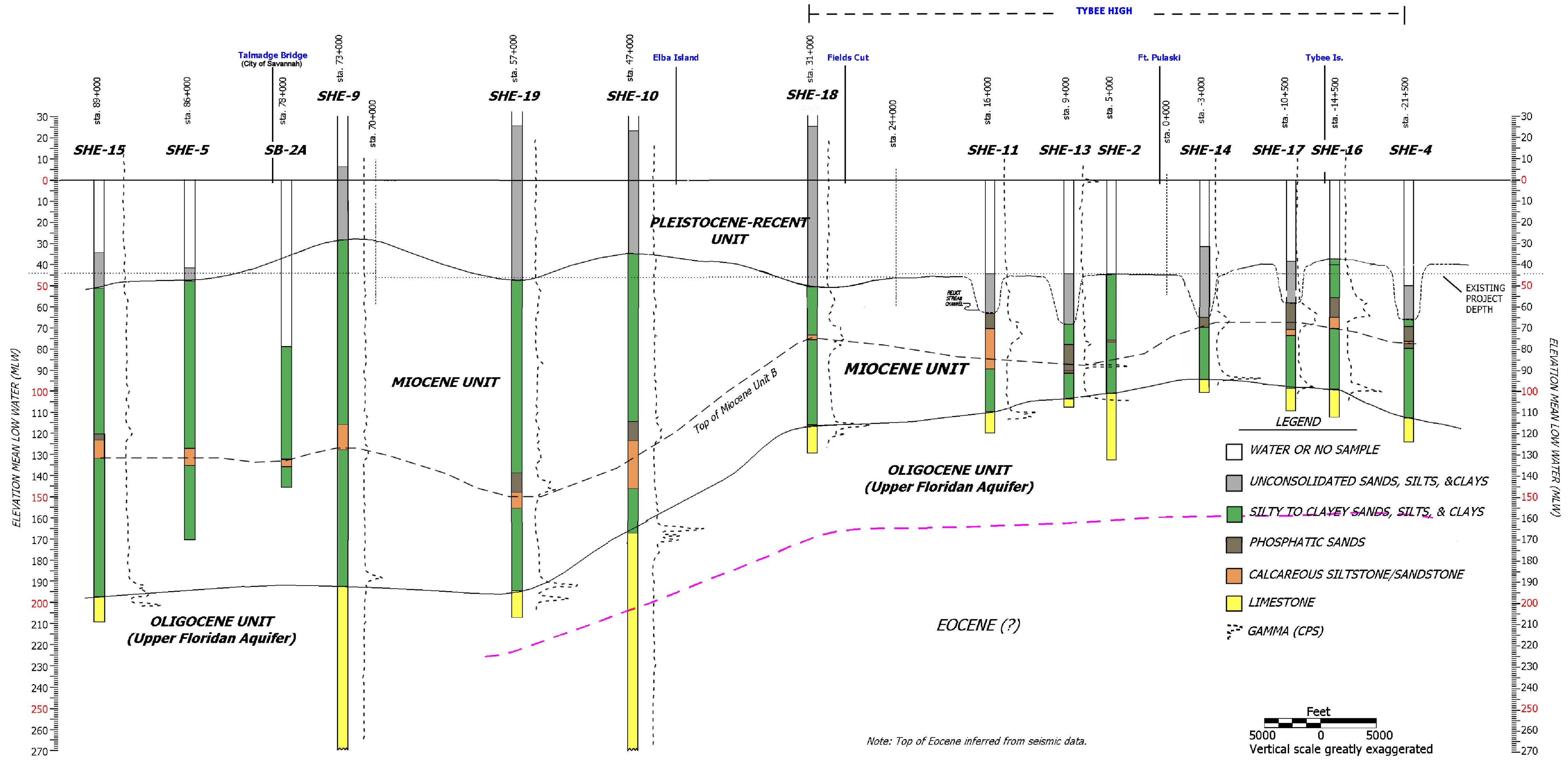
CHLORIDE DISTRIBUTIONS IN THE UPPER FLORIDAN AQUIFER IN THE YEAR 2000, 2050, AND 2200 FOR DREDGING AND NO-DREDGING SCENARIOS

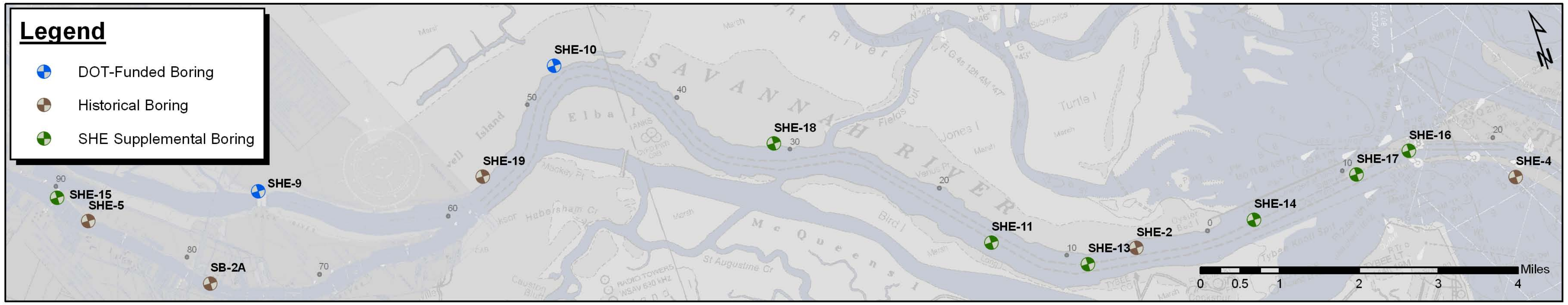
SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS OF ENGINEERS
SAVANNAH DISTRICT

Source: CDM

FIGURE 5-9



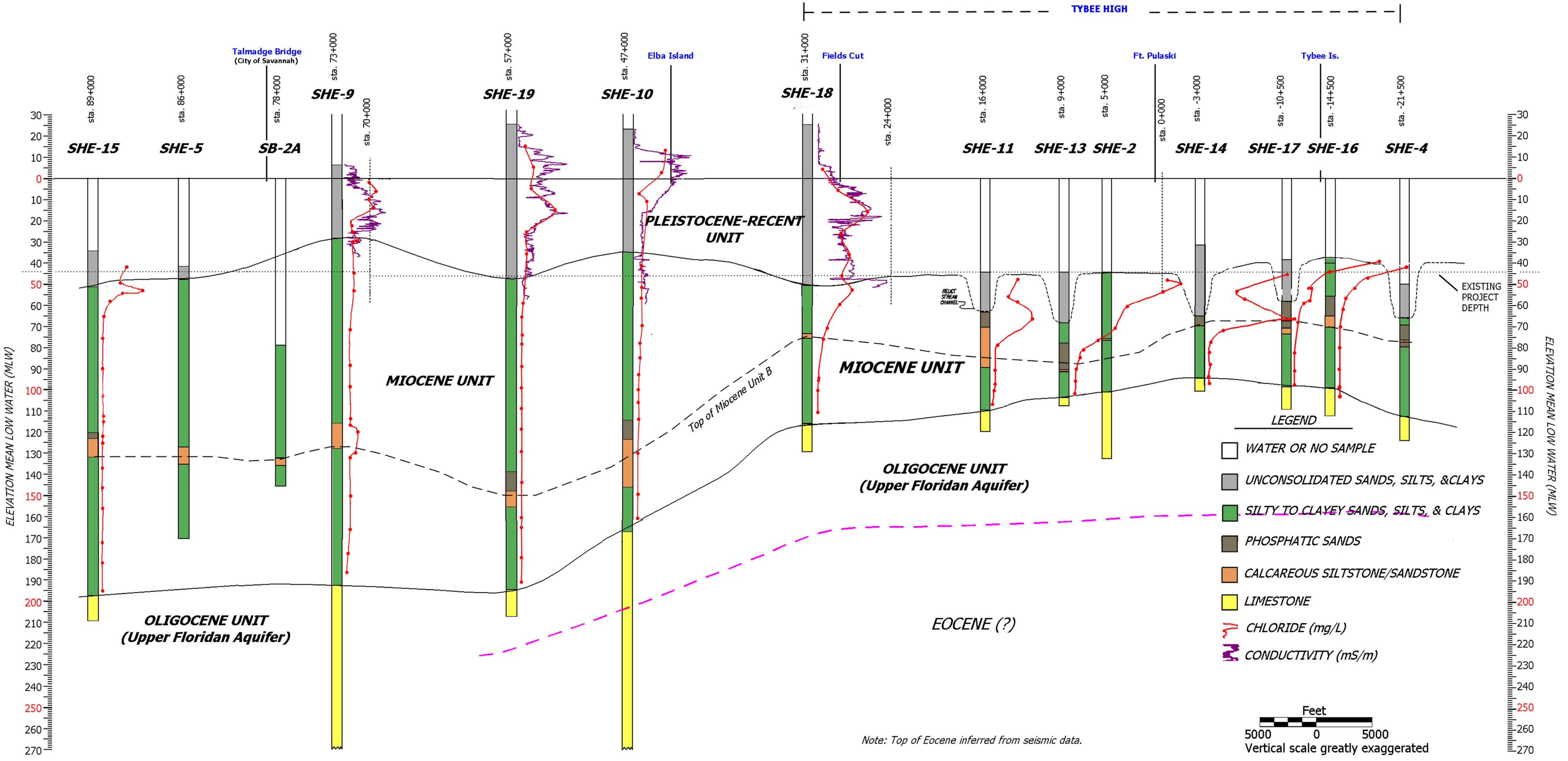


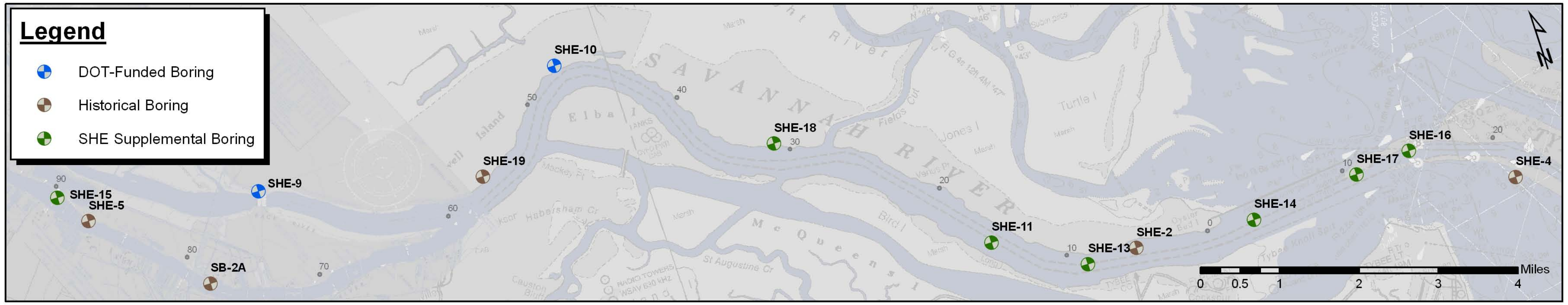
GEOLOGIC CROSS SECTION OF STUDY AREA SHOWING GAMMA LOGS

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-11



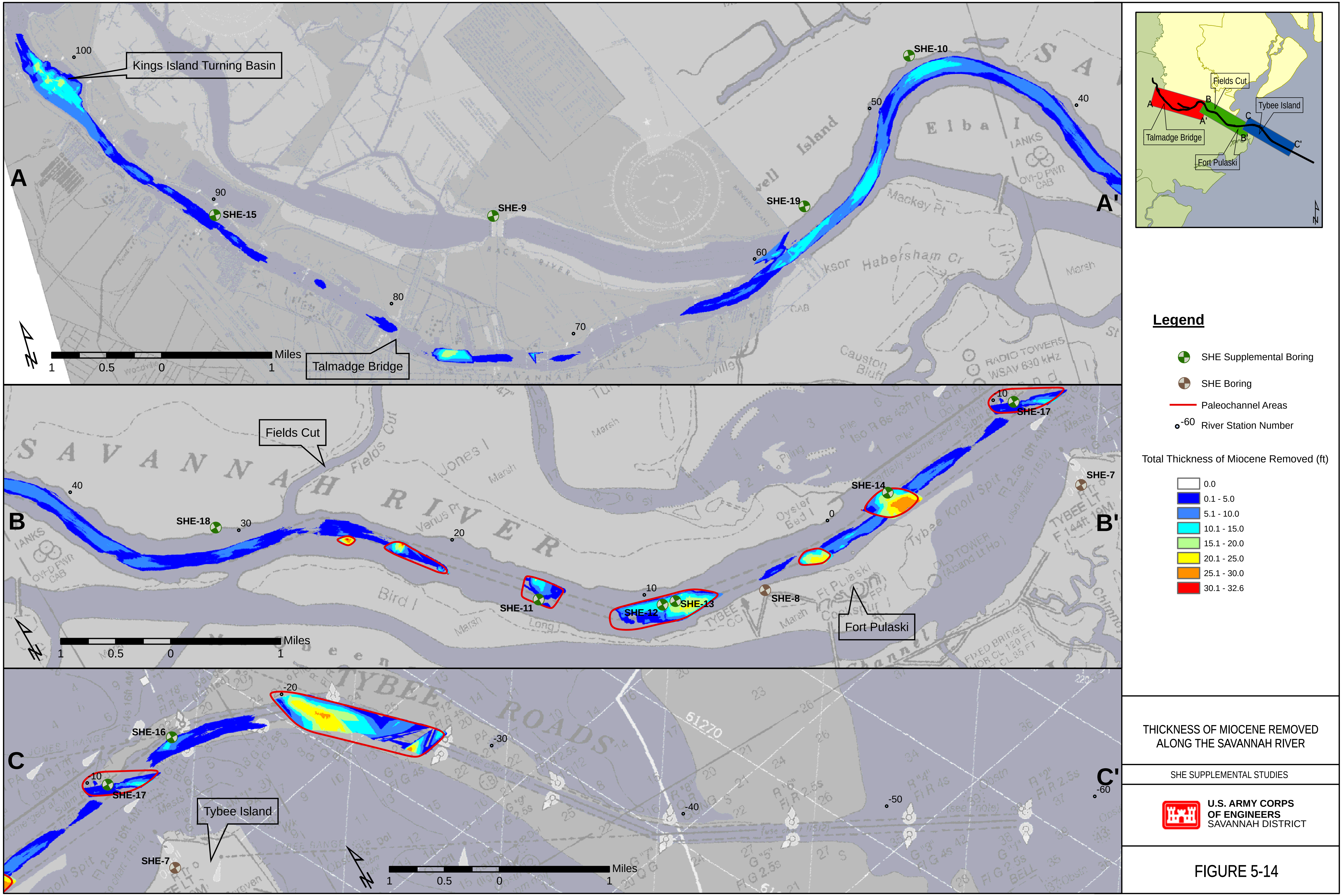


GEOLOGIC CROSS SECTION OF STUDY AREA SHOWING CORRELATION OF SOIL CONDUCTIVITY LOGS AND POREWATER PROFILES

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-12

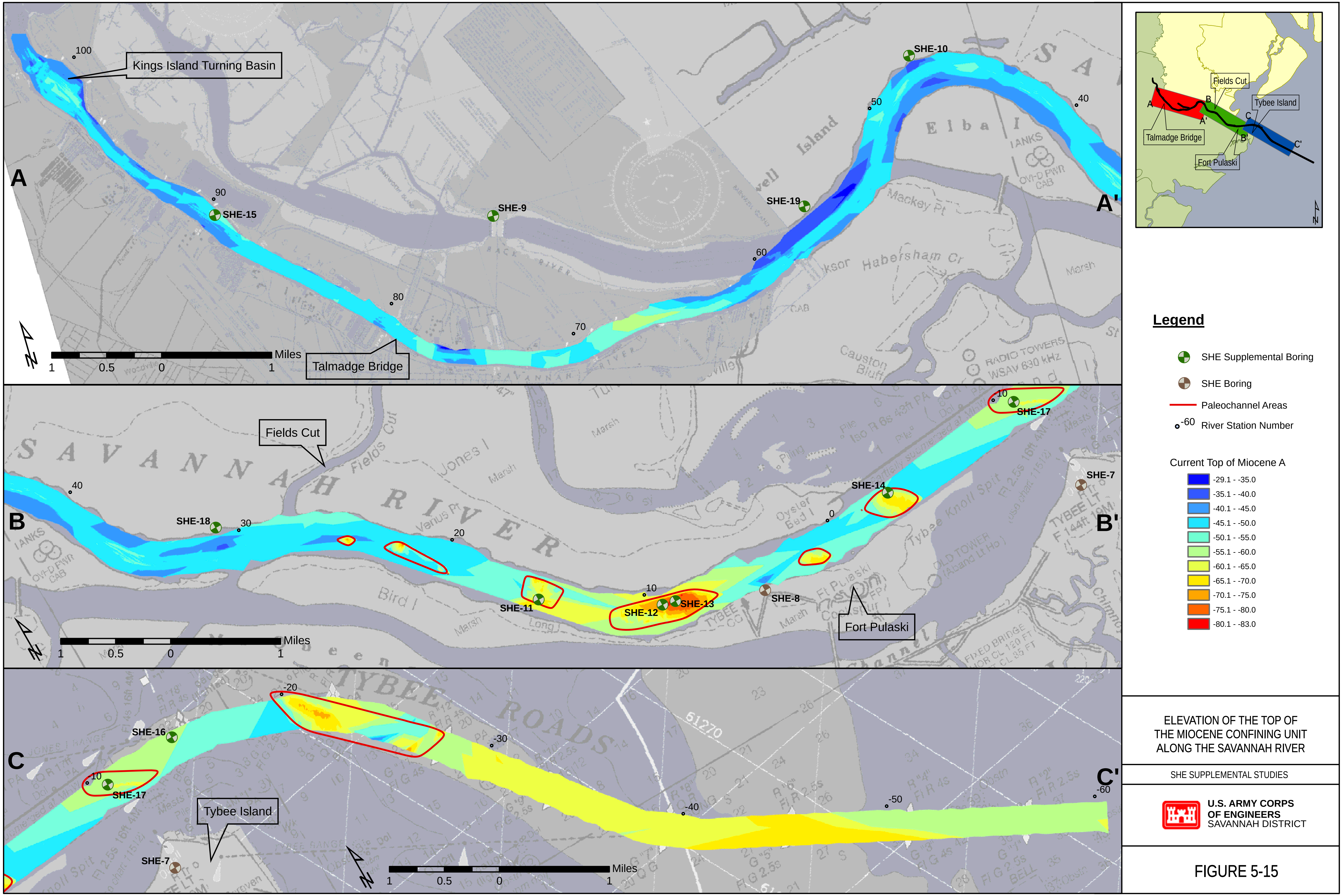


THICKNESS OF MIOCENE REMOVED
ALONG THE SAVANNAH RIVER

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-14

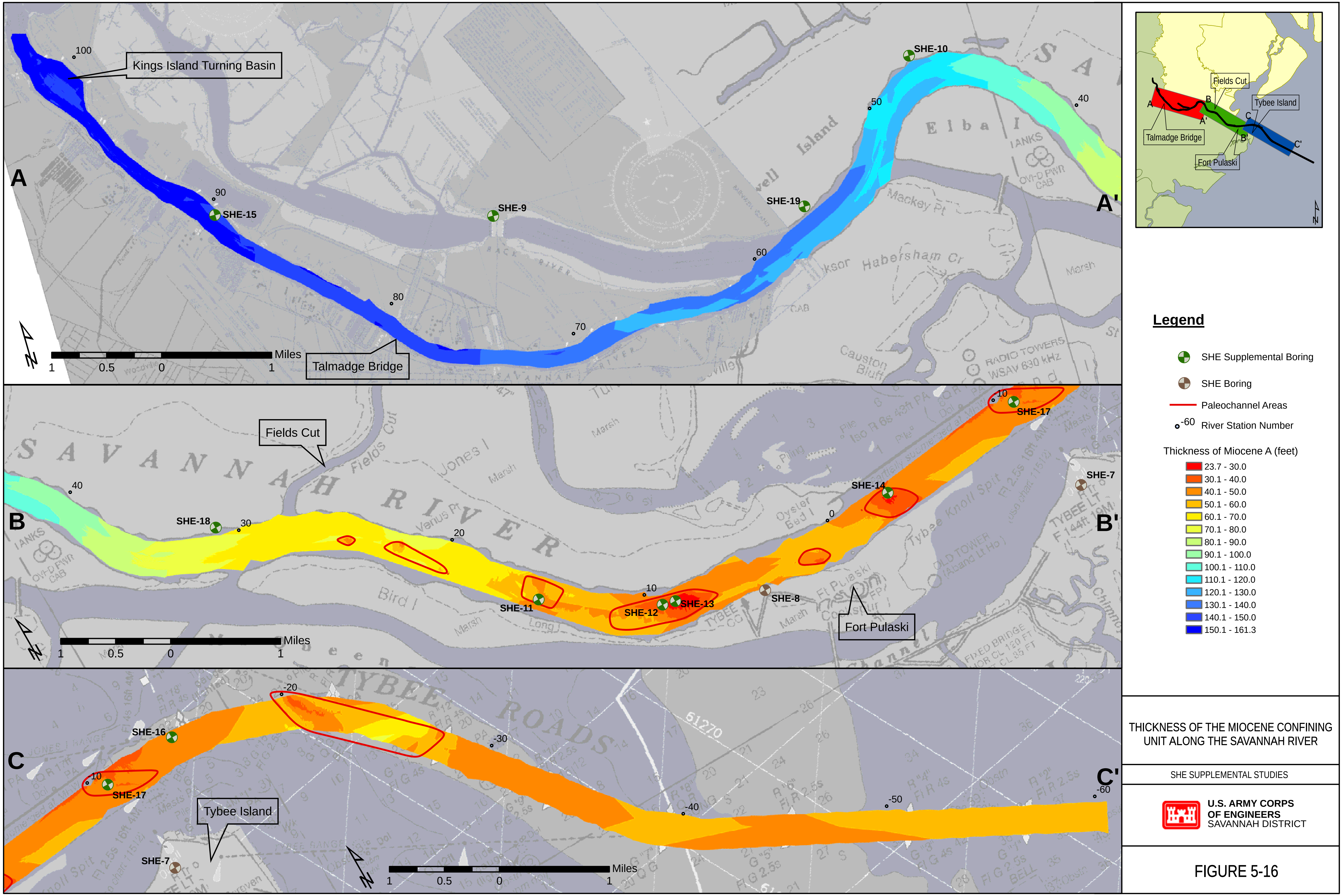


ELEVATION OF THE TOP OF
THE MIOCENE CONFINING UNIT
ALONG THE SAVANNAH RIVER

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-15

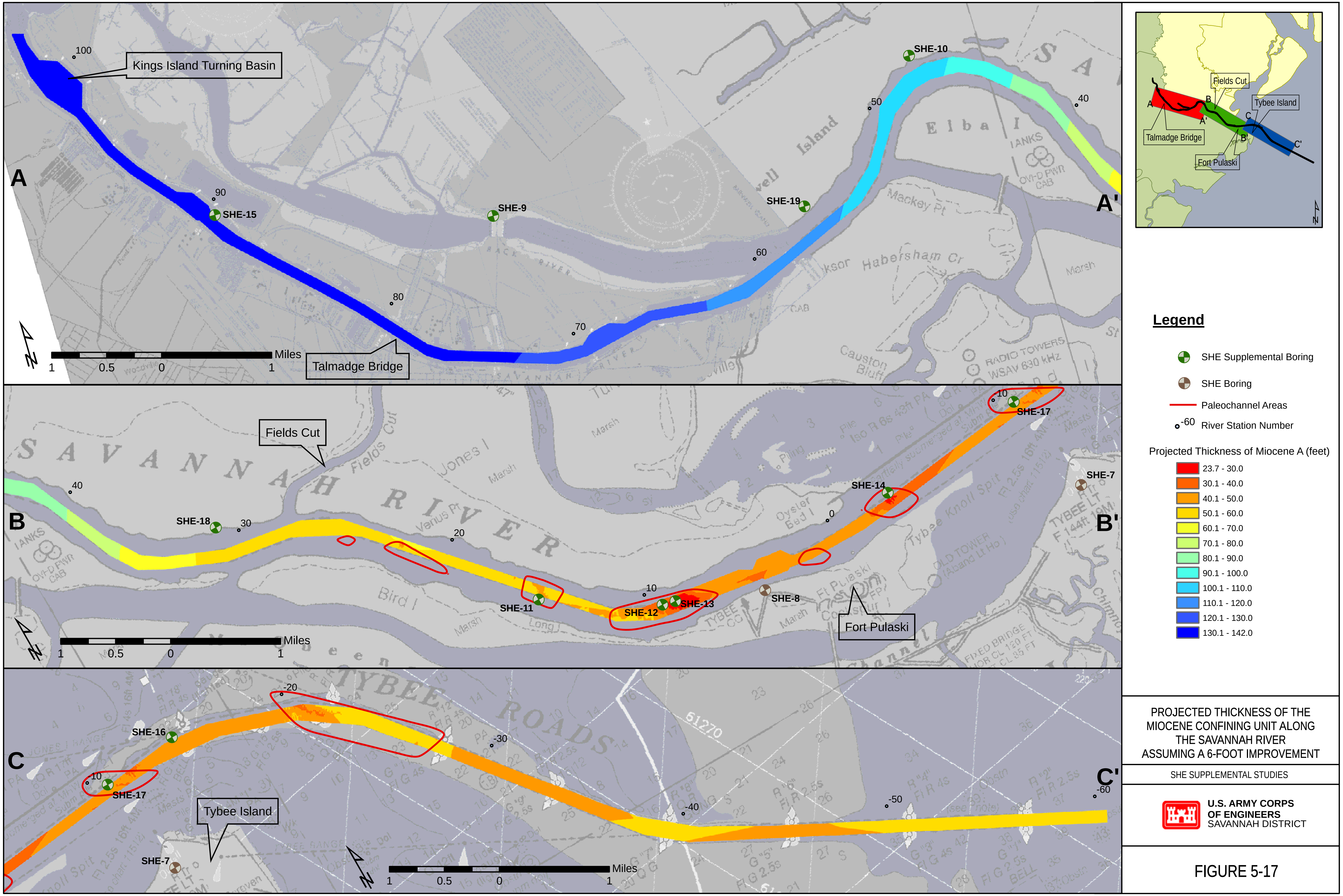


THICKNESS OF THE MIOCENE CONFINING UNIT ALONG THE SAVANNAH RIVER

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-16



PROJECTED THICKNESS OF THE
MIOCENE CONFINING UNIT ALONG
THE SAVANNAH RIVER
ASSUMING A 6-FOOT IMPROVEMENT

SHE SUPPLEMENTAL STUDIES

U.S. ARMY CORPS
OF ENGINEERS
SAVANNAH DISTRICT

FIGURE 5-17

6. SUMMARY

The supplemental studies conducted as part of the Tier II EIS were intended to expand upon previous studies, particularly the 1998 USACE feasibility study entitled *Potential Ground-Water Impacts*. The study was conducted according to six major tasks outlined in Table 4-1. Each task provided a wealth of information that, when combined, form a comprehensive picture of the geology and hydrogeology underlying the navigation channel and surrounding area.

The detailed approach allowed for a greater understanding of the geologic and hydrogeologic framework underlying the navigation channel. Measured porewater data, hydraulic conductivity data, head data, seismic data, and confining layer thickness data were used to build upon a regional model built by USGS and refine it to address water quality issues specifically associated with dredging impacts. In order to ensure the model results were conservative, the dredging scenarios were run assuming an additional three feet of material would be removed below the proposed dredging depths. In addition, the model outputs used two values of hydraulic conductivity and provided two sets of results that bracketed true conditions, yielding a best-case and worst-case scenario for both dredging and no dredging conditions. Selected results are summarized below.

6.1. POREWATER PROFILES

The porewater data derived from this work indicate that, as expected, seawater is moving downward through the Miocene confining layer toward the Oligocene limestone (Upper Floridan aquifer), and, in some locations, low concentrations of chlorides appear to have migrated entirely through the confining layer and into the limestone. The pronounced profiles show that chloride concentration decreases with depth from the top to the bottom of the confining layer, and chloride values ranged from a high of 20,000 mg/L near the top of the layer to a low of 15 mg/L near the bottom of the layer. The data also suggest somewhat enhanced leakage of salt water in areas where deep paleochannels cut across the present navigation channel that are underlain by punctuated decreases in chloride concentration below the Miocene unit A contact.

6.2. GEOPHYSICAL SURVEY

The subbottom seismic survey provided a comprehensive data set of the stratigraphy underlying the navigation channel within the area of concern (river stations 30+000 to –30+000). The seismic profiles generated from the survey were used to better understand the three dimensional relationship of the navigation channel, paleochannels, and the confining layer. In general, subbottom data indicated that the paleochannel features identified in the entrance channel are oriented oblique to the present-day course of the river. The subbottom data indicated that *RCCF 4* had downcut into the confining material more than any other paleochannel feature, and the minimum thickness of Miocene confining material underlying the navigation channel was 26 feet near boring SHE-13.

6.3. GROUND-WATER MODEL

The ground-water model indicated that the expected increase in downward volume of flow of saline water from the area underlying the Savannah River navigation channel due to dredging is small. The area affected by dredging accounted for a total downward flow between 50 to 250 gallons per minute depending on the hydraulic conductivity assigned to the Miocene confining unit. Dredging the navigation channel increased the total downward flow between 2 to 7 gallons per minute, or 3 to 4 percent. The contribution is negligible when compared to ground-water production in the Savannah area from the Upper Floridan aquifer, which is on the order of 80 million gallons per day (55,555 gallons per minute).

The concentrations presented represent only the contribution from the river and navigation channel. Other salt-water sources (salt marshes, offshore) were not simulated in order to simulate the explicit impacts of dredging.

In the year 2200, the upstream chloride concentrations in the Upper Floridan aquifer beneath the river were simulated to be approximately 0 mg/L for low-value hydraulic conductivity simulations and up to 100 mg/L for the mid-range hydraulic conductivity simulations. Downstream, chloride concentrations directly beneath the river approached 500 mg/L after 200 years for the low-value hydraulic conductivity simulations. For the mid-range hydraulic conductivity simulations, total breakthrough (equilibrium) occurred after approximately 100 years, and the maximum chloride concentration in the Upper Floridan aquifer occurred in the downstream portion of the study area (1,400 mg/L).

In the upstream reaches of the river, where the surface water model predicted minimum increases in chloride concentrations, the differences in chloride concentrations in the top of the Upper Floridan aquifer between the dredging and no dredging scenarios were minor. Downstream, where higher surface water chloride concentrations were predicted to occur, the corresponding differences in concentrations in the Upper Floridan aquifer directly below the river ranged from 10 to 200 mg/L and were typically observed 50 or more years into the future. These concentrations represent only a small percentage of the total concentrations expected in the aquifer, thereby yielding the contribution from dredging to the total concentration in the aquifer insignificant when compared with the combined chloride contributions from other salt-water sources.

6.4. SIMULATED PUMPING TEST

Results from the simulated pump tests indicate that it would be difficult to conduct a meaningful aquitard test. The simulations showed that response times in the surficial aquifer and Miocene confining unit would be relatively slow with expected drawdowns of only a few inches. In addition, an aquitard test would have to be at least two months in duration and pump at least 1,000 gpm to develop sufficient data with which to assess the vertical hydraulic conductivity of the Miocene confining unit. In addition, the interference expected from tidal variations, local pumping wells, and regional pumping trends would further obscure any meaningful results. The long duration and sustained pumping rate required combined with the expected minimal and indistinct response make the task of performing an aquitard test impractical.

6.5. SOILS LABORATORY DATA

6.5.1. Hydraulic Conductivity

The vertical hydraulic conductivity results of the Miocene samples were very similar to those reported in the 1998 study, and the results from paleochannel material indicate that, although the paleochannel sediments are variable in lithology, portions of them contain properties similar to the confining material. The average value of hydraulic conductivity measured from paleochannel material 3.72 x 10^{-7} cm/sec (1.05 x 10^{-3} ft/day) was less than that observed in the Miocene sediments 2.13 x 10^{-6} cm/sec (6.04 x 10^{-3} ft/day). Additionally, the minimum value observed in paleochannel material was within the same order of magnitude as the minimum values observed in samples collected from the Miocene units, and the maximum value observed in relict channel samples was two orders of magnitude less than that observed in Miocene samples.

6.6. OTHER CONSIDERATIONS

Bartholomew et al. (2000) observed fractures in Eocene and Pliocene to Holocene (but not specifically Miocene) surface outcrops in the coastal area. It has been suggested that if similar vertical or near-vertical fractures exist in the Miocene confining layer in the lower reaches of the Savannah River, they may provide pathways for enhanced downward movement of salt water through the confining layer toward the Upper Floridan aquifer.

In the study area, the top of the Miocene confining unit occurs near –40 MLW under fully saturated conditions and considerable lithostatic pressure. CPT tests conducted along the Savannah River indicate the top of the Miocene confining layer is recognized by a distinctive high pore pressure signature. This high pore pressure is characteristic of well-confined, well-consolidated materials. If fractures existed in the confining layer, the high pore pressure response that is typical of Miocene sediments would not occur. Instead, the pore pressure measurements would be lower, as fractures allow avenues for pore pressure to escape and dissipate.

7. CONCLUSIONS

The results from field work, ground-water modeling, and GIS analyses conducted as part of this study provided the most comprehensive picture of the geology and hydrogeology underlying the Savannah River to date. The conclusions and recommendations listed below are based on compiled historic data as well as data collected specifically for the supplemental studies. Whenever applicable, conservative assumptions were applied in order to ensure recommendations were based on a worst-case impact.

A site-specific seismic subbottom survey was performed from river station 30+000 to –30+000, and the results of the survey provided detailed stratigraphy and information about all major paleochannels within the area of concern. The location, attitude, and extent of all paleochannels were mapped and incorporated into the Miocene surfaces created for the GIS and the ground-water model to determine their role in potential dredging impacts. Ground-water model results indicated that any additional contribution of chloride by the paleochannels is negligible when compared to the total contribution from other adjacent salt-water sources outside paleochannels along the river bottom. The impacts of dredging in the in-fill sediments of the paleochannels, which were simulated in the model to represent sand, were small when compared to the impacts of dredging elsewhere in the channel where Miocene confining unit is impacted. GIS analyses indicated that the minimum thickness of Miocene confining material occurs where paleochannels have incised into the top of the unit, and the proposed dredging activities would not further impact the Miocene confining layer in these areas.

Concern over the possible existence of fractures within the confining unit underlying the navigation channel was addressed. The in-situ conditions under which the confining layer exists in the project area (-40 feet MLW and under considerable lithostatic pressure), the nature of the confining material (considerable clay content and plasticity), and the lack of any physical evidence all indicate that fractures most likely do not exist in the project area. If they did exist in the past, the in-situ conditions would not allow them to exist as open pathways for enhanced downward flow. Instead, the lithostatic pressure and plastic nature of the material would cause any open fractures to heal themselves. **The absence of observable vertical joints in Miocene-aged surface exposures and subsurface cores of the Miocene, as well as lack of any historical evidence (springs), reinforce the notion that fractures or joints are not a factor in the hydraulics of the confining layer in the Savannah area.**

Conducting a trial pumping test on two existing Upper Floridan wells was proposed in order to determine the feasibility of performing a full aquitard test on the confining unit. Initially, several model simulations were performed to evaluate the potential response in the surficial aquifer and Miocene confining unit to a long-term pumping test conducted with a well in the Upper Floridan aquifer. The inherent properties of the Miocene confining material (well-compacted, low hydraulic conductivity, and general “tight” nature) are characteristic of geologic units that would typically show very little response to pumping. The simulation results indicated slow response times (months) and small drawdowns (inches), which would make performing a meaningful aquitard test difficult at best. **The simulation results, as well as the response from previous tests conducted at the Tybee Island Test Well Cluster, led to a decision not to conduct the additional trial pumping test, and it is felt that full aquitard testing is not warranted.**

Since the 1880’s, increasing withdrawals of water from the aquifer have lowered the water levels in the aquifer to as much as 100 feet below MLW. The net effect of this lowering of water level has reversed the natural pre-development flow of ground water from the aquifer upward through the confining layer to a downward flow of water through the confining layer toward the center of the area of greatest pumping from the aquifer (Savannah). **The ground-water model simulation results indicated that these head gradients are the dominant force contributing to downward movement of salt water through the Miocene confining unit.**

GIS analyses of removal of confining material through time and ground-water model results indicated that historic dredging has probably had minimal influence on the rate of salt-water intrusion. The GIS analyses indicated that the majority of confining material removed along the navigation channel has occurred since 1992, which, relative to ground-water flow rates, can be considered current conditions. Furthermore, the model simulations were run assuming up to nine feet of confining material were removed and showed very little difference between the dredging and no dredging projected impacts.

All model results and concentrations reported are based on chloride concentration effects specifically associated with dredging the navigation channel. They do not account for other salt-water sources including salt marshes or the Atlantic Ocean. As such, the values reported *do not* represent total concentrations or distributions expected; they represent the contribution from the river and navigation channel to the total concentration. This contribution is a small percentage when compared to the total concentration expected from other salt-water sources.

The location of the maximum negative head gradient, i.e. the center of the cone of depression, poses the largest potential for enhanced salt-water leakage through the confining layer. The porewater data and model results, however, showed that the thickness of the confining unit (>100 feet) and the lower salinity of the river water at this upstream location minimize this impact in the upstream reaches of the navigation channel and production wells located in and around Savannah.

The downstream areas, however, specifically near the Tybee high, showed a gradual increase in chloride concentrations in the Upper Floridan aquifer ranging from 500 to 1400 mg/L depending on hydraulic conductivity of the confining layer. The enhanced salt-water intrusion in this area is attributed to a combination of factors: the induced negative head gradient from pumping in Savannah; the overlying seawater or saline water with minimal freshwater input from the Savannah River; the naturally thin confining layer (40-60 feet); and the paleochannels that have further removed Miocene material.

Although lab results indicated that zones within the paleochannel fill material have comparable hydraulic conductivities to the Miocene material, porewater profiles constructed within paleochannels suggest that they still have some influence on the rate of salt-water intrusion. The porewater profiles also showed that chloride concentrations decrease rapidly below the Miocene contact. This punctuated reduction in concentration supports the notion that dredging paleochannel material would have minimal effect on the downward rate of salt-water intrusion. Additionally, if the paleochannel material were not considered “confining, ” then dredging in these areas would not reduce the thickness of the underlying confining unit. Instead, the potential impacts on water quality due to dredging should focus on the entire thickness of material overlying the aquifer and the amount of Miocene-aged material removed.

Near the Tybee high, the aquifer is predominantly overlain by seawater, and the Miocene confining layer is thin. These two naturally occurring factors significantly contribute to the enhanced salt-water intrusion in the area and locally affect water quality in the Upper Floridan aquifer. However, the model results showed that the proposed dredging would have little effect on this process. The ground-water model results showed that, in the year 2200, the concentration increase in the navigation channel due to dredging translated to only a small increase in the aquifer directly below the navigation channel (10-200 mg/L dependent on hydraulic conductivity). Production wells located in the downstream reaches of the river showed negligible differences between the dredging and no dredging scenarios, and the contribution to total chloride concentrations increased by a range of 0 to 50 mg/L after 200 years.

The ground-water model simulations were run 200 years into the future with a constant pumping rate in the Savannah area, and the results indicated that this rate of pumping would cause total breakthrough of seawater to occur *regardless of dredging* at some downstream locations in approximately 100 to 300 years depending on hydraulic conductivity of the confining layer.

In summary, the negative head gradient induced by pumping in Savannah has caused limited breakthrough of chlorides to occur in the downstream reaches of the Savannah River. The porewater profiles and model results from this study indicated that increased salinity in the Savannah River and the reduced thickness of the confining layer due to dredging will not significantly affect the timing of breakthrough of chlorides along the navigation channel in the Upper Floridan aquifer. Furthermore, the study results showed that the proposed dredging would have minimal impacts on water quality in production wells that tap the Upper Floridan aquifer in and around the city of Savannah.

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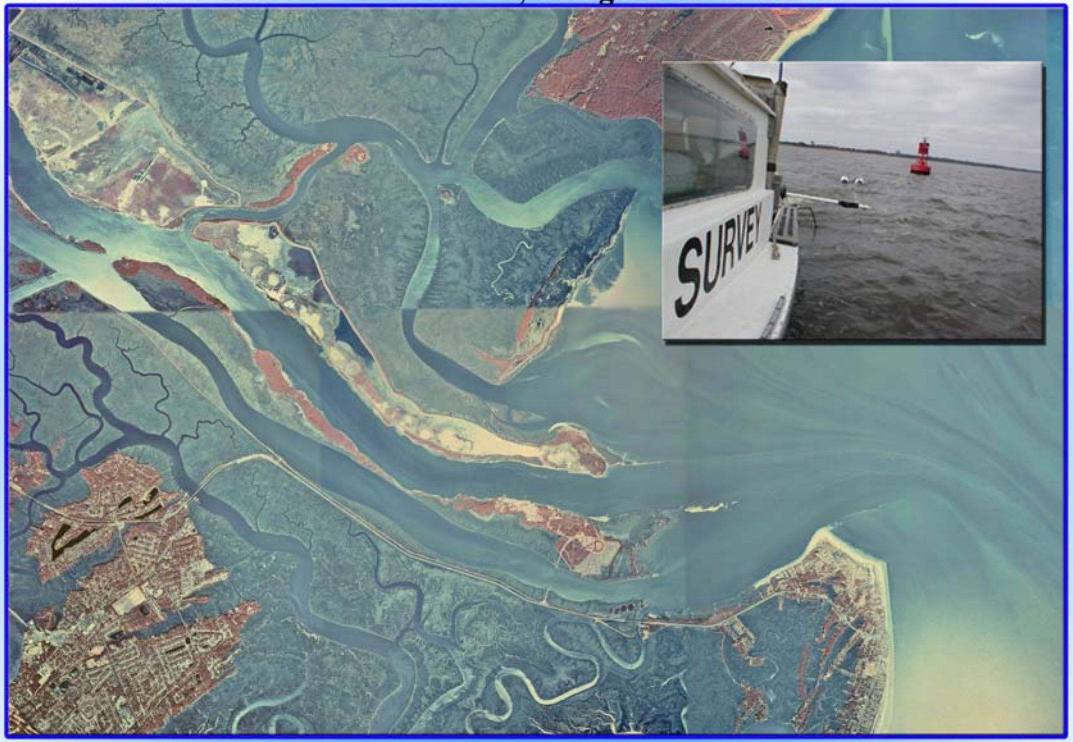
APPENDIX A

OSI Geophysical Survey Investigation Report

Geophysical Survey Investigation
Subbottom Profiling
Savannah River Entrance Channel
Savannah, Georgia



OSI Report No. 04ES007
February 2004

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Submittal Date: 17 June 2004

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II. Survey Field Log

III. Summary Table Comparing ACOE Boring Units and Subbottom Reflectors

& Master Summary Table of Relic Channel Cut and Fill Features and Limestone

IV. Interpretive Profiles

Digital Appendix (provided on CD included with report)

- Subbottom pick files (EXCEL format) for each subbottom data record that profiled a relic channel cut and fill feature

- Project Drawing Files (Microstation CADD format)

FINAL REPORT
Geophysical Survey Investigation
Subbottom Profiling
Savannah River Entrance Channel
Savannah, Georgia

1.0 INTRODUCTION

During the period 11-17 February 2004, Ocean Surveys, Inc. (OSI) conducted a geophysical survey investigation in the Savannah River Entrance Channel between River Stations 30+000 and –30+000 (Figure 1). The investigation, conducted for the Army Corps of Engineers (ACOE) - Savannah District, was completed under an Indefinite Delivery Contract OSI has with the ACOE - Philadelphia District (Contract Number DACW61-03-D-0003, Task Order Number 3). The investigation was specifically designed to complement and expand upon subbottom data acquired by OSI during a similar survey investigation of the river performed for the ACOE - Savannah District in 1997.

2.0 PROJECT SUMMARY

2.1 Project Background and Objectives

Contingent plans call for the expansion and deepening of the present-day Savannah Harbor and Entrance Channel to safely accommodate larger bulk and container ships than can presently use the river for commerce. The survey investigation described herein, is part of a multi-disciplinary comprehensive study designed by the ACOE to evaluate the feasibility of the proposed project.

Previous investigations have helped to identify the subsurface stratigraphy underlying the river that might be affected by dredging the channel to a deeper depth. The generalized sequence of geological formations identified in ascending order are: the upper Floridan Aquifer (a highly permeable limestone of mainly Oligocene and Late Eocene age and the primary source of fresh water in the Savannah area), a Miocene confining unit made up of a complex sequence of clastics that mainly contain low-permeability clays, silts, clayey silts, and sand), and a Pleistocene-Recent sedimentary unit (principally composed of silts and clays).

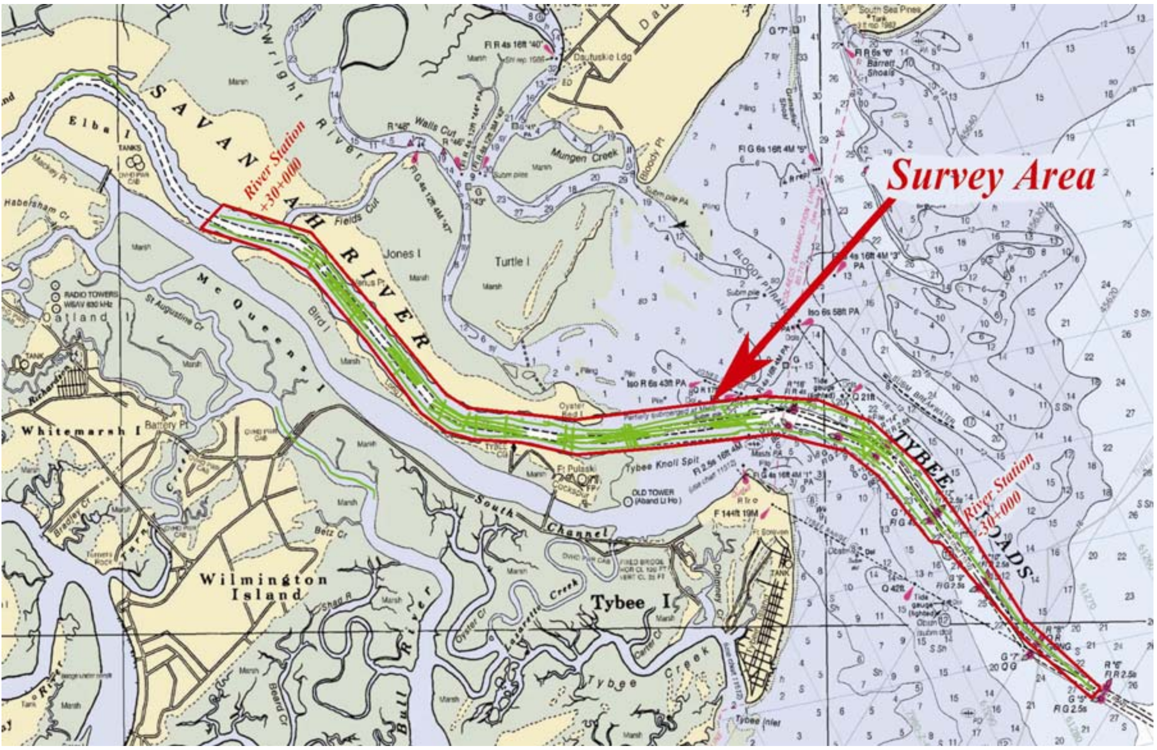


Figure 1 – Site Location map (taken from NOAA Chart No. 11513 entitled St. Helena Sound to Savannah River, 22nd Edition, 1997). Note: green lines in figure are representative of survey vessel tracklines.

Subbottom geophysical surveys, including the OSI subbottom investigation completed in October 1997 (OSI Report No. 97ES076), have revealed the existence of several buried relic stream channels (underlying the present-day navigation channel) which incise or cut into the Miocene confining unit and have been in-filled. It has been theorized by others, that if the relic stream channel cuts were in-filled by higher permeability sediments than those comprising the Miocene confining unit, then deepening the navigation channel might result in a more direct migration pathway for saltwater intrusion to the underlying aquifer system than currently exists (references citied in the U.S. Army Corps of Engineers, 1998, Savannah Harbor Expansion Feasibility Study).

The primary objective of the current survey investigation was to provide data to help the ACOE determine if deepening the Entrance Channel might have an adverse impact on the Upper Floridan Aquifer system. The OSI survey investigation was designed with the intent of identifying and profiling the significant Relic Channel Cut and Fill (*RCCF*) features underlying the navigation channel between Savannah River Stations 30+000 and –30+000, the area deemed most significant by the ACOE. These data will provide a means for locating future borings within the *RCCF* features to better understand their importance and to evaluate whether they provide a more direct migration pathway to the underlying aquifer. Separate studies, designed by the ACOE, conducted by others, are addressing other issues such as the composition and permeability of the fill sediments within the relic channel cut and fill features.

2.2 Summary of Field Survey & Equipment

Prior to OSI's mobilization and departure to Savannah, GA, a digital CAD drawing showing the proposed survey trackline layout was provided by the ACOE. This initial trackline layout consisted of two primary survey lines set along either edge of the navigation channel between Savannah River Stations 30+00 and -30+00. Upon arrival on-site, the OSI field team met with ACOE-Savannah District representative and project coordinator, Mr. Cardwell Smith. During this initial meeting, horizontal and vertical control stations were identified and project strategies and objectives were discussed. Mr. Smith remained with the OSI field team for the duration of the survey to provide direction and logistical support.

Following this meeting, the survey investigation was initiated by an OSI survey crew consisting of a geophysical specialist and navigator/geophysical technician. Survey operations were conducted from OSI's R/V "Parker", a 26-foot survey vessel equipped with an array of geophysical survey and support equipment. A Real Time Kinematic Differential Global Positioning System (RTK DGPS) receiver was installed on the survey vessel and interfaced with a radio link to a shoreside DGPS base station and an onboard computer. This integrated 3-dimensional precision positioning system provided the field team with the ability to navigate the survey vessel precisely along tracklines throughout the survey area and to correct soundings for tidal variation in real-time. The accuracy of the positioning system was verified daily by occupying known survey control monuments within the survey area provided by the ACOE. Survey investigations were performed in feet and are referenced to the Georgia State Plane Coordinate System, East Zone, GA-1001 (NAD83). Vertical reference for the project is ACOE mean low water (MLW). The DGPS base station was established at the outset of the survey investigation by the OSI crew on Point "CARD" located on Oyster Bed Island. The site was secure and its location provided a clear line of site to the entire survey area. The geographical coordinates and elevation of the point, as provided by the ACOE, are as follows:

Point	Latitude (WGS84)	Longitude (WGS84)	ACOE MLW Elevation
"CARD"	32° 02' 24.0049"	080° 53' 49.38506"	33.17'

A summary of the primary equipment installed on the survey vessel and employed to complete this investigation and its capabilities is presented in the following table. Equipment specification sheets are included in Appendix I.

Equipment	Equipment Function
Trimble 7400 MSi "OTF" Differential Global Positioning System (DGPS)	Real-time kinematic GPS, capable of providing centimeter level positioning accuracy. The system consists of two 7400MSi GPS receivers, GPS volute antennas and cables, RS232 output data cables, and Pacific Crest radio links to transfer differential corrections. Fully automated with OTF (on-the-fly) initialization, the Trimble 7400 MSi provides means for 9-channel simultaneous satellite tracking of L1 C/A code, L1/L2 full cycle carrier. One 7400MSi unit is mounted on the survey vessel and continuously receives differential satellite correction factors via radio link from the other 7400MSi receiver set as a reference station on a known horizontal control point onshore. The Trimble 7400 MSi accepts the correction factors relayed to it via radio link and applies these corrections to obtain continuous, high accuracy, real time position updates. The Trimble system is interfaced with an onboard data logging and navigation system for trackline control.
Modified version of Coastal Oceanographic's HYPACK ® MAX PC-based navigation and data-logging software package	Survey vessel trackline control was accomplished by using a computer-based navigation software package (Coastal Oceanographic's HYPACK ® MAX) in conjunction with the Trimble 7400 GPS receiver onboard the vessel. Vessel position data obtained from the GPS receiver, updated at 1.0-second intervals, were input into the navigation

Equipment	Equipment Function
(software package cont.)	computer system, which in real-time processed these data into the desired coordinate system (Georgia State Plane, East Zone (1001), NAD 83). While surveying, the incoming raw and processed position data are continuously logged onto the computer hard drive and displayed on a video monitor enabling the vessel's helmsman to guide the survey vessel accurately along proposed tracklines. Proposed survey tracklines, along with NOAA charts for the area, the locations of project control monuments, and other targets of project significance are projected onto the video monitor relative to the location of the survey vessel to aid the helmsman in maneuvering throughout the area.
Innerspace Model 448 digital depth sounder	Water depth measurements were obtained by employing an Innerspace Model 448 depth sounder with a 200 kHz. - 8° beam over-the-side mounted transducer. The Model 448 recorder provides precise, high-resolution depth records using a solid-state thermal printer as well as digital data output, which allows integration with the navigation software. The Model 448 also incorporates both tide and draft corrections plus a calibration capability for local water mass sound speed.
OSI 300-joule high resolution "Boomer" subbottom profiling system interfaced with a TSS 360 series shallow seismic processor/data logger and an EPC model GSP-1086 gray scale thermal printer.	Subsurface profiler that generates a high-energy acoustic pulse in the water column in the range of 400 Hz. - 8 kHz via towed transducer. The acoustic pulse generated propagates downward to the riverbed where it is partially reflected at the water-sediment interface. The balance of this signal continues into the bottom and is partially reflected at each successive subsurface interface (e.g. changes in sediment characteristics or rock surfaces). The boomer system is interfaced with a multifunctional digital processor (that provides a means to filter, enhance, and log the subbottom data set in SEG-Y format) and thermal graphic printer. Under ideal conditions the resolution of the subbottom "boomer" profiling system as configured during this survey is expected to be approximately 3 feet.

Hydrographic data were acquired concurrently with subbottom profiling along all tracklines investigated. Initially, data were acquired along the proposed tracklines established along each edge of the navigation channel between Savannah River Stations 30+00 and -30+00. Following acquisition and a brief field review of these data by the OSI geophysical specialist and the ACOE representative, a supplemental set of tracklines was established within the survey area. Supplemental tracklines were established in areas where subbottom data revealed the presence of prominent *RCCF* features. Supplemental tracklines were oriented both parallel and perpendicular to the course of the existing navigation channel and were variably spaced. In total, more than 50 survey lines (greater than 60-statute miles of tracklines) were investigated. Near the conclusion of the survey and at the request of the ACOE representative, two-reconnaissance tracklines were investigated outside the pre-designated survey site near historic ACOE boring locations. The first line was located in the

Bull River near the Bull River Marina and the second line was located in the Savannah River in the vicinity of Elba Island.

The following table provides a general chronology of events for the survey investigation.

Task	Dates	Task Description
Mobilization	10-11 February 2003	Survey crew and vessel depart Old Saybrook, CT and transit to Savannah, GA. Afternoon of 11 February survey crew launches vessel, prepares survey vessel and equipment on-site and meets with ACOE representative.
Establish GPS Base Station, Testing/ Tuning Survey Gear On-site	12 February 2003	Survey crew establishes GPS base station on Oyster Bed Island and performs verification checks to prove accuracy of the GPS positioning system. Check, test/tune survey gear on-site for operation and perform necessary calibrations.
Survey Operations	13-16 February 2003	Conduct survey operations. Acquire sounding and subbottom "boomer" profiling data along proposed and supplemental survey lines.
Survey Operations and Demobilization	17 February 2003	Survey investigation completed. Recover GPS base station, haul survey vessel, and demobilize vessel on-site for travel. Survey crew and vessel departs Savannah, GA and returns to OSI office Old Saybrook, CT.

2.3 Data Processing and Products

Following completion of the survey investigation, the acquired data sets were brought back to OSI's Old Saybrook, CT office for processing, interpretation and construction of data deliverables. Immediately upon return, an all-inclusive daily field log (presented in Appendix II) detailing survey lines investigated and their associated data file names (both HYPACK ® MAX and SEG-Y formats), and a survey trackline plot (Microstation CADD format) were generated. This log and plot were forwarded to the ACOE along with all project HYPACK ® MAX survey data files (raw and edited formats) and subbottom records (paper and SEG Y formats) as an interim deliverable prior to submittal of this report.

Subbottom profile data were reviewed and interpreted with the primary task of identifying the prominent *RCCF* features existing within the project area. Final data are presented in both plan and profile formats on OSI Drawing 04ES007.1-.2. Drawing 04ES007.1 presents an overview of investigated survey tracklines highlighting areas where the *RCCF* features were identified and representative profile sections were constructed. Included on this drawing are the limits of the existing navigation channel, Savannah River Stationing, the location of recent ACOE borings obtained in support of the project, and an aerial photograph of the project area. This drawing is presented at a horizontal scale of 1"=2,000'. OSI Drawing 04ES007.2, Sheets 1-3 are panel drawings which provide sets of profiles and plan view contour plots of: the riverbed, the *RCCF* features, and the upper surface of limestone, for each area where the *RCCF* features were identified. These latter drawing sheets are presented at a horizontal scale of 1"=600' and a vertical scale of 1"=60'. All project drawings are included in full scale in sleeves at the end of this report. A digital drawing file of each sheet, which is in Microstation CADD format, is presented in a digital appendix on a compact disc (CD) included with this report.

The following table summarizes the processing steps and deliverables associated with each of the acquired data sets.

Table of Data Processing Tasks and Project Deliverables

DATA SET	DATA PROCESSING TASK PERFORMED	DATA DELIVERABLE
Survey Tracklines	Survey tracklines were reconstructed and computer plotted from the x-y coordinates logged at each "fix" point using the HYPACK ® MAX software package. Once reconstructed on the computer, these tracklines were used for the subsequent task of interpretation and review of the acquired sounding and subbottom data. To aid in review, tracklines on which an *RCCF* feature was detected have been assigned an interpretive line number.	OSI Drawing 04ES007.1 presents an overview of survey tracklines investigated. Interpretive line number labels are included in the digital CADD drawing. These labels are presented on a separate layer, which has been turned off on the paper plot for display purposes.
Hydrographic	Hydrographic data were first checked against the sounding strip charts for verification of depth quality and then processed and corrected to project datum (based on correctors obtained via the kinematic GPS system) using the HYPACK ® MAX software package. These data were computer contoured at a 2-foot interval using the software package “QuickSurf” Version 5.1 (Schreiber Instruments, Inc.) and used to construct continuous profiles along survey lines that identified *RCCF* features. Hydrographic data were also used in the task of referencing subbottom reflectors to project datum.	Processed hydrographic data for all survey tracklines are included in the digital OSI Drawing 04ES007.1 on a layer turned off for display purposes. Plan view hydrographic contours and constructed profile sections for areas where *RCCF* features were identified are included on OSI Drawing 04ES007.2, Sheets 1-3.

DATA SET	DATA PROCESSING TASK PERFORMED	DATA DELIVERABLE
Subbottom Reflection	Subbottom “Boomer” reflection data (SEG Y files) were processed and enhanced using ReflexW, version 3.0 - a Windows based modular software package by Sandmeier Software (Karlsruhe, Germany). Subbottom records revealed evidence of numerous continuous and semi-continuous subsurface acoustic reflectors that could be confidently mapped and tied directly to horizons/stratigraphic units identified in ACOE borings. An overview table was constructed to summarize comparisons made between subbottom reflectors and units identified in the ACOE borings.	Summary table comparing ACOE boring units and subbottom reflectors (Appendix III).
	Subbottom reflectors correlative with the base of the *RCCF* features and the upper surface of the limestone (Floridan Aquifer) have been interpreted and traced (picked) for each subbottom profile using the ReflexW program. Reflector “picks” were adjusted for sensor offsets (relative to the GPS antennae), converted to thickness (based on an average acoustical velocity of 5,300 ft/sec for the nearsurface sediments), pasted into an EXCEL format spreadsheet and referenced to the project vertical datum. Considering the resolution of the boomer subbottom profiler and the ability to accurately reference reflectors to the project vertical datum (based on an assumed average acoustic velocity), the accuracy of the presented “picks” is approximately +/-10% the mapped depth of the reflectors.	Interpretive subbottom profiles highlighting subbottom reflector “picks” correlative with *RCCF* features and the upper surface of limestone (Appendix IV). Subbottom “pick” files constructed in EXCEL format are presented in the digital appendix included on a CD presented with this report.
	A master table was constructed that summarizes the subbottom interpretation on an area and line-by-line basis. Included in this master summary table are: field run and interpretive line designations, the SEG-Y and interpretive “pick” file names, summaries of the base depth of the *RCCF* features and upper limestone surface, ACOE boring tie information, and thickness estimates of sediment between the base of the *RCCF* features and the top of the limestone.	Master summary table of relic channel cut and fill features and limestone (Appendix III).
	Similar to hydrographic data, depths to the base of the *RCCF* features and the top of limestone (relative to MLW) have been computer contoured at a 2-foot interval using the QuickSurf program. (In some cases, data acquired along cross-river survey tracks were removed from the data set prior to computer contouring, in order to generate a more aesthetically pleasing contour plot). Based on this information representative subbottom profiles have been constructed for each of the prominent *RCCF* features identified.	Depths to the base of the *RCCF* features and the top of limestone are included in the digital CADD Drawing 04ES007.1. These depths are presented on separate layers, which have been intentionally turned off on the paper plot for display purposes. Plan view contours of the *RCCF* features and the top of limestone and representative subbottom profiles are included on OSI Drawing 04ES007.2, Sheets 1-3.

Data acquired in the Bull River and in the Savannah River near Elba Island were included in the interim deliverable. These data have not been processed or interpreted and subsequently are not discussed herein as it is beyond the scope of this current analysis.

3.0 SUBBOTTOM DATA ANALYSIS AND DISCUSSION

3.1 Overview

Subbottom profiling records revealed evidence of numerous continuous and semi-continuous subsurface acoustic reflectors that could be confidently mapped. Since the primary focus of the investigation was to identify the significant *RCCF* features in the survey site and provide data to help the ACOE evaluate the impact that deepening the navigation channel might have on the Upper Floridan Aquifer system, only those reflectors correlative with the base of the *RCCF* features and the upper surface of the aquifer (limestone) have been mapped. In almost all cases, the thickness of recent sediment deposits in the channel was minimal or absent, and therefore was not included in the mapping. It is believed that natural erosional processes in the river and/or maintenance dredging of the current navigation channel have removed the recent deposits.

Several survey tracklines were run directly over historic ACOE boring locations in an effort to groundtruth the subbottom data set and accurately tie relevant reflectors to specific horizons/stratigraphic units. Subbottom data were reviewed and compared closely with ACOE boring logs. (Boring logs provided by the ACOE are not included with this report). Under ideal conditions, the expected resolution of the subbottom profiling system utilized during this investigation is approximately three feet. This margin of error was taken into account when comparing core data with subbottom records. A table provided in Appendix III presents comparisons between contacts documented in the borings and acoustic reflectors observed on the subbottom records. Based on these comparisons an average acoustical velocity of 5,300 feet/second was found to best represent the sediments in the river overlying the Upper Floridan Aquifer.

Subbottom reflectors could be traced for appreciable distances along survey lines throughout the majority of the area investigated. Therefore, correlations between subbottom reflectors and specific horizons/stratigraphic units identified in the ACOE borings could be confidently correlated over large areas. Figure 2 provides a section of a subbottom "boomer" profile record that exemplifies some of the more prominent reflectors observed during the investigation and illustrates an area where a relic stream had incised the Miocene sediment sequence and was later filled in. The reflectors identified in the profile could be confidently traced back to an ACOE boring, based on ties with intersecting survey lines. Four prominent subbottom reflectors have been identified and color-coded on Figure 2. The red and blue reflectors represent the base of the *RCCF* feature and the upper surface of the Floridan Aquifer (limestone), respectively. The yellow reflector appears to relate to a contact within the Miocene sediments and the green reflector is believed to correlate with a deep contact within the Floridan Aquifer. In several sections of subbottom data, orange has been used to

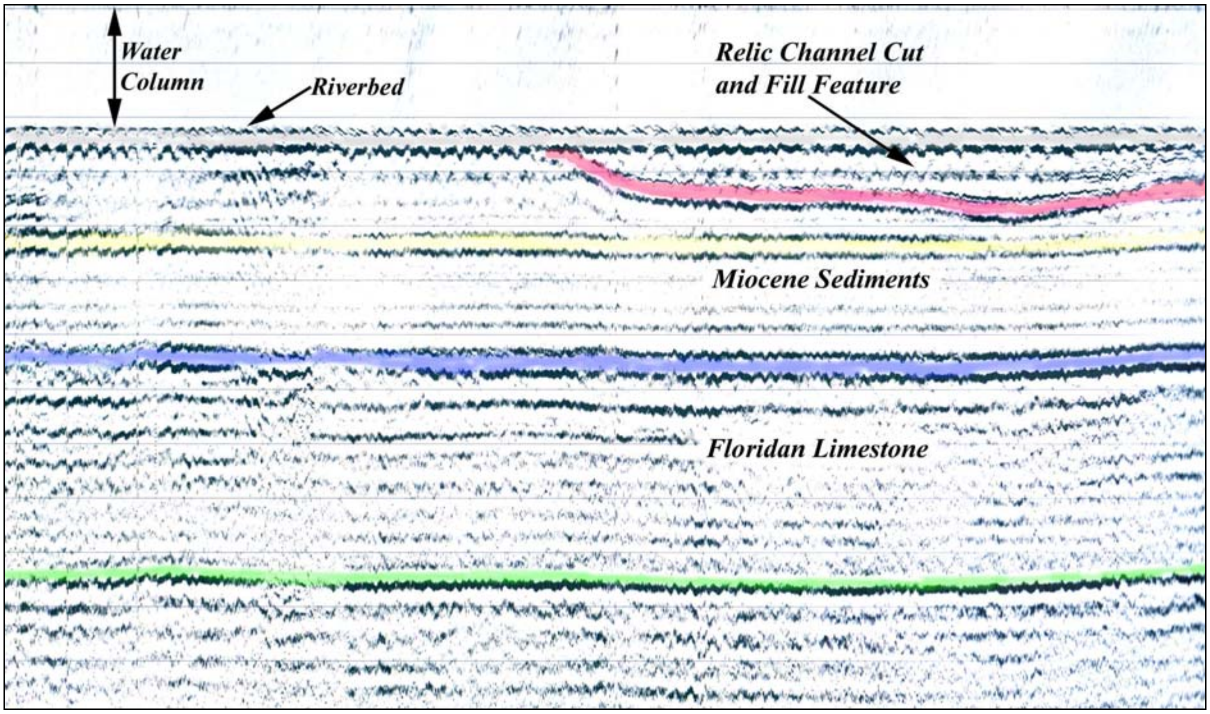


Figure 2 – Figure 2, a reproduced section of subbottom "boomer" profile record acquired during the investigation that exemplifies some of the more prominent reflectors observed.

differentiate reflectors correlative with the base of a younger *RCCF* feature identified adjacent to or traversing the primary or red-coded *RCCF* feature detected in an area (not illustrated in figure 2). The color scheme of reflectors and their relationship to specific horizons/stratigraphic units mentioned above are consistent in the figures and profile sections presented throughout this report and in the project drawings.

3.2 Summary of Identified Relic Channel Cut and Fill Features

Subbottom profiling data acquired during the current survey confirmed the existence of several *RCCF* features within the Savannah River Entrance Channel previously identified and revealed the presence of several additional *RCCF* features that had not yet been identified during previous investigations of the river. Eight of these features appear to be significant in size, underlie the navigation channel, and warrant further discussion regarding their potential impact to the project. The remaining *RCCF* features identified between Savannah River Station 30+000 and –30+000 were detected along only a single survey line and/or along survey lines located outside the navigation channel. The significant *RCCF* features detected during the current investigation are referred to as *RCCF 1-8* and are centered on the following Savannah River Stations summarized below:

- *RCCF 1* - Station 22+000
- *RCCF 2* - Station 20+000
- *RCCF 3* - Station 15+000
- *RCCF 4* - Station 9+000
- *RCCF 5* - Station 1+500
- *RCCF 6* - Station -3+000
- *RCCF 7* - Station -11+000
- *RCCF 8* - Station -21+000

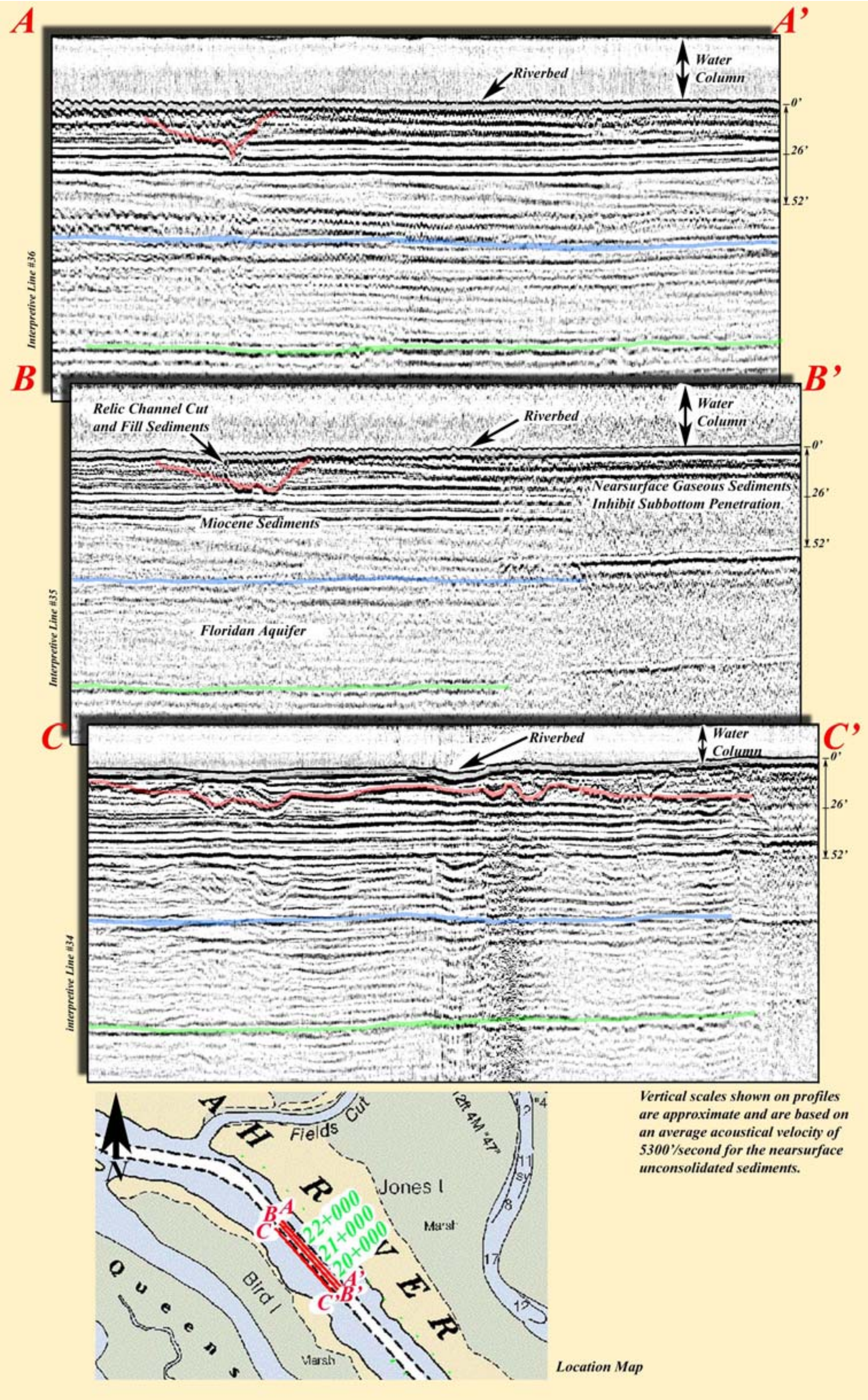
Appendix III provides a master summary table, which presents the maximum depths (relative to MLW) that the *RCCF* features have incised into the Miocene sediments, the interpreted depth of the upper surface of limestone underlying the identified features, and the calculated thickness of sediment between the two interfaces on a survey line-by-line basis. These summaries are provided for each identified *RCCF* feature and are based on the subbottom "pick files" included in the digital appendix of this report. Refer to the "pick files" (EXCEL format) for a more detailed data presentation. Note in the "pick files" and on the project drawings, red and orange-coded *RCCF* features have not been differentiated from one another.

Subbottom penetration was restricted or partially restricted along several segments of the tracklines investigated during the current survey. In general, this restriction was intermittent and attributed to the presence of trapped gas bubbles within the nearsurface sediments. The gaseous manifestations, interpreted to be a by-product of the breakdown of organics originating in the sediments of paleo-estuarine environments, significantly reduce the level of acoustic signal propagation through the sediment. This reduction in signal propagation adversely affects the ability of the subbottom profiler to identify underlying subsurface acoustic reflectors. Other phenomena that might have been responsible for inhibiting the subbottom profiler from resolving reflectors at depth are changes in sediment type, compaction, lithification and/or recent dredging/disturbance of the surficial sediments.

The following sections present a synopsis of findings for the significant *RCCF* features identified underlying the Savannah River Entrance Channel (progressing from up-to-downriver). Refer to the associated OSI project drawings, interpretive profiles, tables, and digital "pick" files presented with this report while reviewing the following sections.

3.2.1 *RCCF 1 and RCCF 2* (OSI Drawing 04ES007.2, Sheet 1)

Two *RCCF* features were detected between River Stations 22+000 and 20+000 (*RCCF 1 and RCCF 2*, respectively). The detected *RCCF* features appear to be related as subbottom data acquired along a survey trackline that passed through both areas traced a common subbottom reflector at the base of both *RCCF* features. Both features are primarily located along the southern side of the navigation channel and do not appear to span across the navigation channel. *RCCF 1* appears to extend further into the channel than *RCCF 2* and is better defined. Nearsurface gaseous sediments encountered on the downriver side of *RCCF 2* made it difficult to assess whether the feature actually extends underneath the navigation channel. Neither of the features incise very deeply into the Miocene sediment sequence (-80’ and -64’ MLW for *RCCF 1 and RCCF 2*, respectively). Minimum thickness of sediment recorded below the *RCCF* features and above the upper surface of limestone was 36 and 55 feet, respectively. Figure 3 shows three sections of subbottom data that represent the two detected RCCF features, the reflector that ties the two features together, and identifies the area of nearsurface gaseous sediments that hindered the mapping near Station 20+000. Note the reflector correlative with the upper surface of limestone underlying both of these areas is generally weak and flat-lying and exists at approximately –116’ MLW. The reflectors association with the upper limestone surface is based on information obtained downriver from ACOE boring 11 (located near Station 15+000).



Vertical scales shown on profiles are approximate and are based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

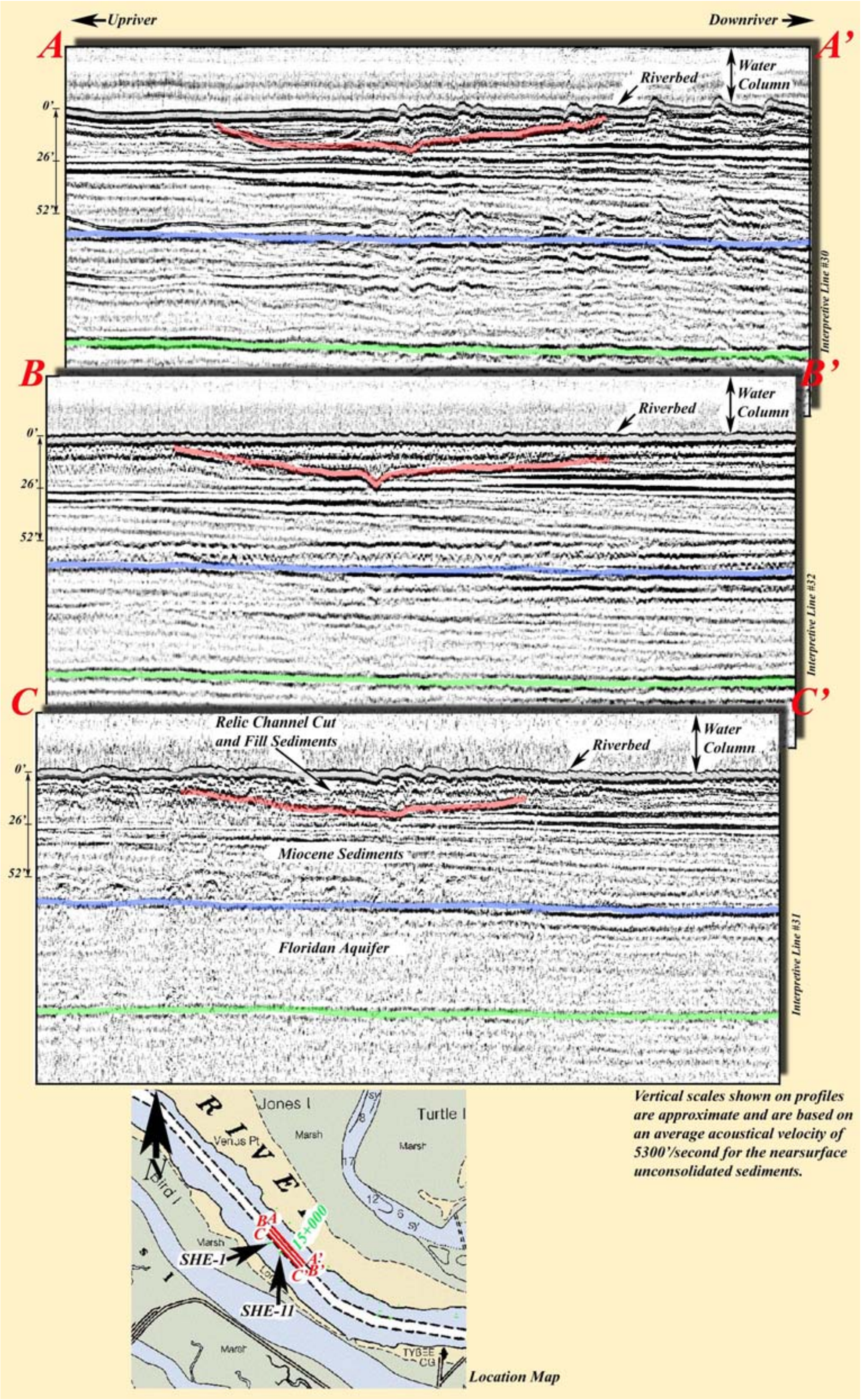
Figure 3 – Representative subbottom profiles of *RCCF* features identified between Savannah River Stations 22+000 and 20+000.

3.2.2 *RCCF 3* (OSI Drawing 04ES007.2, Sheet 1)

RCCF 3 detected in the vicinity of Station 15+000, is one of the better examples of a cut and fill feature recognized during the investigation. The *RCCF* feature detected in this area extends across the channel and was profiled along both the north and south offset survey lines and all lines in-between. ACOE borings SHE-11 and SHE-1, located within and nearby the *RCCF* feature, respectively, correlated well with the presented interpretation. This *RCCF* feature appears to reach approximately -74' MLW, although in the channel it appears to be closer to –70' MLLW. The minimum thickness of Miocene sediments observed between the base of the *RCCF* feature and the top of limestone is 42 feet. The upper surface of limestone was detected at approximately –112 MLW throughout the area. Figure 4 provides three examples of subbottom data which best represent the detected *RCCF* feature in the vicinity of Station 15+000.

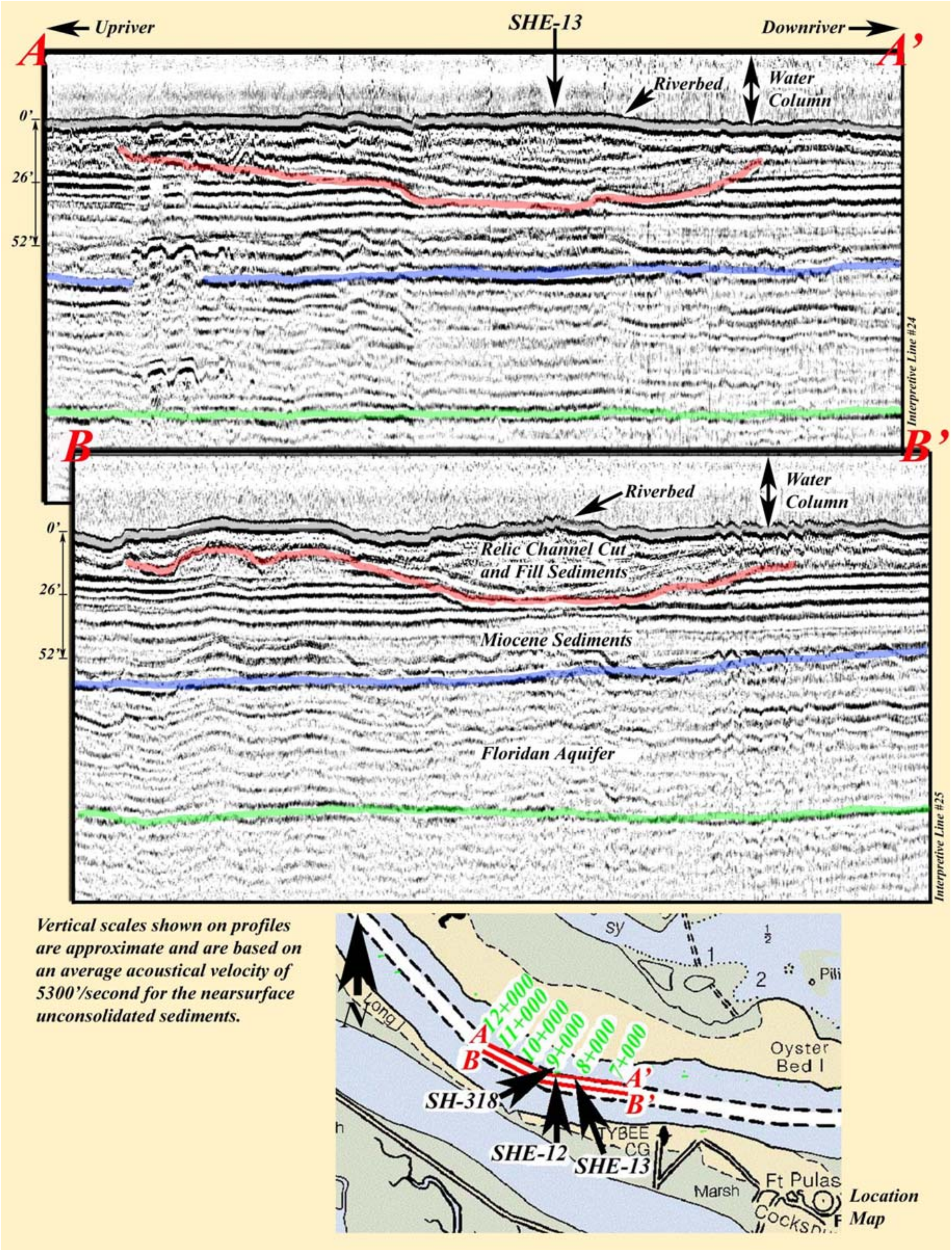
3.2.3 *RCCF 4* (OSI Drawing 04ES007.2, Sheet 2)

RCCF 4, detected between Stations 7+000 and 12+000, extends over a much larger area than any of the other *RCCF* features identified during this investigation. The feature, somewhat complex in shape, underlies most of the navigation channel in this area, but appears to have incised most deeply (approximately -83' MLW) on the north side of the channel in the vicinity of Station 8+500. The minimum thickness of Miocene sediments observed below the base of this *RCCF* feature and above the top of limestone is approximately 26 feet. In the area where the *RCCF* feature was detected, the upper surface of limestone appears to fluctuate around –108' MLW. Nearsurface gaseous sediments inhibited subbottom penetration along sections of the north and south offset survey lines in this area. ACOE borings SHE-12, SHE-13, and SH-318 were all acquired within the area where the *RCCF* feature was detected. Unfortunately, SHE-12 and SH-318 were shallow borings and did not penetrate deep enough to sample sediments and/or the limestone below the *RCCF* feature. Fortunately SHE-13 penetrated through the *RCCF* feature and encountered the upper limestone surface. Horizon depths correlate well with the subbottom profiler data. In figure 5, two representative sections of subbottom data acquired between Stations 7+000 and 12+000 best represent the identified feature.



Vertical scales shown on profiles are approximate and are based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

Figure 4 – Representative subbottom profiles of *RCCF* feature identified in the vicinity of Savannah River Station 15+000.



Vertical scales shown on profiles are approximate and are based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

Figure 5 – Representative subbottom profiles of *RCCF* feature identified in between Savannah River Stations 7+000 and 12+000.

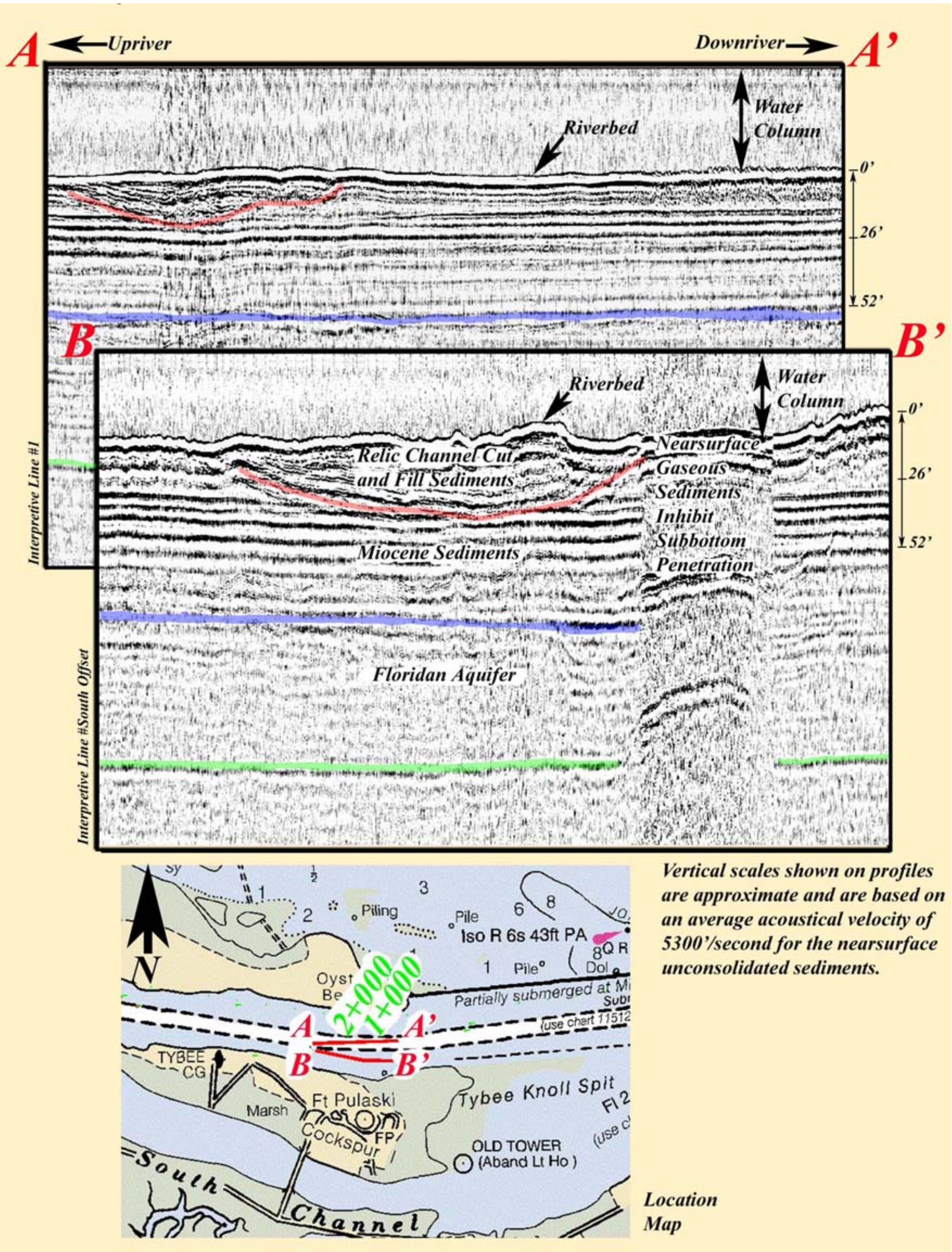
3.2.4 *RCCF 5* (OSI Drawing 04ES007.2, Sheet 2)

The *RCCF* feature detected between Stations 1+000 and 2+000 is one the smallest significant *RCCF* features profiled during the investigation. The feature appears to extend across much of the navigation channel but is most pronounced along its southern edge. This *RCCF* feature has incised in this area to approximately -70’ MLW. The minimum thickness of Miocene sediments observed below the base of the *RCCF* feature and above the top of limestone is 38 feet. The upper surface of limestone (based on correlations made with ACOE boring SHE-14) was detected at approximately -107’ MLW. Figure 6 illustrates subbottom data that best represent the detected *RCCF* feature in this area. Note that the two subbottom sections representing the feature were acquired along the southern side of the navigation channel.

3.2.5 *RCCF 6* (OSI Drawing 04ES007.2, Sheet 2)

The *RCCF* feature detected at Station -3+000 is a well-defined subsurface feature that extends across the river and was mapped on all survey lines collected in the area. This feature, in comparison with all other *RCCF* features detected during the current investigation, is probably the best example of a preserved relic channel cut and fill feature imaged by the subbottom profiler. On the southern side of the navigation channel subbottom profiler data show a younger relic channel incising the primary *RCCF* feature identified. Figure 7, a fence diagram that was constructed based on subbottom data acquired along a longitudinal and a cross-river survey track in the area, identifies both the primary (shaded red) and younger *RCCF* features (shaded orange).

The subbottom profiler revealed numerous flat-lying reflectors underlying the *RCCF* feature. ACOE boring SHE-14, drilled on the northern side of the navigation channel within the *RCCF* feature, provided the necessary information to identify which reflector correlates with the upper surface of limestone. A second ACOE boring, SH-327, was also drilled within this

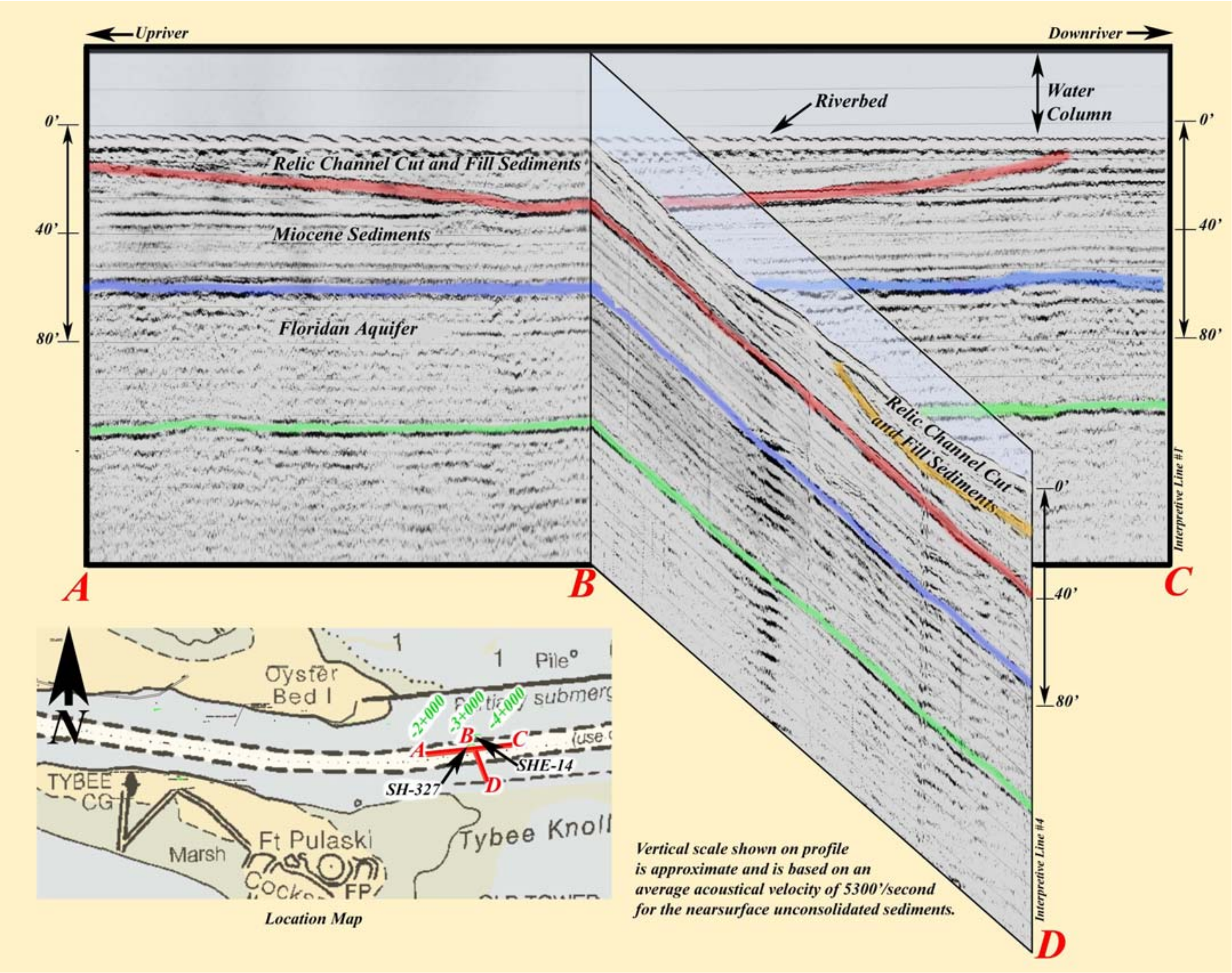


Vertical scales shown on profiles are approximate and are based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

Figure 6 – Representative subbottom profiles of *RCCF* feature identified between Savannah River Stations 1+000 and 2+000.

RCCF feature. However, SH-327 was a shallow boring and did not penetrate deep enough to sample sediments and/or the limestone below the *RCCF* feature.

The maximum the *RCCF* feature appears to have incised in this area is to approximately -70' MLW. The minimum thickness of Miocene sediments observed below the base of the *RCCF* feature and above the top of limestone is approximately 28 feet. Subbottom data suggest that the upper surface of limestone lies at approximately –98' MLW in this area.



Vertical scale shown on profile is approximate and is based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

Figure 7 – Constructed subbottom profile sections of *RCCF* features identified between Savannah River Stations -2+000 and -4+000. Note the second *RCCF* feature incising the primary *RCCF* feature in the B to D profile.

3.2.6 *RCCF 7* (OSI Drawing 04ES007.2, Sheet 3)

The *RCCF* feature detected between Stations -9+000 and -13+000 is a complex feature that extends across the river between the north and south offset tracklines. On the north side of the channel, the feature is actually comprised of two cut and fill features juxtaposed on one another. Figure 8, a representative profile constructed from three subbottom profile sections acquired in the area, illustrates the relationship between the two identified *RCCF* features. Note that it appears that the *RCCF* feature shaded orange in the figure, identified on the north side of the channel, has actually incised the *RCCF* feature shade red that extends across the river from the south.

Nearsurface gaseous sediments reduced subbottom penetration and made it difficult to trace reflectors along several survey tracklines in the area. However, successful subbottom penetration attained on adjacent tracklines provided the data necessary to construct the representative contour plots of the *RCCF* feature and top of limestone. Figure 9, provides the four primary sections of subbottom data used as the basis to construct the contour plots and representative profile of the area.

The maximum the *RCCF* feature appears to have incised in this area is to approximately -67' MLW. The minimum thickness of Miocene sediments observed below the base of the *RCCF* feature and above the top of limestone is 34 feet. The upper surface of limestone in the area was detected between approximately -94 and -105' MLW. ACOE boring SHE-3, located downriver from the identified *RCCF* feature (near Station –14+500), was the principal boring used to reference subsurface reflectors to specific horizons. Since the current survey investigation did not have any tracklines that passed over the SHE-3 boring location, subbottom data acquired during the 1997 OSI survey of the river was used to make this cross-correlation.

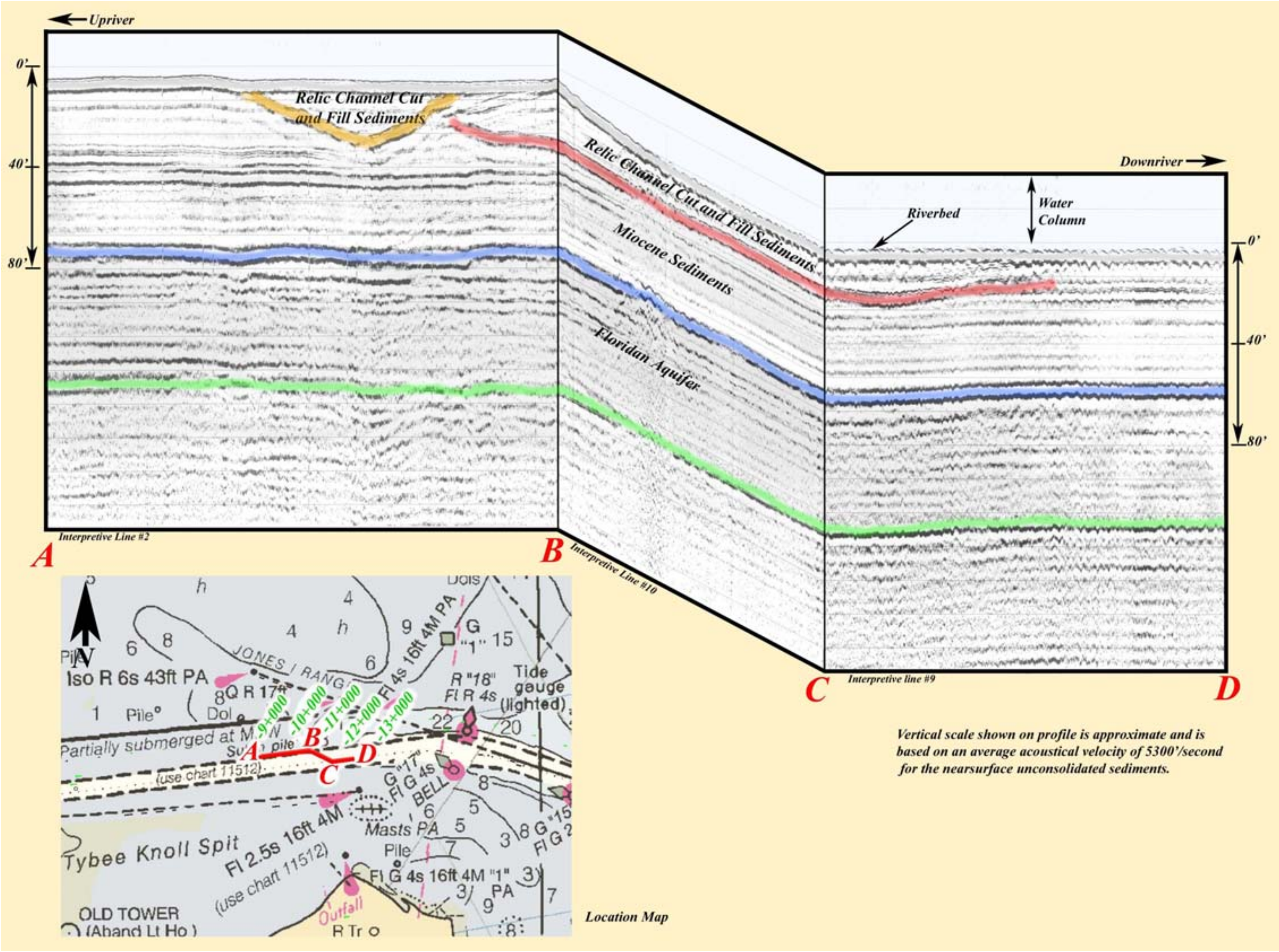
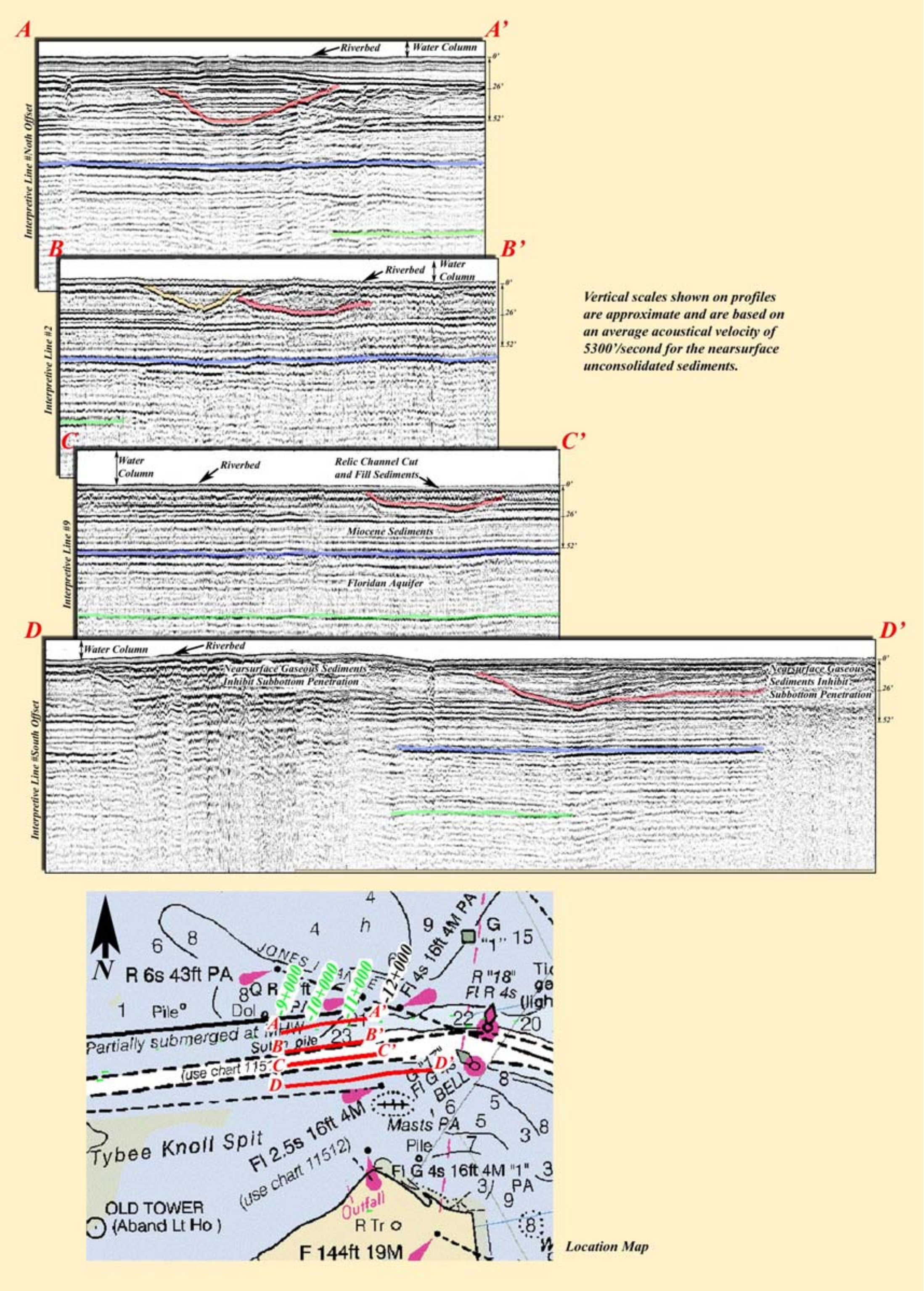


Figure 8 – Constructed subbottom profile sections of *RCCF* features identified between Savannah River Stations -9+000 and –13+000. Note the second *RCCF* feature incising the primary *RCCF* feature in the A to B section.



Vertical scales shown on profiles are approximate and are based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

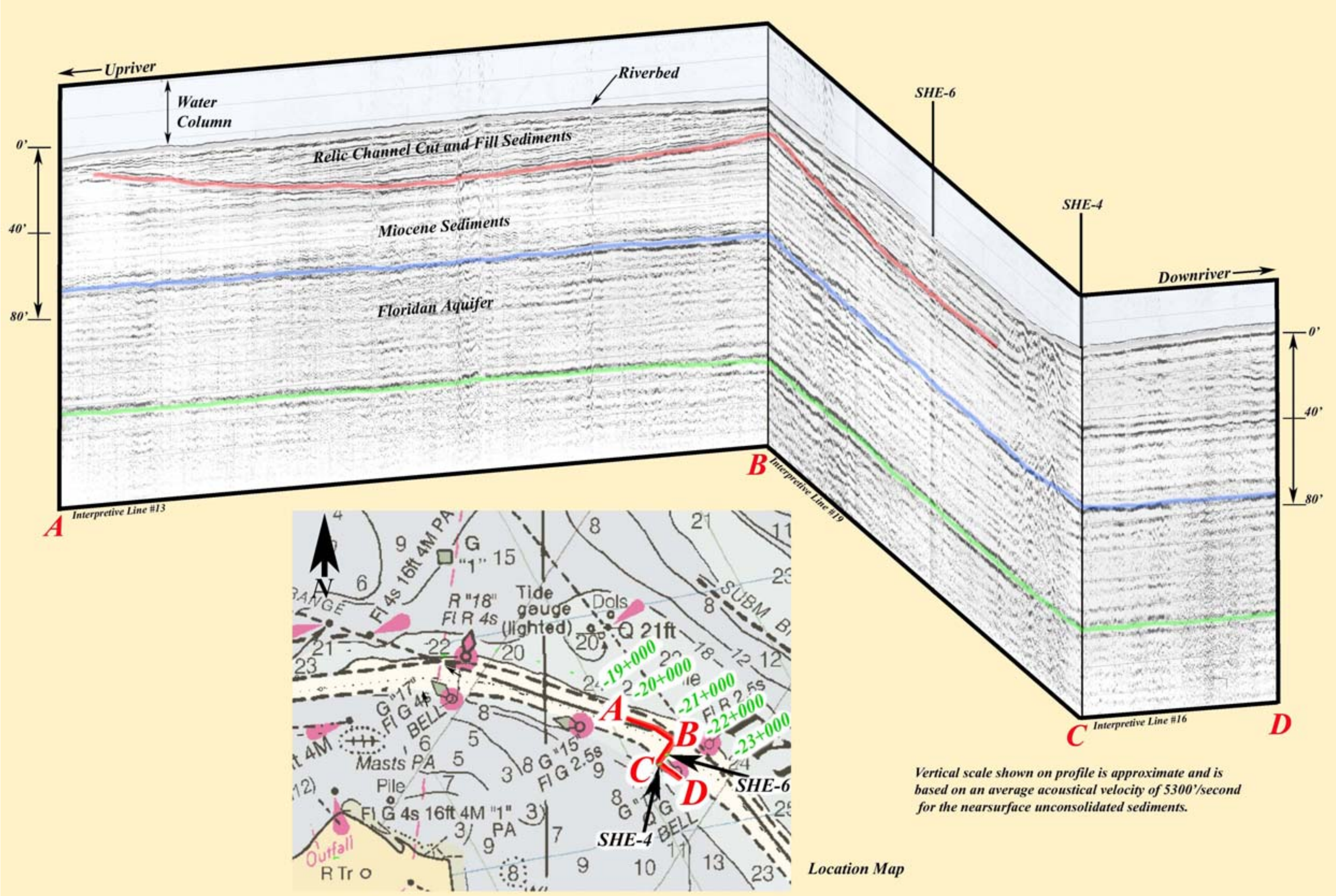
Figure 9 **–** Representative subbottom profiles of *RCCF* feature identified between Savannah River Stations -9+000 and -13+000.

3.2.7 *RCCF 8* (OSI Drawing 04ES007.2, Sheet 3)

The *RCCF* feature detected between Stations –19+000 and -23+000 is the second largest *RCCF* feature identified during this investigation (second only to *RCCF 4* identified between Stations 7+000 and 12+000). The feature appears to extend across the river and was detected underlying both the north and south offset survey lines and all lines between. A review of subbottom data suggests a reworking of the nearsurface sediments in the area. This reworking is more pronounced in an offshore direction and in some areas appears to have masked detection or removed the downriver side of the *RCCF* feature. Several minor pockets of nearsurface gaseous sediments were also observed in the area where the *RCCF* feature was detected, but their presence did not adversely impact the interpretation.

Two ACOE borings were drilled in the vicinity of the *RCCF 8* feature. ACOE boring SHE-4 was located just outside the southern edge of the navigation channel and was drilled to the underlying limestone. This boring formed the basis for identifying the reflector correlative with the upper limestone surface in the area. A second ACOE boring, SHE-6, located just inside the southern edge of the navigation channel and within the *RCCF* feature, provided data to characterize the sediments in the feature, but was a shallow boring and did not penetrate deep enough to sample sediments and/or the limestone below the *RCCF* feature. Figure 10, a representative fence diagram constructed from three subbottom profile sections acquired in the area, illustrates the *RCCF 8* feature and identifies the location of the two ACOE borings drilled in the area.

The maximum the *RCCF* feature appears to have incised in this area is to approximately -73’ MLW. The minimum thickness of Miocene sediments observed below the base of this *RCCF* feature and the top of limestone is 36 feet. In the area where the *RCCF* feature was detected, the upper surface of limestone appears to fluctuate around -110’ MLW.



Vertical scale shown on profile is approximate and is based on an average acoustical velocity of 5300'/second for the nearsurface unconsolidated sediments.

Figure 10 – Constructed subbottom profile sections of *RCCF* features identified between Savannah River Stations -19+000 and –23+000. Note the locations of the two ACOE borings accomplished in the area; SHE-4 was used to identify the limestone reflector.

4.0 SUMMARY

A major source of fresh water for the Savannah area is the Floridan Aquifer. The Aquifer is a porous limestone that underlies a sequence of unconsolidated sediments in the Savannah River. The ACOE-Savannah District is charged with maintaining the Savannah River Entrance Channel and is considering deepening the channel. As part of the overall project the ACOE needs to assess the impact dredging would have on the Aquifer underlying the river.

Previous geophysical surveys have identified relic stream channels located beneath the Savannah River. These features, underlying the entrance channel (between Savannah River Stations 30+000 and –30+000), incise a sequence of Miocene-age sediments that serve as the Floridan Aquifer’s confining unit. If these relic stream channel cuts were in-filled by higher permeability sediments (than those comprising the confining unit), then deepening the channel might result in a more direct migration pathway for saltwater intrusion to the underlying aquifer system than currently exists. The geophysical survey described herein was designed to identify (by means of a high-resolution subbottom profiler) all of the significant relic stream channel features within the survey area. Separate studies, designed by the ACOE, conducted by others, are addressing other issues such as the composition and permeability of the fill sediments within the relic channel features. Detailed comparison of sedimentary composition is therefore not included in this report.

Subbottom profiling data acquired during the current investigation confirmed the presence of several previously identified relic channel cut and fill (*RCCF)* features in the entrance channel and identified several new features, which until this survey had not yet been recognized. In total, eight *RCCF* features that appeared significant were identified in the Savannah River Entrance Channel. The significant *RCCF* features detected during the current investigation are referenced as *RCCF 1-8.* For each of these areas, subbottom reflectors, correlative with the base of the *RCCF* features and the upper surface of the underlying limestone surface (Floridan Aquifier), have been referenced to project datum (MLW). These data formed the basis to construct the plan view contour plots and profiles included with this report. The thickness of recent sediment deposits overlying the *RCCF* features was minimal and/or not discernable by the subbottom profiler utilized during this investigation and hence is not represented on the contour plots or profiles. It is believed that natural erosional processes in the river and/or maintenance dredging of the current navigation channel have removed these deposits. The following table identifies the location of each of the *RCCF* features and summarizes the maximum incision depths of the features into the Miocene sediment sequence, the average depth at which limestone exists below the identified features, and the minimum thickness of sediment detected between the base of the *RCCF* features and the upper surface of the underlying limestone. Depths presented in the following table are based on the interpretation of subbottom profiling records. Considering the resolution of the boomer subbottom profiler and the assumptions made to convert raw subbottom data to depths referenced to the project vertical datum, the accuracy of the interpretation is approximately +/- 10% of the mapped depth of the correlative reflectors. This accuracy should be taken into account when reviewing the project and comparing depths in the following table.

Feature Designation	*Feature centered on approximate Savannah River Station*	*Maximum Incision depth of RCCF feature (MLW)*	*Average depth of upper limestone surface (MLW)*	*Minimum thickness of sediment detected between base of RCCF feature and upper limestone surface (Floridan Aquifer)*
RCCF 1	Station 22+000	-80’	-116’	36’
RCCF 2	Station 20+000	-64’	-116’	55’
RCCF 3	Station 15+000	-74’	-112’	42’
RCCF 4	Station 9+000	-83’	-108’	26’
RCCF 5	Station 1+500	-70’	-107’	38’
RCCF 6	Station -3+000	-70’	-98’	28’
RCCF 7	Station -11+000	-67’	-99’	34’
RCCF 8	Station -21+000	-73’	-110’	36’

As summarized in the preceding table, the *RCCF 4* feature appears to have incised more deeply into the Miocene confining unit than any of the other features detected in the entrance channel. This feature, detected between Savannah River Station 7+000 and 12+000, also impacts a much larger area than any of the other *RCCF* features identified.

In general, subbottom data suggest that the *RCCF* features identified in the entrance channel are oriented perpendicular to the present-day course of the river and maintain a general north-south orientation. These findings suggest that historic drainage patterns in the area differed significantly from present-day patterns and/or that survey trackline orientation may have played a role in the ability to detect the *RCCF* features. A large percent of survey tracklines (during the recent and past survey investigations of the river) were oriented parallel to the river's course. Survey tracklines oriented parallel to the river's course are more conducive to detecting features oriented perpendicular or oblique to the river's course. It is possible that *RCCF* features oriented parallel to the river's course and not within the boundaries of the limited cross-river survey tracklines investigated may not have been recognized or their presence may have been masked among other subsurface reflectors identified in the area. Future surveys might consider acquisition of subbottom data along a series of evenly spaced cross-river survey transects lines to supplement data acquired during this investigation.

Historic ACOE boring logs provided lithological descriptions for correlation with subbottom reflectors identified during the survey and enhanced the geophysical interpretation. Since the completion of this survey investigation, OSI has been in communication with the ACOE-Savannah District and has helped to identify areas where additional borings may be most useful to support the objectives of the project and further groundtruth the acquired subbottom data set. It is recommended that the results of any additional boring programs be reviewed with the subbottom data to further confirm the interpretation presented herein.

5.0 REFERENCES

Foyle, A.M., Henry Jr., V.J., and Alexander, C.R., 2001. The Miocene Aquitard and the Floridan Aquifer of the Georgia / South Carolina Coast: Geophysical Mapping of Potential Seawater Intrusion Sites, Georgia Department of Natural Resources Bulletin 132.

Ocean Surveys, Inc., 1998. Final Report Submitted to the U.S. Army Corps Of Engineers – Savannah District" Entitled "Geophysical Investigation, Savannah Harbor, Savannah, Georgia, OSI Report No. 97ES076.

U.S. Army Corps of Engineers, 1998. Savannah Harbor Expansion Feasibility Study, http://www.sysconn.com/harbor/Study%20Reports/1998%20Aquifer/98Aquifer.html.

APPENDIX I

EQUIPMENT SPECIFICATION SHEETS

Trimble

SURVEYING AND MAPPING PRODUCTS

7400MSi™

High precision real-time GPS receiver for dynamic control systems

Real-time centimeter guidance for a wide range of applications.

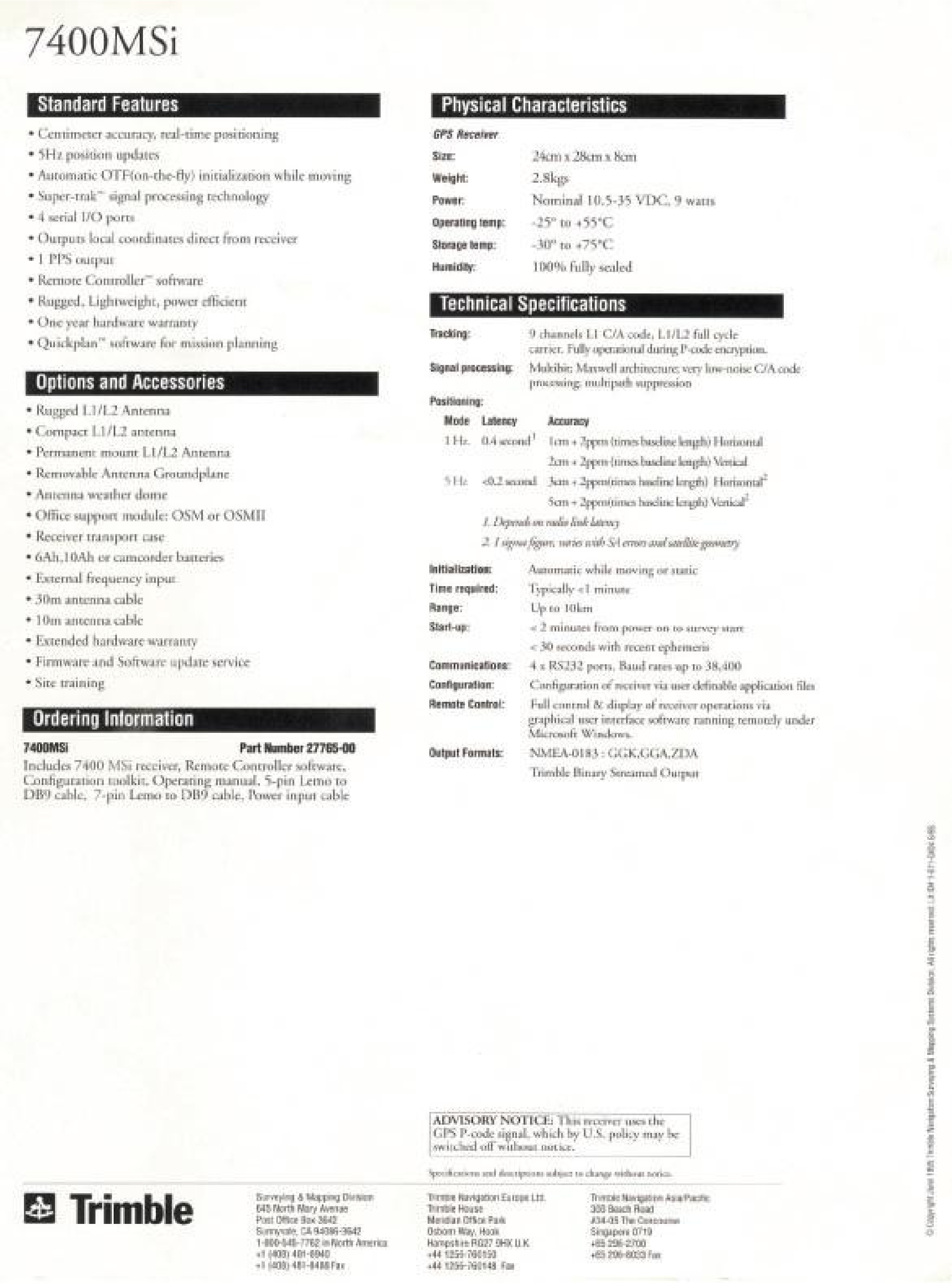
The 7400MSi is Trimble's fourth generation real-time kinematic (RTK) GPS system, representing major technological breakthroughs. It offers low-latency, fast-update centimeter accuracy positioning. Designed specifically for dynamic machine control applications, it is the most advanced GPS receiver available today.

Based on Trimble's field-proven RTK technology, the 7400MSi features fully automatic OTF (on-the-fly) initialization. Centimeter-level position updates are computed five times per second with a latency of less than 2/10ths of a second. This ensures the response and accuracy necessary for precise dynamic applications on moving equipment.

The 7400MSi delivers both performance and simple interfacing. The receiver is designed for reliable operation in construction, mining and other precise positioning environments. Trimble's Supertrak™ multibit GPS signal technology provides superior satellite tracking in the most adverse environments, including the presence of radio interference. Trimble's Maxwell GPS chip architecture enables the 7400MSi to provide sub-meter accuracy positions prior to initialization and rapid reliable initialization for centimeter accuracy on the move.

The 7400MSi provides a simple interface to PC-computers, external processing devices, or control systems via any one of its four serial ports. An easy-to-use application file interface enables a user to completely program the receiver operations with a single command. Real-time kinematic operation, the active coordinate system and all other receiver operations can be set using the application file interface or by the included Remote Controller software. The 7400MSi can be configured as an autonomous reference station or a roving unit. Streamed outputs are sent from the receiver to give detailed information which includes position, quality assurance data and GPS satellite information. Coordinates can be output in user-defined or pre-loaded datum and map projection reference frames.The receiver also includes a one pulse per second(1PPS) output for precise timing of other interfaced equipment.

The 7400MSi addresses a vast range of applications that include construction and mining equipment positioning, robotic equipment control, marine construction and hydrographic surveying.



7400MSi

Standard Features

- Centimeter accuracy, real-time positioning
- 5Hz position updates
- Automatic OTF(on-the-fly) initialization while moving
- Super-trak™ signal processing technology
- 4 serial I/O ports
- Outputs local coordinates direct from receiver
- 1 PPS output
- Remote Controller™ software
- Rugged, Lightweight, power efficient
- One year hardware warranty
- Quickplan™ software for mission planning

Options and Accessories

- Rugged L1/L2 Antenna
- Compact L1/L2 antenna
- Permanent mount L1/L2 Antenna
- Removable Antenna Groundplane
- Antenna weather dome
- Office support module: OSM or OSMII
- Receiver transport case
- 6Ah,10Ah or camcorder batteries
- External frequency input
- 30m antenna cable
- 10m antenna cable
- Extended hardware warranty
- Firmware and Software update service
- Site training

Ordering Information

7400MSi **Part Number 27765-00**

Includes 7400 MSi receiver, Remote Controller software, Configuration toolkit, Operating manual, 5-pin Lemo to DB9 cable, 7-pin Lemo to DB9 cable, Power input cable

Physical Characteristics

GPS Receiver

Size:	24cm x 28cm x 8cm
Weight:	2.8kgs
Power:	Nominal 10.5-35 VDC, 9 watts
Operating temp:	-25° to +55°C
Storage temp:	-30° to +75°C
Humidity:	100% fully sealed

Technical Specifications

Tracking: 9 channels L1 C/A code, L1/L2 full cycle carrier. Fully operational during P-code encryption.

Signal processing: Multibit; Maxwell architecture; very low-noise C/A code processing; multipath suppression

Positioning:

Mode	Latency	Accuracy
1 Hz.	0.4 second[1]	1cm + 2ppm (times baseline length) Horizontal 2cm + 2ppm (times baseline length) Vertical
5 Hz	<0.2 second	3cm + 2ppm(times baseline length) Horizontal[2] 5cm + 2ppm(times baseline length) Vertical[2]

1. Depends on radio link latency

2. 1 sigma figure, varies with S/A errors and satellite geometry

Initialization: Automatic while moving or static

Time required: Typically <1 minute

Range: Up to 10km

Start-up: < 2 minutes from power on to survey start
< 30 seconds with recent ephemeris

Communications: 4 x RS232 ports, Baud rates up to 38,400

Configuration: Configuration of receiver via user definable application files

Remote Control: Full control & display of receiver operations via graphical user interface software running remotely under Microsoft Windows.

Output Formats: NMEA-0183 : GGK,GGA,ZDA
Trimble Binary Streamed Output

ADVISORY NOTICE: This receiver uses the GPS P-code signal, which by U.S. policy may be switched off without notice.

Specifications and descriptions subject to change without notice.

Trimble

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Coastal Oceanographics, Inc.

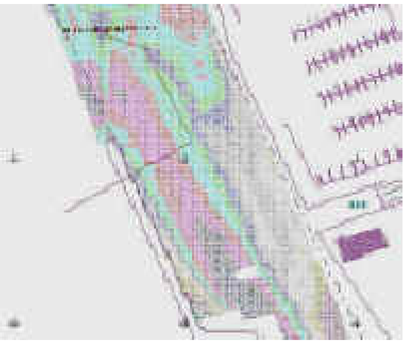
HYPACK® MAX

Hydrographic Survey Software

HYPACK® is PC-based Windows software for planning, conducting, editing and publishing hydrographic surveys. Read on for additional information about each of HYPACK®'s software modules.

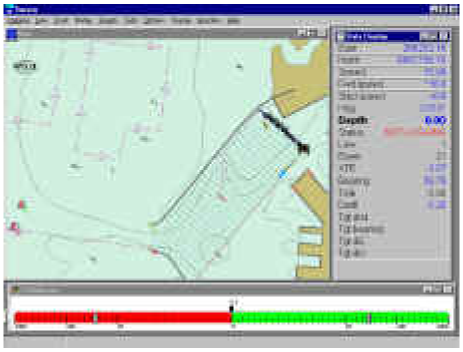
Design

HYPACK® MAX contains powerful tools that let you quickly design your survey and display your results. Its powerful drawing engine can display background files in DXF, DGN, TIF, S-57, BSB raster, C-Map, and VPF files at any rotation and scale. Design tools allow you to quickly create planned lines. HYPACK® MAX automatically stores your information to a project directory, allowing you to set up new surveys or to quickly switch to an existing survey. All of this in the easy drag-and-drop environment of Windows® 95, 98, or NT.



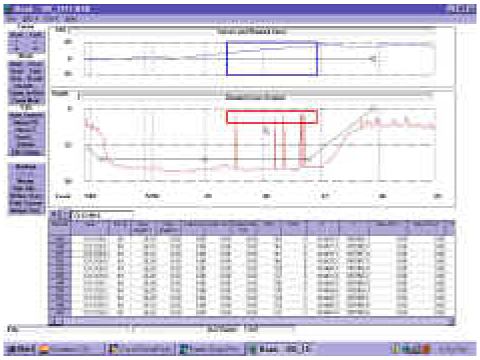
Survey

HYPACK® MAX's SURVEY program allows the flexibility and power needed to perform your work. It supports GPS, Range-Azimuth, and Range-Range navigation systems. It supports single beam, dual frequency, multiple transducer, and mulitbeam echosounders, along with gyros, magnetometers, telemetry tide gauges, and other survey devices. The SURVEY program can be configured to display and track single vessels, multiple vessels, or the main vessel and ROVs or towfish. Users can display the vessel positions against background files of DXF, DGN, TIF, S-57, BSB, C-Map, or VPF file format.



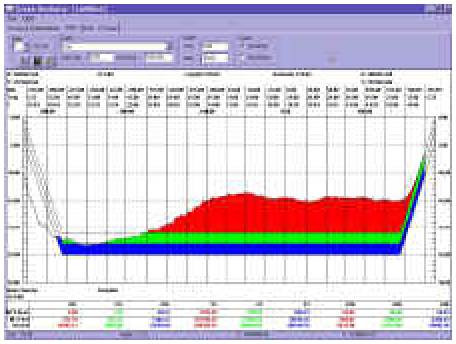
Editing

HYPACK® MAX's graphical editing routines allow you to quickly edit your survey data. Water level corrections can be automatically determined using RTK GPS water level techniques, telemetry tide gauges, manual observations, or downloaded from NOAA web sites. Sound velocity corrections can be applied. Users can quickly review and edit individual points or blocks of data. HYPACK® MAX's new "Field to Finish" process now allows you to automatically remove data spikes, perform final sounding selection, and generate smooth sheets or export info to CAD before you hit the dock.



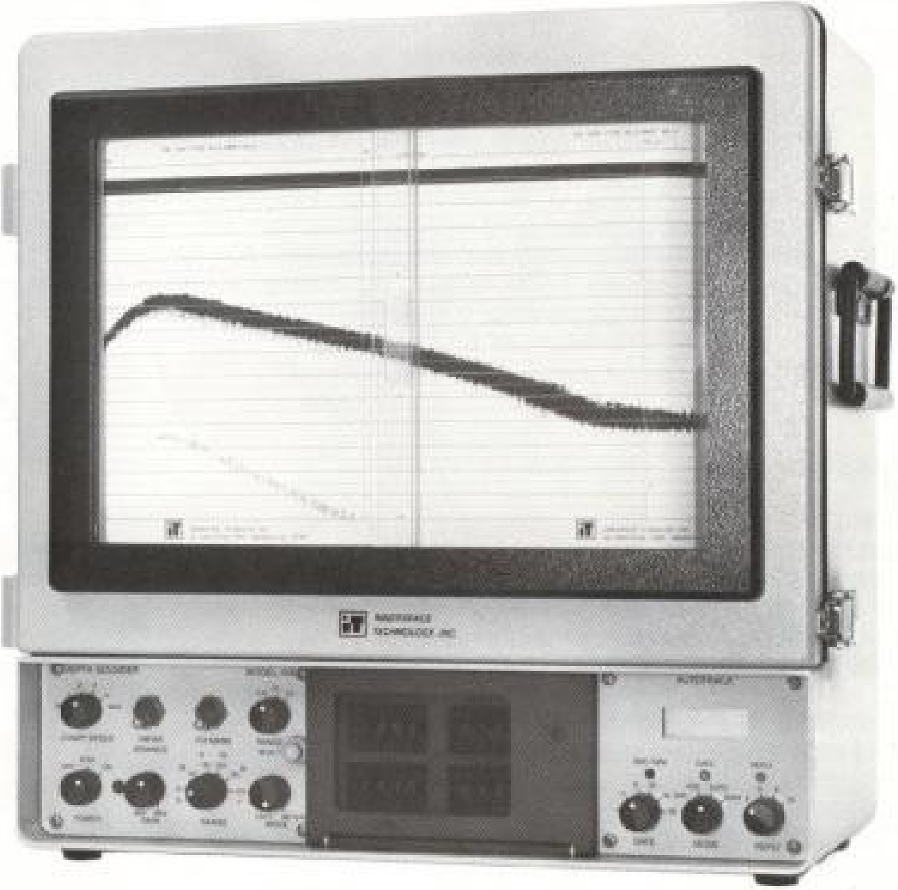
Final Products

What really puts HYPACK® MAX above the other hydrographic packages is the variety of final product programs. The Cross Section and Volume program is the standard used by the U.S. Army Corps of Engineers for calculation of dredge volume quantities throughout the USA. The Surface Modeling program generates 3-D models, contours, and also computes volumes between surfaces for beach erosion studies. The Export program allows users to import HYPACK® MAX data into CAD and GIS packages in either DXF or DGN format.



INNERSPACE

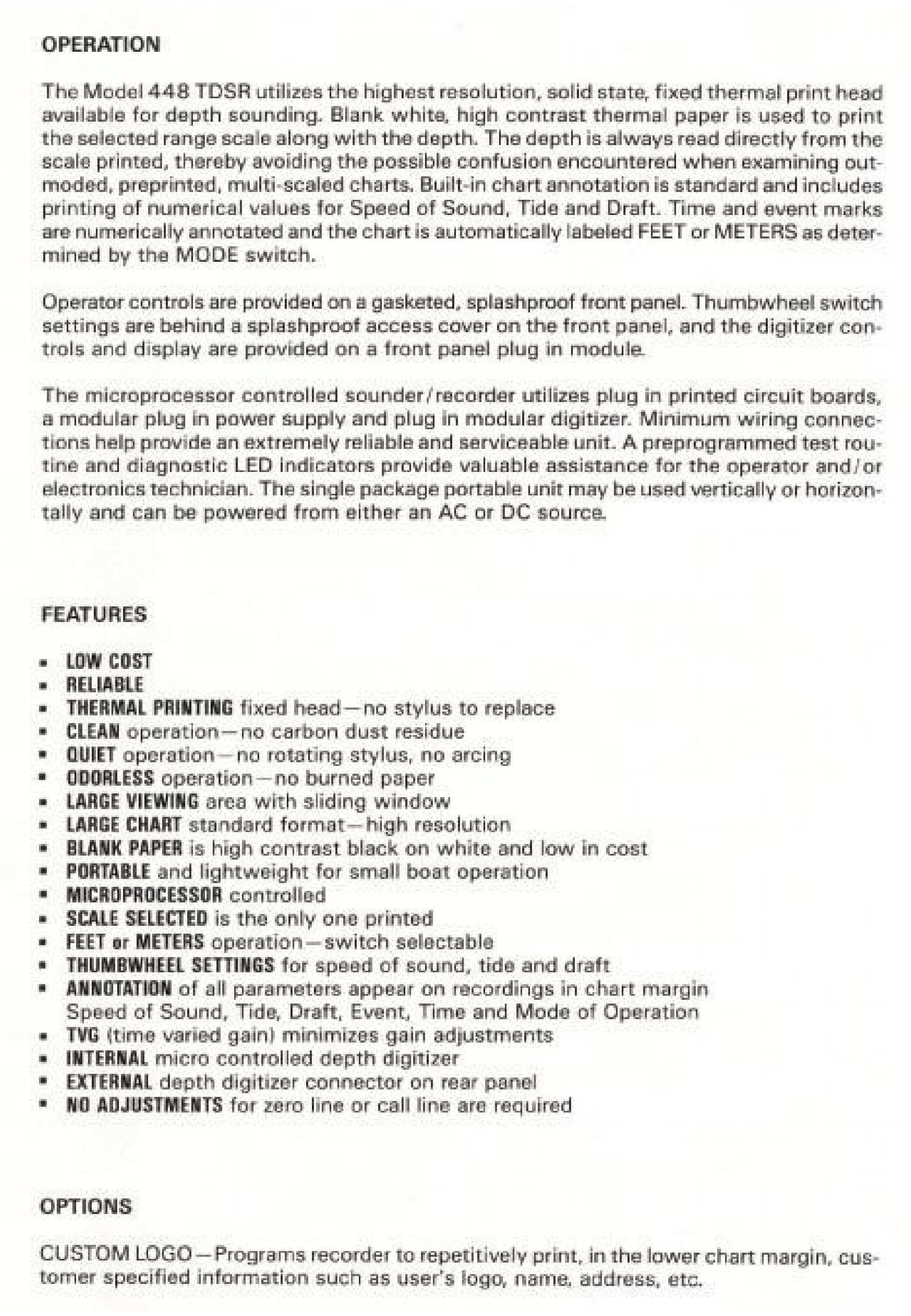
THERMAL DEPTH SOUNDER RECORDER
MODEL 448



DESCRIPTION

The Innerspace Technology Model 448 Thermal Depth Sounder Recorder provides survey precision, high resolution depth recordings using SOLID STATE THERMAL PRINTING. The lightweight, portable unit is designed for use in small boat surveying as required for nautical chart production, engineering surveys, harbor and channel maintenance, pre and post dredge surveys, etc. The Model 448 TDSR uses a thermal printing technique pioneered by Innerspace for depth sounding which provides the high resolution and accuracy required by groups such as the U.S. Army Corps of Engineers, dredging companies, survey companies, port administrations, etc. The state of the art design allows integration into portable hydrographic survey systems.

INNERSPACE TECHNOLOGY, INC.



OPERATION

The Model 448 TDSR utilizes the highest resolution, solid state, fixed thermal print head available for depth sounding. Blank white, high contrast thermal paper is used to print the selected range scale along with the depth. The depth is always read directly from the scale printed, thereby avoiding the possible confusion encountered when examining outmoded, preprinted, multi-scaled charts. Built-in chart annotation is standard and includes printing of numerical values for Speed of Sound, Tide and Draft. Time and event marks are numerically annotated and the chart is automatically labeled FEET or METERS as determined by the MODE switch.

Operator controls are provided on a gasketed, splashproof front panel. Thumbwheel switch settings are behind a splashproof access cover on the front panel, and the digitizer controls and display are provided on a front panel plug in module.

The microprocessor controlled sounder/recorder utilizes plug in printed circuit boards, a modular plug in power supply and plug in modular digitizer. Minimum wiring connections help provide an extremely reliable and serviceable unit. A preprogrammed test routine and diagnostic LED indicators provide valuable assistance for the operator and/or electronics technician. The single package portable unit may be used vertically or horizontally and can be powered from either an AC or DC source.

FEATURES

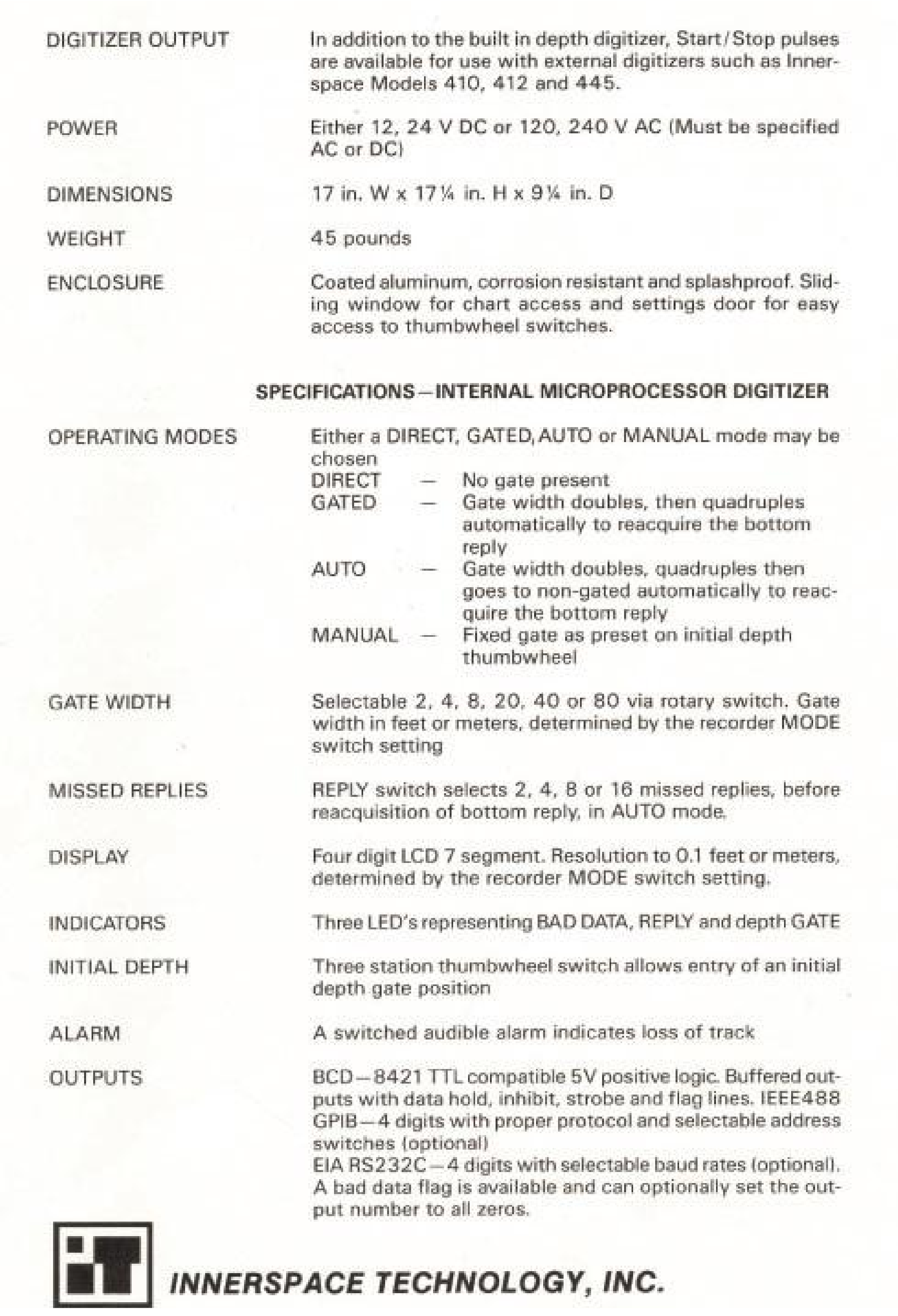
- **LOW COST**
- **RELIABLE**
- **THERMAL PRINTING** fixed head—no stylus to replace
- **CLEAN** operation—no carbon dust residue
- **QUIET** operation—no rotating stylus, no arcing
- **ODORLESS** operation—no burned paper
- **LARGE VIEWING** area with sliding window
- **LARGE CHART** standard format—high resolution
- **BLANK PAPER** is high contrast black on white and low in cost
- **PORTABLE** and lightweight for small boat operation
- **MICROPROCESSOR** controlled
- **SCALE SELECTED** is the only one printed
- **FEET or METERS** operation—switch selectable
- **THUMBWHEEL SETTINGS** for speed of sound, tide and draft
- **ANNOTATION** of all parameters appear on recordings in chart margin
  Speed of Sound, Tide, Draft, Event, Time and Mode of Operation
- **TVG** (time varied gain) minimizes gain adjustments
- **INTERNAL** micro controlled depth digitizer
- **EXTERNAL** depth digitizer connector on rear panel
- **NO ADJUSTMENTS** for zero line or call line are required

OPTIONS

CUSTOM LOGO—Programs recorder to repetitively print, in the lower chart margin, customer specified information such as user's logo, name, address, etc.

SPECIFICATIONS – SINGLE FREQUENCY TDSR MODEL 448

PRINTING	Thermal solid state fixed head thick film
CHART PAPER	8-¾ inches x 200 feet
PAPER SPEEDS	.5,1,2,4 or 8 inches/min. (Depends on scale selected)
DEPTH RANGES	0 to 335 feet or 0 to 80 meters. 6 overlapping phases of 60 feet or 15 meters A x 2 SWITCH multiplies each range by a factor of 2 and A x .5 SWITCH multiplies each range by a factor of .5
ACCURACY	± .1 foot or meter timing and printing resolution
SPEED OF SOUND	Thumbwheel switch selectable 4550 to 5050 feet/sec. or 1350 to 1550 meters/sec. Precision crystal referenced frequency synthesizer using a phase locked loop provides exact calibration.
TIDE	Thumbwheel switch selectable from 0 to ± 25.0 feet or meters
DRAFT	Thumbwheel switch selectable from 0 to + 99.9 feet or meters
EVENT MARK	Front panel switch or remote, increments internal counter
TIME	Internal clock with battery backup
SOUNDER FREQUENCY	208 kHz or 125 kHz standard or others optional
TRANSDUCERS	208 kHz 8 degree beamwidth at −3db 208 kHz 3 degree beamwidth at −3db (optional) 125 kHz 14 degree beamwidth at −3db (optional)
PULSE LENGTH	.15 to .6 ms. Automatically determined by frequency and depth range selected
PULSE POWER	250 watts RMS
SOUNDING RATE	1,200 soundings per minute max
TIME VARIED GAIN (TVG)	Automatically compensates for spreading loss and attenuation over depth range
GAIN CONTROL	Provides manual gain adjustment
STANDBY MODE	Allows transceiver and digitizer (if used) to operate without running chart paper
OUT OF PAPER SENSOR	Indicated by blinking front panel light. Paper motion stops, but sounding continues.
RAPID PAPER ADVANCE	Front panel switch allows for the rapid advance of blank paper
ANNOTATION	The numerical value of Speed of Sound, Tide, Draft, Time and Event are permanently recorded above the chart record periodically



DIGITIZER OUTPUT	In addition to the built in depth digitizer, Start/Stop pulses are available for use with external digitizers such as Innerspace Models 410, 412 and 445.
POWER	Either 12, 24 V DC or 120, 240 V AC (Must be specified AC or DC)
DIMENSIONS	17 in. W x 17¼ in. H x 9¼ in. D
WEIGHT	45 pounds
ENCLOSURE	Coated aluminum, corrosion resistant and splashproof. Sliding window for chart access and settings door for easy access to thumbwheel switches.

SPECIFICATIONS—INTERNAL MICROPROCESSOR DIGITIZER

OPERATING MODES	Either a DIRECT, GATED, AUTO or MANUAL mode may be chosen DIRECT — No gate present GATED — Gate width doubles, then quadruples automatically to reacquire the bottom reply AUTO — Gate width doubles, quadruples then goes to non-gated automatically to reacquire the bottom reply MANUAL — Fixed gate as preset on initial depth thumbwheel
GATE WIDTH	Selectable 2, 4, 8, 20, 40 or 80 via rotary switch. Gate width in feet or meters, determined by the recorder MODE switch setting
MISSED REPLIES	REPLY switch selects 2, 4, 8 or 16 missed replies, before reacquisition of bottom reply, in AUTO mode.
DISPLAY	Four digit LCD 7 segment. Resolution to 0.1 feet or meters, determined by the recorder MODE switch setting.
INDICATORS	Three LED's representing BAD DATA, REPLY and depth GATE
INITIAL DEPTH	Three station thumbwheel switch allows entry of an initial depth gate position
ALARM	A switched audible alarm indicates loss of track
OUTPUTS	BCD—8421 TTL compatible 5V positive logic. Buffered outputs with data hold, inhibit, strobe and flag lines. IEEE488 GPIB—4 digits with proper protocol and selectable address switches (optional) EIA RS232C—4 digits with selectable baud rates (optional). A bad data flag is available and can optionally set the output number to all zeros.

INNERSPACE TECHNOLOGY, INC.

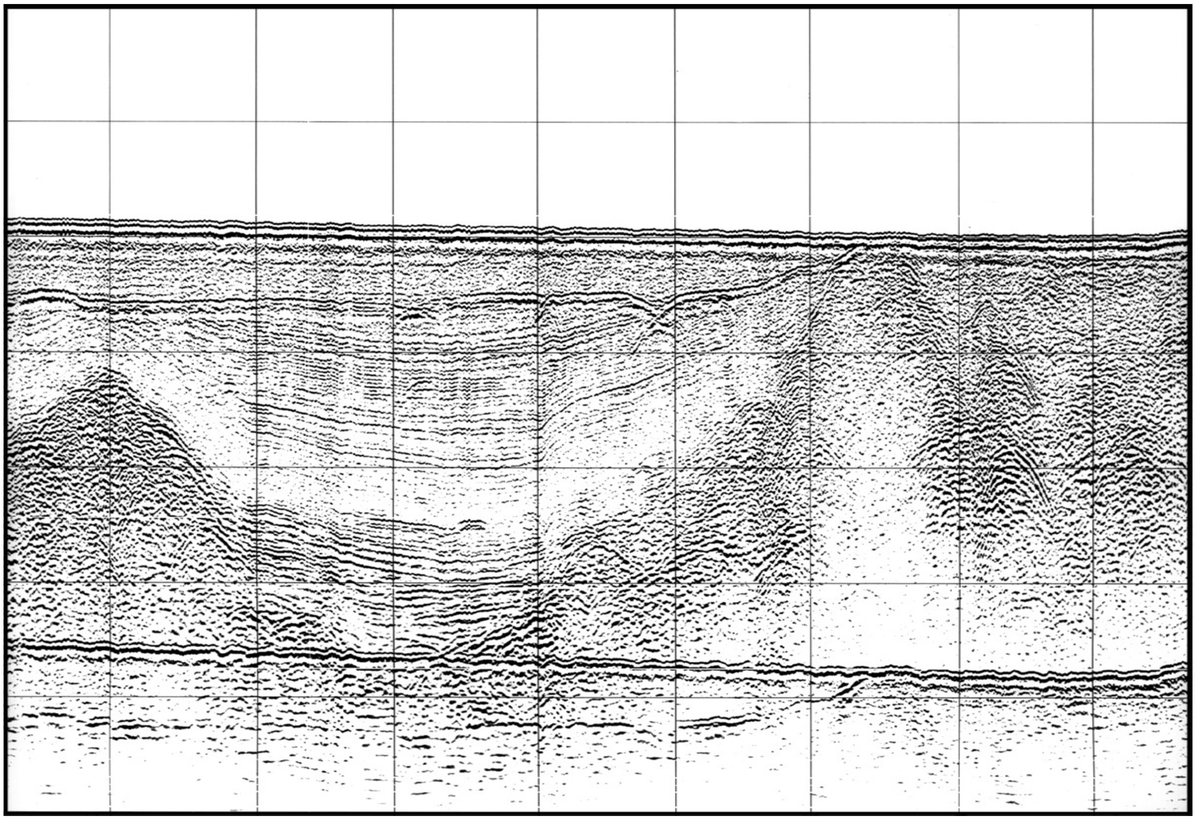
SEISMIC REFLECTION PROFILING "BOOMER" SYSTEM

The 100-1000 joule Boomer is a moderate to deep penetration, moderate resolution transducer utilized for widely varied seismic profiling applications. The electromechanical sound transducer is mounted on a catamaran and is designed to operate with the capacitance energy sources, and matching hydrophone streamer array. This system is typically interfaced with a digital seismic processor for signal amplification, filtering, and TVG controls, and a thermal graphic recorder for displaying the seismic profiles.

The "Boomer's" unique electromechanical assembly consists of an insulated metal plate and rubber diaphragm adjacent to a flat-wound electrical coil. A short duration, high power electrical pulse discharges from the separate energy sources into the coil and the resultant magnetic field explosively repels the metal plate. The plate motion in the water generates a single broadband acoustic pressure pulse.

The elimination of the strong cavitation or ringing pulse associated with the Sparkers, combined with the broadband frequency spectrum, (1) permits the bottom echo to appear as a fine line; and (2) provides a clear cross-sectional record of subbottom materials to depths exceeding 250 feet (given appropriate site conditions). The system operates equally well in salt or fresh water.

Applications for the Boomer include reconnaissance geological surveys, mineral exploration, foundation studies for offshore platforms, harbor development, and cable/pipeline crossing surveys.



SPECIFICATIONS	
Pulse Character Energy Level	@300 watt-seconds
Duration	0.2 milliseconds
Source Level	107 db ref. 1 microbar at 1 meter
Spectrum	400 Hz to 8 kHz
Repetition Rate	1-4 pulses/second
Dimensions	84 cm (W) x 59 cm (H) x 158 cm (L) (33 in x 23 in x 62 in)
Weight	90 kg (200 lbs)
Cable Length	25 meters (80 ft)
Towing Speed	2-5 knots

OCEAN SURVEYS, INC.

Specialists in Marine & Freshwater Site Surveys

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Old Saybrook, CT 06475

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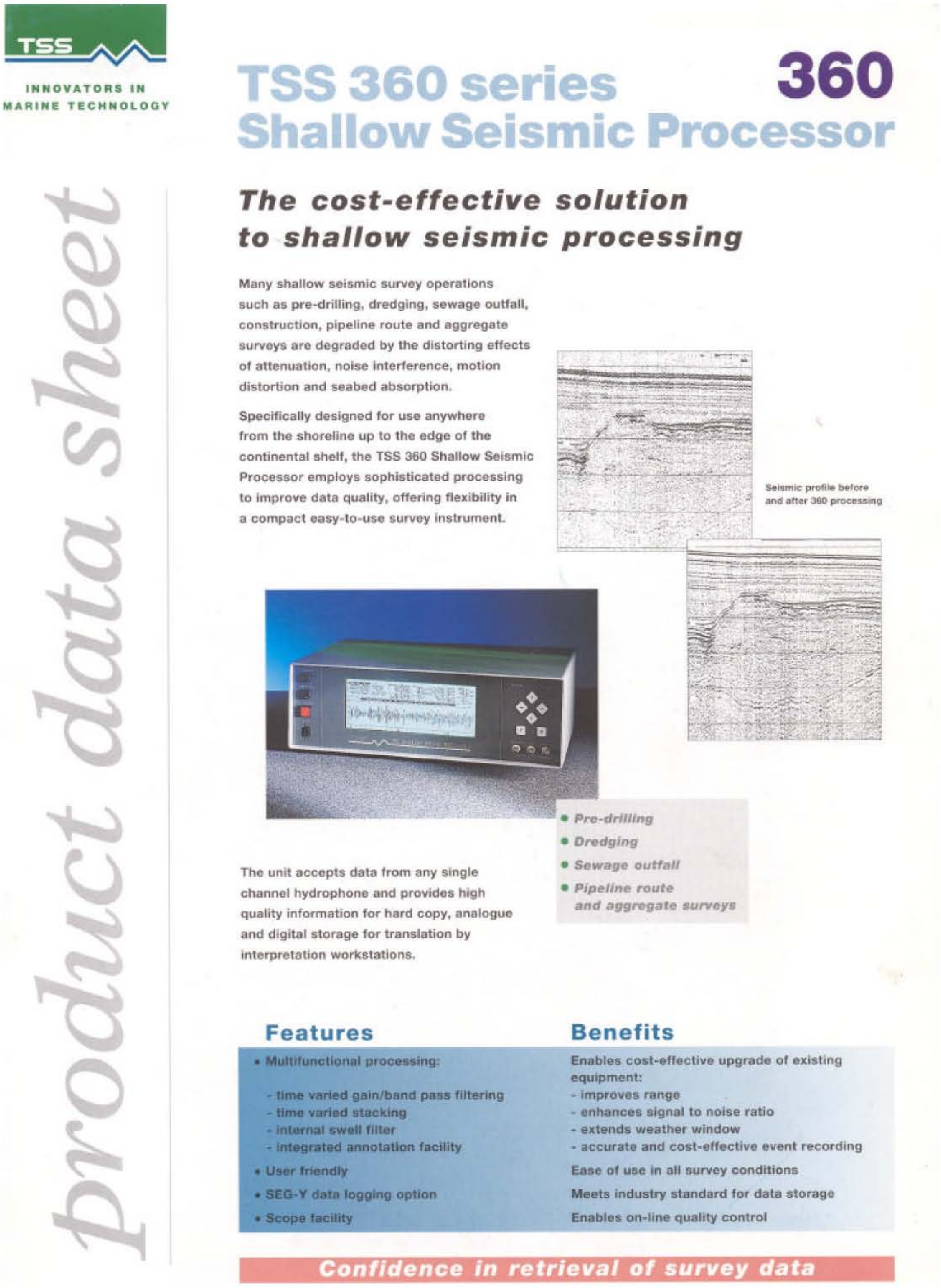


TSS

INNOVATORS IN
MARINE TECHNOLOGY

product data sheet

TSS 360 series Shallow Seismic Processor

360

The cost-effective solution to shallow seismic processing

Many shallow seismic survey operations such as pre-drilling, dredging, sewage outfall, construction, pipeline route and aggregate surveys are degraded by the distorting effects of attenuation, noise interference, motion distortion and seabed absorption.

Specifically designed for use anywhere from the shoreline up to the edge of the continental shelf, the TSS 360 Shallow Seismic Processor employs sophisticated processing to improve data quality, offering flexibility in a compact easy-to-use survey instrument.

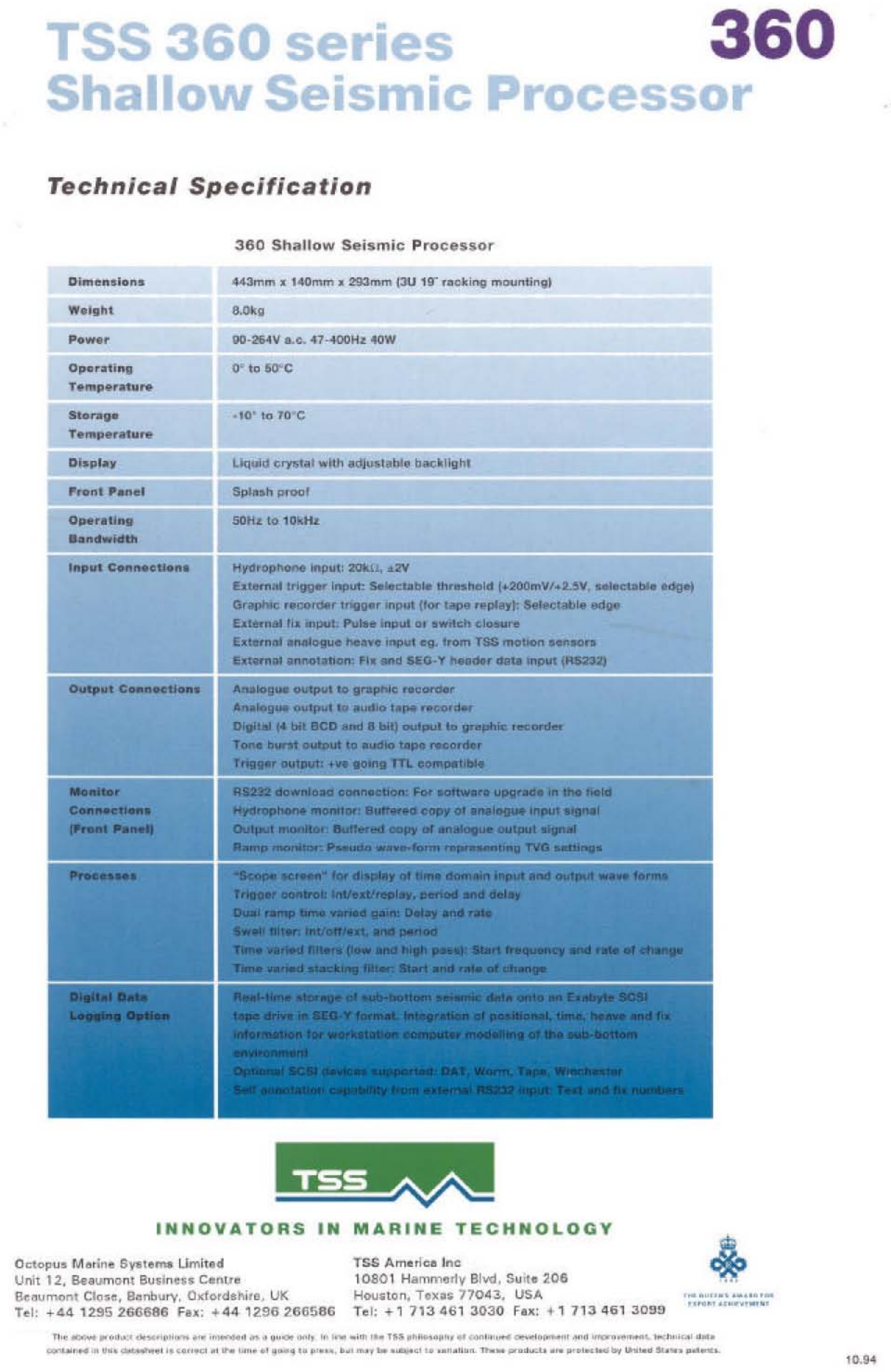
Seismic profile before and after 360 processing

The unit accepts data from any single channel hydrophone and provides high quality information for hard copy, analogue and digital storage for translation by interpretation workstations.

- *Pre-drilling*
- *Dredging*
- *Sewage outfall*
- *Pipeline route and aggregate surveys*

Features	Benefits
• Multifunctional processing: - time varied gain/band pass filtering - time varied stacking - internal swell filter - integrated annotation facility	Enables cost-effective upgrade of existing equipment: - improves range - enhances signal to noise ratio - extends weather window - accurate and cost-effective event recording
• User friendly	Ease of use in all survey conditions
• SEG-Y data logging option	Meets industry standard for data storage
• Scope facility	Enables on-line quality control

Confidence in retrieval of survey data



TSS 360 series Shallow Seismic Processor

360

Technical Specification

360 Shallow Seismic Processor

Dimensions	443mm x 140mm x 293mm (3U 19" racking mounting)
Weight	8.0kg
Power	90-264V a.c. 47-400Hz 40W
Operating Temperature	0° to 50°C
Storage Temperature	-10° to 70°C
Display	Liquid crystal with adjustable backlight
Front Panel	Splash proof
Operating Bandwidth	50Hz to 10kHz
Input Connections	Hydrophone input: 20kΩ, ±2V External trigger input: Selectable threshold (+200mV/+2.5V, selectable edge) Graphic recorder trigger input (for tape replay): Selectable edge External fix input: Pulse input or switch closure External analogue heave input eg. from TSS motion sensors External annotation: Fix and SEG-Y header data input (RS232)
Output Connections	Analogue output to graphic recorder Analogue output to audio tape recorder Digital (4 bit BCD and 8 bit) output to graphic recorder Tone burst output to audio tape recorder Trigger output: +ve going TTL compatible
Monitor Connections (Front Panel)	RS232 download connection: For software upgrade in the field Hydrophone monitor: Buffered copy of analogue input signal Output monitor: Buffered copy of analogue output signal Ramp monitor: Pseudo wave-form representing TVG settings
Processes	"Scope screen" for display of time domain input and output wave forms Trigger control: int/ext/replay, period and delay Dual ramp time varied gain: Delay and rate Swell filter: int/off/ext, and period Time varied filters (low and high pass): Start frequency and rate of change Time varied stacking filter: Start and rate of change
Digital Data Logging Option	Real-time storage of sub-bottom seismic data onto an Exabyte SCSI tape drive in SEG-Y format. Integration of positional, time, heave and fix information for workstation computer modelling of the sub-bottom environment Optional SCSI devices supported: DAT, Worm, Tape, Winchester Self annotation capability from external RS232 input: Text and fix numbers

TSS

INNOVATORS IN MARINE TECHNOLOGY

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Houston, Texas 77043, USA
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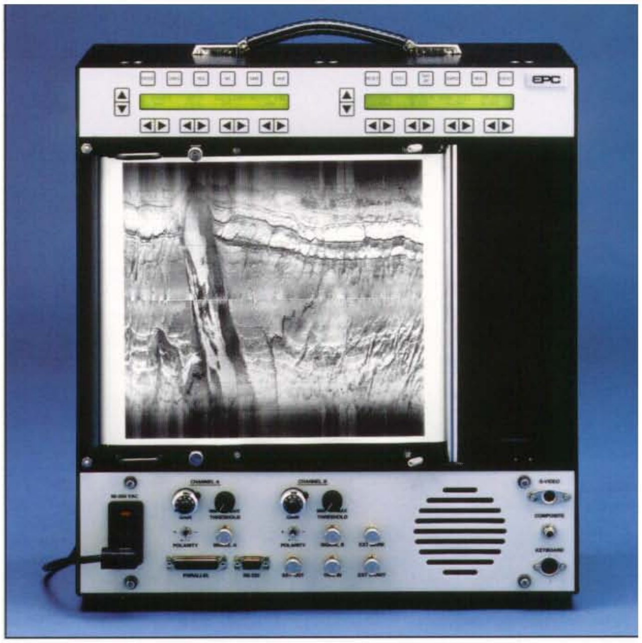
THE QUEEN'S AWARD FOR EXPORT ACHIEVEMENT

The above product descriptions are intended as a guide only. In line with the TSS philosophy of continued development and improvement, technical data contained in this datasheet is correct at the time of going to press, but may be subject to variation. These products are protected by United States patents.

10.94

MODEL GSP-1086 SERIES
GRAY SCALE PRINTER



The EPC Model GSP-1086 is an all purpose, continuous image printer. Photographic quality images are printed using a 2048 pixel thermal printhead with a dot density of eight dots/millimeter. Pixel depth is selectable up to eight bits.

Two LCD displays and a sealed membrane control panel provide the operator with a simple user interface which displays system status at all times. Because the control panel is software defined, the printer can easily be configured for a wide range of custom applications.

Sonar and imaging applications are easily accommodated by the 1086's standard interface suite:
Dual Channel Analog, Centronics Compatible Parallel, and RS-232 Serial I/O.

Keeping with EPC tradition, the 1086 is packaged in a rugged, field-ready sheet metal case. An optional transport case and rack mount kit are available for ship-of-opportunity and fixed based operations, respectively.

The 500 Series incorporates exciting new features like Bandpass Filtering and Time Varied Gain. Data throughput, system diagnostics, and reliability have also been improved in the 500 Series. A mini keyboard, tie-down loops and enhanced documentation are included.

EPC LABORATORIES INC., 42A Cherry Hill Drive, Danvers, MA 01923 USA PHONE: (978) 777-1996
FAX: (978) 777-3955 EMAIL: sales@epclabs.com WEB: http://www.epclabs.com

HARDWARE

Host Processor
486DX2 /66 MHz
CPU Bus
16 Bit Industry Standard Architecture (ISA)
Control Panel
Sealed membrane type, software defined
Displays
Twin 2x40 LCD displays with LED backlights

POWER

Power Supply
350 Watt, auto-sensing, universal input
84-265 VAC, 50-60 Hz
Power Consumption
80 Watts non-printing
130 Watts Peak

PHYSICAL

Dimensions & Weight
17.6"W x 19.3"H x 6.7"D
50 LBS.
Media
Heat sensitive thermal paper or high grade
plastic film - 23dB dynamic range
Paper Length: 150 feet
Film Length: 130 feet
Temperature (non-condensing)
0°C to 65°C - Operating
-28°C to 65°C - Storage

PRINTING

Gray Levels & Resolution
Selectable: 8, 16, 32, 64 Levels
Printhead: 2048 Pixels @ 203 DPI
Maximum Line Speeds (nominal)
@ 8 Shades: 15 ms
@ 16 Shades: 18 ms
@ 32 Shades: 26 ms
@ 64 Shades: 43 ms
Chart Speeds (Lines Per Inch)
Fixed: 75, 80, 100, 120,150, 200, 240, 300
Variable: 1.6 kHz max clock, BNC input
1 / 1200th inch per clock

Warranty: One Year Limited Parts & Labor.

ANALOG INTERFACE

Dual Signal Input
0V to 10V SIGNAL BNC inputs
(2KW Input Impedance)
External Trigger Input (slave)
TTL EXT TRIG BNC input with slope sense
Internal Key Output (master)
TTL KEY OUT BNC with polarity selection
(62.5us pulse width)
Gain, Threshold, Polarity
Independent controls for each channel
Minimum printable signal 150 mV
Time Bases
1.5 MHz A/Ds with 8 Bit resolution
Scan - 5 mS to 10 secs, 1 ms resolution
Key - 5 mS to 10 secs, 1 ms resolution
Delay - 0 secs to 8 secs, 1 ms resolution

PARALLEL INTERFACE

Interconnect
25 Pin Sub D, metal shell
Data Input (Pins 2-9)
Eight Bit Centronics Compatible
2048 bytes per raster line
White = 0X00; Black = selectable
Handshake
Low Active host/STB on Pin 1
Low Active printer/ACK on Pin 10
High Active printer BUSY on Pin 11
BUSY cycles on end of line (2048 bytes)
/ACK cycles on every /STB
Burst Rate Bandwidth: Over 250 kHz
Sustained Bandwidth: Based on gray levels

COMMAND INTERFACE

QWERTY Keyboard
Jack for commands and annotation
RS-232 Serial Data Input (DCE)
9 Pin Sub 'D' for commands & GPS

NEW FEATURES

Time Varied Gain
255 Logarithmic curves to choose from.
Band Pass Filtering
LOW PASS: 1kHz, 1.2kHz, 2kHz, 2.4kHz, 3kHz,
4kHz, 6k and 12kHZ
HIGH PASS: 83Hz, 100Hz, 166Hz, 200Hz, 250Hz,
333Hz, 500Hz and 1kHz.

Specification subject to change.

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FAX: (978) 777-3955 EMAIL: sales@epclabs.com WEB: http://www.epclabs.com

APPENDIX II

SURVEY FIELD LOG

Date	Run	Line	BOL event	EOL event	HYPACK ® MAX File Name	SEG Y file	Event SEG Y file opened	Survey line river direction	ACOE boring accomplished on survey line	Comment
2/13/2004	1	2	132	277	002_1340.044	13020400 SEG	149	up-down		Recon offset south , end @ ~Sta -11, actual begin event 149
						13020401 SEG	189			
						13020402 SEG	229			
						13020403 SEG	272			
2/13/2004	2	1	278	372	001_1451.044	13020404 SEG	278	down-up		Recon offset north
						13020405 SEG	331			
2/13/2004	3	1	373	455	001_1533.044	13020406 SEG	373	down-up	SHE-14	
						13020407 SEG	438			
2/13/2004	4	1	456	774	001_1638.044	13020408 SEG	456	down-up	SHE-2	SHE-2 boring offline
						13020409 SEG	526		SHE-12	
						13020410 SEG	587			
						13020411 SEG	647			
						13020412 SEG	700			
2/13/2004	5	2	775	984	002_1852.044	13020413 SEG	775	up-down		end of line lost kinematic GPS / diff mode
						13020414 SEG	847			
						13020415 SEG	909			
2/13/2004	6	1	985	1170	001_2006.044	13020416 SEG	985	down-up		begin of line lost kinematic GPS / diff mode
						13020417 SEG	1034			
						13020418 SEG	1073			
						13020419 SEG	1109		SHE-3	SHE-3 boring offline
2/14/2004	7	2	1172	1299	002_1540.045	14020400 SEG	1171	up-down		Recon offset

Date	**Run**	**Line**	**BOL event**	**EOL event**	**HYPACK ® MAX File Name**	**SEG Y file**	**Event SEG Y file opened**	**Survey line river direction**	**ACOE boring accomplished on survey line**	**Comment**
										south
						14020401 SEG	1226			
						14020402 SEG	1280			
2/14/2004	7_continue	2	1300	1518	002_1630.045	14020403 SEG	1326	up-down	SHE-1	SHE-1 boring offline
						14020404 SEG	1379			
						14020405 SEG	1444			
2/14/2004	8	1	1519	1672	001_1806.045	14020406 SEG	1519	up-down		
						14020407 SEG	1586			
2/14/2004	9	1	1673	1800	001_1908.045	14020408 SEG	1673	down-up	SH-327	
						14020409 SEG	1755			
2/14/2004	10	1	1801	1860	001_1955.045	14020410 SEG	1801	up-down		lost kinematic GPS, need to correct file for tide
2/14/2004	11	2	1861	1878	002_2029.045	14020411 SEG	1861	south-north	SH-327	SH-327 boring offline
2/14/2004	12	3	1879	1895	003_2037.045	14020412 SEG	1879	north-south		
2/14/2004	13	4	1896	1905	004_2050.045	14020413 SEG	1896	south-north		448 paper off on-line
2/14/2004	14	4	1906	1920	004_2103.045	14020414 SEG	1906	south-north		448 paper off on-line
2/15/2004	15	1	1921	2027	001_1459.046	15020400 SEG	1921	south-north		Bull River survey line
						15020401 SEG	1981			
2/15/2004	16	1	2028	2059	001_1636.046	15020402 SEG	2028	up-down		
2/15/2004	17	2	2069	2102	002_1653.046	15020403 SEG	2069	down-up		
2/15/2004	18	1	2103	2131	001_1712.046	15020404 SEG	2103	up-down		
2/15/2004	19	4	2134	2164	004A1730.046	15020405 SEG	2134	south-north		

Date	Run	Line	BOL event	EOL event	HYPACK ® MAX File Name	SEG Y file	Event SEG Y file opened	Survey line river direction	ACOE boring accomplished on survey line	Comment
2/15/2004	20	5	2165	2212	005_1800.046	15020406 SEG	2165	up-down		Lost kinematic GPS, end of file RTK float mode
2/15/2004	21	5	2213	2273	005_1830.046	15020407 SEG	2213	up-down		
2/15/2004	22	6	2274	2429	006_1857.046	15020408 SEG	2274	up-down		Offshore channel modification (~Sta -30), adverse wx conditons affect data, end of line GPS in stand-alone mode
						15020409 SEG	2328			
2/15/2004	23	2	2430	2462	002_2025.046	15020410 SEG	2430	down-up		
2/15/2004	24	1	2463	2495	001_2043.046	15020411 SEG	2463	up-down		
2/15/2004	25	3	2496	2534	003_2100.046	15020412 SEG	2496	down-up		
2/15/2004	26	1	2535	2560	001_2125.046	15020413 SEG	2535	up-down	SHE-4, SHE-6	
2/15/2004	27	5	2561	2591	005_2136.046	15020414 SEG	2561	down-up		
2/15/2004	28	3	2592	2616	003_2156.046	15020415 SEG	2592	north-south		
2/15/2004	29	2	2617	2637	002_2208.046	15020416 SEG	2617	south-north	SHE-4, SHE-6	
2/16/2004	30	23	2638	2655	023_1425.047	16020400 SEG	2638	north-south		
2/16/2004	31	23	2656	2672	024_1436.047	16020401 SEG	2656	south-north		
2/16/2004	32	21	2673	2694	021_1447.047	16020402 SEG	2673	down-up		lost kinematic GPS, need to correct file for tidal reference
2/16/2004	33	22	2695	2720	022_1522.047	16020403 SEG	2695	up-down		

Date	**Run**	**Line**	**BOL event**	**EOL event**	**HYPACK ® MAX File Name**	**SEG Y file**	**Event SEG Y file opened**	**Survey line river direction**	**ACOE boring accomplished on survey line**	**Comment**
2/16/2004	34	26	2721	2764	026_1530.047	16020404 SEG	2721	up-down		
2/16/2004	35	25	2765	2781	025_1551.047	16020405 SEG	2765	north-south	SHE-14	
2/16/2004	36	14	2782	2859	014_1611.047	16020406 SEG	2782	down-up		
2/16/2004	37	16	2860	2932	016_1637.047	16020407 SEG	2860	up-down	SHE-12	SHE-12 boring offline
2/16/2004	38	15	2933	3008	015_1708.047	16020408 SEG	2933	down-up	SHE-13	
2/16/2004	39	17	3009	3025	017_1740.047	16020409 SEG	3009	north-south		
2/16/2004	40	18	3026	3040	018_1754.047	16020410 SEG	3026	south-north	SHE-12, SH-318	
2/16/2004	41	19	3041	3055	019_1803.047	16020411 SEG	3041	north-south	SHE-13	
2/16/2004	42	20	3056	3071	020_1816.047	16020412 SEG	3056	south-north		
2/16/2004	43	11	3072	3105	011_1834.047	16020413 SEG	3072	down-up		
2/16/2004	44	10	3106	3139	010_1846.047	16020414 SEG	3106	up-down		
2/16/2004	45	13	3140	3173	013_1902.047	16020415 SEG	3140	down-up		
2/16/2004	46	12	3174	3189	012_1919.047	16020416 SEG	3174	south-north	SHE-11	
2/16/2004	47	5	3190	3235	005_1935.047	16020417 SEG	3190	down-up		lost kinematic GPS, need to correct file for tidal reference
2/16/2004	48	6	3236	3279	006_1949.047	16020418 SEG	3236	up-down		lost kinematic GPS, need to correct file for tidal reference
2/16/2004	49	9	3280	3324	009_2011.047	16020419 SEG	3280	down-up		
2/16/2004	50	7	3325	3337	007_2032.047	16020420 SEG	3325	north-south		
2/16/2004	51	8	3338	3352	008_2045.047	16020421 SEG	3338	South-		

Date	Run	Line	BOL event	EOL event	HYPACK ® MAX File Name	SEG Y file	Event SEG Y file opened	Survey line river direction	ACOE boring accomplished on survey line	Comment
								north		
2/16/2004	52	4	3353	3374	004_2058.047	16020422 SEG	3353	down-up		
2/16/2004	53	1	3375	3395	001_2108.047	16020423 SEG	3375	up-down		
2/16/2004	54	3	3396	3410	003_2122.047	16020424 SEG	3396	north-south		
2/16/2004	55	1	3411	3475	001_2149.047	16020425 SEG	3411	down-up		Survey near Elba Island, very end of line GPS non-differential mode

APPENDIX III

SUMMARY TABLE COMPARING ACOE BORING UNITS AND SUBBOTTOM REFLECTORS
&
MASTER SUMMARY TABLE OF RELIC CHANNEL CUT AND FILL FEATURES AND LIMESTONE

Summary Table Comparing ACOE Boring Units and Subbottom Reflectors

Field Run	Interpretive line designation	*RCCF* feature reference	SEG-Y file	Approximate navigation event # in vicinity of boring (adjusted for layback)	Boring on-line	Overburden thickness based on core	time to river bed (ms)	time to reflector (ms)	Overburden thickness based on assumed velocity @ core location	Comment
3	North Offset	6	13020406 SEG	388.7	SHE-14	60.0	14.658	38.372	62.8	Match with limestone contact (Blue reflector)
						33.6	14.658	24.673	26.5	Match with A/B contact (yellow reflector), which lies just below relic channel cut, difficult pick since relic channel cut slightly masks underlying reflector
9	2	6	14020409 SEG	1769	SH-327	27.7	20.958	30.587	25.5	Match with base of relic channel cut (red reflector), based on where core wash stopped - not an absolute correlation
35	4A	6	16020405 SEG	2768.3	SHE-14	60.0	13.65	37.028	62.0	Match with limestone contact (Blue reflector)
						33.6	13.65	24.470	28.7	Match with A/B contact (yellow reflector)
26	16	8	15020413 SEG	2545	SHE-4	73.2	18.942	45.969	71.6	Match with limestone contact (Blue reflector)
						37.2	18.942	33.151	37.7	Match with A/B contact (yellow reflector)
29	19	8	15020416 SEG	2625.5/2622	SHE-6/SHE-4	73.2	17.934	45.922	74.2	SHE-6 not deep enough / SHE-4 outside RCC detects A/B and limestone contacts (yellow and blue reflectors), match shown on this line with limestone contact (Blue reflector) SHE-4
						37.2	17.934	32.800	39.4	Match shown on this line with A/B contact (yellow reflector) SHE-4

Field Run	Interpretive line designation	*RCCF* feature reference	SEG-Y file	Approximate navigation event # in vicinity of boring (adjusted for layback)	Boring on-line	Overburden thickness based on core	time to river bed (ms)	time to reflector (ms)	Overburden thickness based on assumed velocity @ core location	Comment
37	24	4	16020407 SEG	2896.5	SHE-13	62.0	18.816	43.074	64.3	Match with limestone contact (Blue reflector)
						33.0	18.37	31.929	35.9	Match with base of relic channel cut (red reflector)
41	28	4	16020411 SEG	3044.7	SHE-13	62.0	19.404	43.988	65.1	Match with limestone contact (Blue reflector)
						33.0	19.404	32.775	35.4	Match with base of relic channel cut (red reflector)
46	33	3	16020416 SEG	3179	SHE-11	79.8	15.624	45.912	80.3	Match with limestone contact (Blue reflector)
						33.3	15.624	27.948	32.7	Match with base of relic channel cut (red reflector)

Master Summary Table of Relic Channel Cut and Fill Features and Limestone

Field Run	Interpretive line designation	*RCCF* Feature Reference	SEG-Y file	Interpretive file name (*_sheet.xls)	Navigation event # in vicinity of relic channel cut feature	Boring acquired on-line	Maximum base depth of relic channel cut feature based on subbottom data (MLW, feet)	Depth of upper limestone surface based on subbottom data @ maximum depth of relic channel cut feature (MLW, feet)	Thickness of sediment below maximum depth of relic channel cut feature and top of limestone (feet)	Core Tie	Comment
		Relic Channel Cut and Fill Features Deemed Significant									
4	North Offset	1	13020411	Not represented	668				NA	SHE-11 /offsite	
6	South Offset	1	14020401 SEG	Not represented	1277				NA	SHE-11 /offsite	
46	34	1	16020417 SEG	16020417	3228		-59	-115	56	SHE-11 /offsite	
48	35	1	16020418 SEG	16020418	3248.5		-69	-116	47	SHE-11 /offsite	
49	36	1	16020419 SEG	16020419	3313		-80	-116	36	SHE-11 /offsite	
50	37	1	16020420 SEG	16020420	3330		-71	-119	48	SHE-11 /offsite	
4	North Offset	2	13020410 SEG /13020411 SEG	Not represented	646				NA	SHE-11 /offsite	RCC not detected
7	South Offset	2	14020402 SEG	14020402	1300		-64	-119	55	SHE-11 /offsite	
47	34	2	16020417 SEG	16020417	3204		-59	-115	56	SHE-11 /offsite	
48	35	2	16020418 SEG	Not represented	3270				NA	SHE-11 /offsite	Gasesous sediments
49	36	2	16020419 SEG	Not represented	3300				NA	SHE-11 /offsite	RCC not detected
51	38	2	16020421 SEG	16020421	3342		-56	-115	59	SHE-11 /offsite	
4	North Offset	3	13020409 SEG /13020410 SEG	13020409(15+000) / 13020410	601		-74	-117	43	SHE-11	
8	South Offset	3	14020403 SEG	14020403	1536		-69	-116	47	SHE-11	
43	30	3	16020413 SEG	16020413	3091		-67	-113	46	SHE-11	
44	31	3	16020414 SEG	16020414	3123		-67	-111	44	SHE-11	
45	32	3	16020415 SEG	16020415	3158		-71	-113	42	SHE-11	
46	33	3	16020416 SEG	16020416	3183	SHE-11	-70	-115	45	SHE-11	
4	North Offset	4	13020408 SEG/ 13020409 SEG	13020408 / 13020409 (7to12+000)	534		-83	-109	26	SHE-13	
7	South Offset	4	14020404 SEG	14020404	1427		-71	-106	35	SHE-13	
7	South Offset	4	14020404 SEG	1402404(11+000)	1396		-56	-114	58	SHE-13	
36	23	4	16020406 SEG	16020406	2814		-78	-110	32	SHE-13	
37	24	4	16020407 SEG	16020407	2893	SHE-13	-82	-109	27	SHE-13	
38	25	4	16020408 SEG	16020408	2972		-81	-107	26	SHE-13	
39	26	4	16020409 SEG	16020409	3015		-66	-112	46	SHE-13	
40	27	4	16020410 SEG	16020410	3035		-75	-109	34	SHE-13	
41	28	4	16020411 SEG	16020411	3045	SHE-13	-81	-110	29	SHE-13	
3	North Offset	5	1302406 SEG /1302407 SEG	Not represented	439					SHE-14 /offsite	No RCC observed

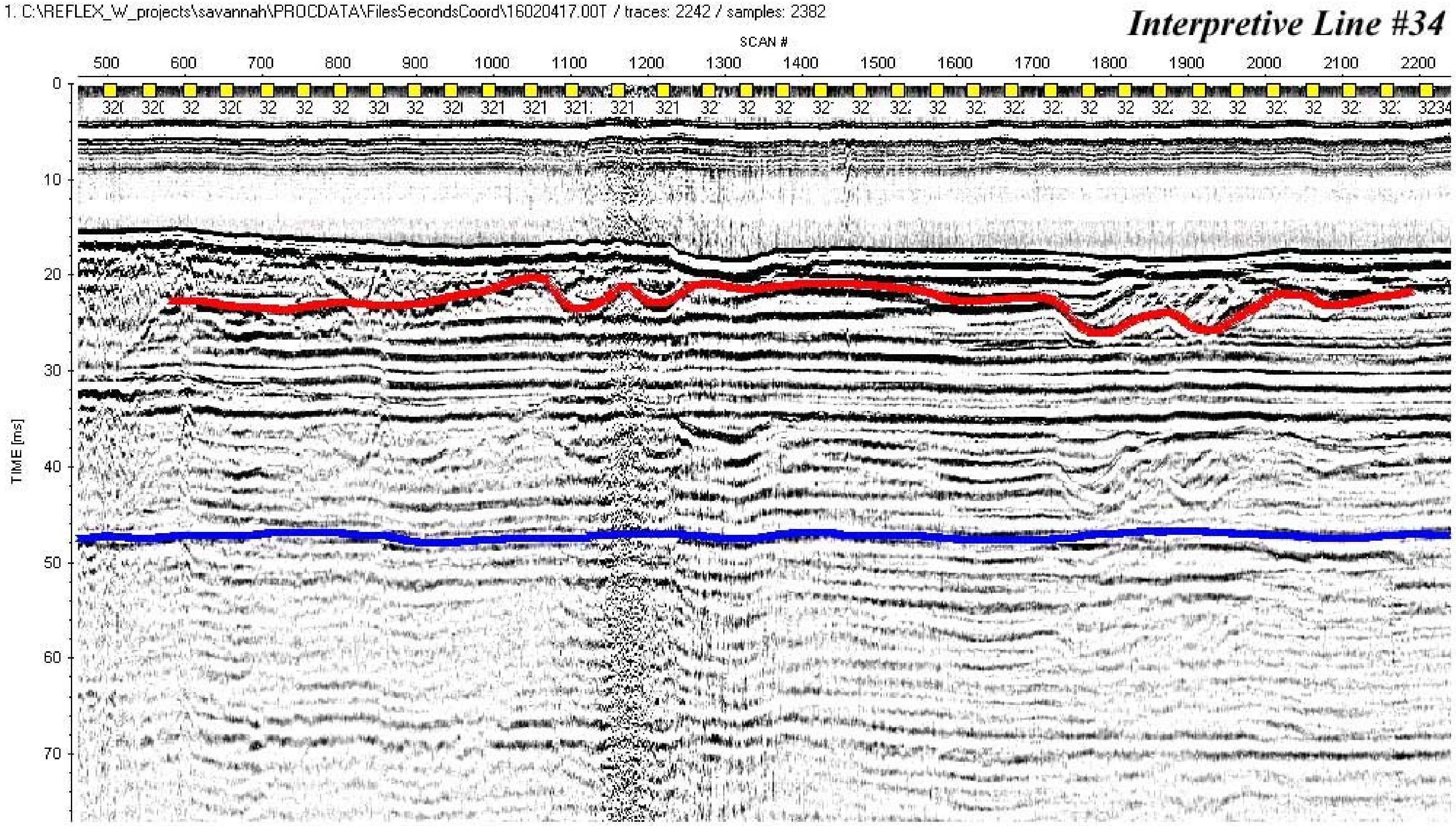
Field Run	Interpretive line designation	*RCCF* Feature Reference	SEG-Y file	Interpretive file name (*_sheet.xls)	Navigation event # in vicinity of relic channel cut feature	Boring acquired on-line	Maximum base depth of relic channel cut feature based on subbottom data (MLW, feet)	Depth of upper limestone surface based on subbottom data @ maximum depth of relic channel cut feature (MLW, feet)	Thickness of sediment below maximum depth of relic channel cut feature and top of limestone (feet)	Core Tie	Comment
7	South Offset	5	14020405 SEG	14020405	1497		-70	-110	40	SHE-14 /offsite	
34	1A	5	16020403 SEG	Not represented	2703					SHE-14 /offsite	RCC not resolved
8	1	5	14020406 SEG	14020406(1to2)	1525		-66	-106	40	SHE-14 /offsite	
31	20	5	16020401 SEG	16020401	2659		-67	-105	38	SHE-14 /offsite	
30	21	5	16020400 SEG	16020400	2651		-67	-110	43	SHE-14 /offsite	
32	22	5	16020402 SEG	16020402	2687					SHE-14 /offsite	No RCC observed LS only
3	North Offset	6	13020406 SEG	13020406	393	SHE-14	-65	-96	31	SHE-14	
1	South Offset	6	13020401 SEG	13020401	199		-70	-99	29	SHE-14	
8	1	6	14020406 SEG	14020406	1573		-69	-97	28	SHE-14	
34	1A	6	16020404 SEG	16020404	2749.5		-69	-98	29	SHE-14	
9	2	6	14020409 SEG	14020409	1769	SH-327	-70	-99	29	SHE-14	
10	3	6	14020410 SEG	14020410	1834		-68	-100	32	SH-327, SHE-14	
11	4	6	14020411 SEG	14020411	1869		-70	-103	33	SHE-14	
35	4A	6	16020405 SEG	16020405	2773	SHE-14	-70	-102	32	SHE-14	
12	5	6	14020412 SEG	14020412	1887		-69	-98	29	SHE-14	
14	6	6	14020414 SEG	14020414	1910		-65	-96	31	SHE-14	
2	North Offset	7	13020404 SEG	13020404	307		-62	-95	34	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	RCC coded orange included in red contour
5	South Offset	7	13020413 SEG	13020413	821		-65	-104	39	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	
8	1	7	14020407 SEG	14020407	1652.5		-63	-102	39	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	
9	2	7	14020408 SEG	14020408	1693		-62	-104	42	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	Has two relic channel cut features (coded red and orange) modified to single pick
16	7	7	15020402 SEG	15020402	2043.5		-58	-102	44	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	
17	8	7	15020403 SEG	15020403	2080		-67	-102	35	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	
18	9	7	15020404 SEG	15020404	2125		-67	-103	36	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	
19	10	7	15020405 SEG	15020405	2148		-67	-105	38	SHE-3 /offsite, reflectors traced by examing intersecting 97' survey data and the north offset survey line	Has two relic channel cut features (coded red and orange) modified to single pick

Field Run	Interpretive line designation	*RCCF* Feature Reference	SEG-Y file	Interpretive file name (*_sheet.xls)	Navigation event # in vicinity of relic channel cut feature	Boring acquired on-line	Maximum base depth of relic channel cut feature based on subbottom data (MLW, feet)	Depth of upper limestone surface based on subbottom data @ maximum depth of relic channel cut feature (MLW, feet)	Thickness of sediment below maximum depth of relic channel cut feature and top of limestone (feet)	Core Tie	Comment
6	North Offset	8	13020418 SEG	13020418	1086		-66	-111	46	SHE-4	
5	South Offset	8	13020414 SEG /13020415 SEG	13020414 / 13020415	918		-68	-113	45	SHE-4	13020415 use mod file for red picks
20	11	8	15020406 SEG	15020406	2192		-73	-112	39	SHE-4	
23	13	8	15020410 SEG	15020410	2450		-72	-110	38	SHE-4	
24	14	8	15020411 SEG	15020411	2477		-72	-109	37	SHE-4	
25	15	8	15020412 SEG	15020412	2522		-71	-108	37	SHE-4	
26	16	8	15020413 SEG	15020413	2545	SHE-4	-60	-110	50	SHE-4	
27	17	8	15020414 SEG	15020414	2578		-72	-113	41	SHE-4	
28	18	8	15020415 SEG	15020415	2601		-70	-106	36	SHE-4	
29	19	8	15020416 SEG	15020416	2626	SHE-4/SHE-6	-73	-113	40	SHE-4	SHE-6 not deep enough / SHE-4 outside RCC detects yellow and blue reflectors, match with blue LS reflector
Relic Channel Cut and Fill Features Detected Outside Navigation Channel Deemed Insignificant											
4	North Offset	Sta. 25+000	13020411 SEG	Not represented	699					SHE-11 /offsite	
7	South Offset	Sta. 25+000	14020401 SEG	14020401	1251		-74	-116	42	SHE-11 /offsite	
52	39	Sta. 25+000	16020422 SEG	Not represented	3365					SHE-11 /offsite	RCC not detected
53	40	Sta. 25+000	16020423 SEG	Not represented	3388					SHE-11 /offsite	RCC not detected
54	41	Sta. 25+000	16020424 SEG	16020424	3407		-70	-114	44	SHE-11 /offsite	
6	North Offset	Sta. -27+500	13020416 SEG	13020416	1004		-72	-112	40	SHE-4 /offsite	
5	South Offset	Sta. -23+000 to Sta. -27+000	13020415 SEG	13020415 (-23to-27+000)	957		-77	-115	38	SHE-4 /offsite	same file
5	South Offset	Sta. -23+000 to Sta. -27+000	13020415 SEG	13020415 (-23to-27+000)	940.5		-49	-119	70	SHE-4 /offsite	same file

APPENDIX IV

INTERPRETED SUBBOTTOM PROFILES

*Note: subbottom profiles presented in this appendix are oriented based on the direction in which they were surveyed and are not always presented north up.



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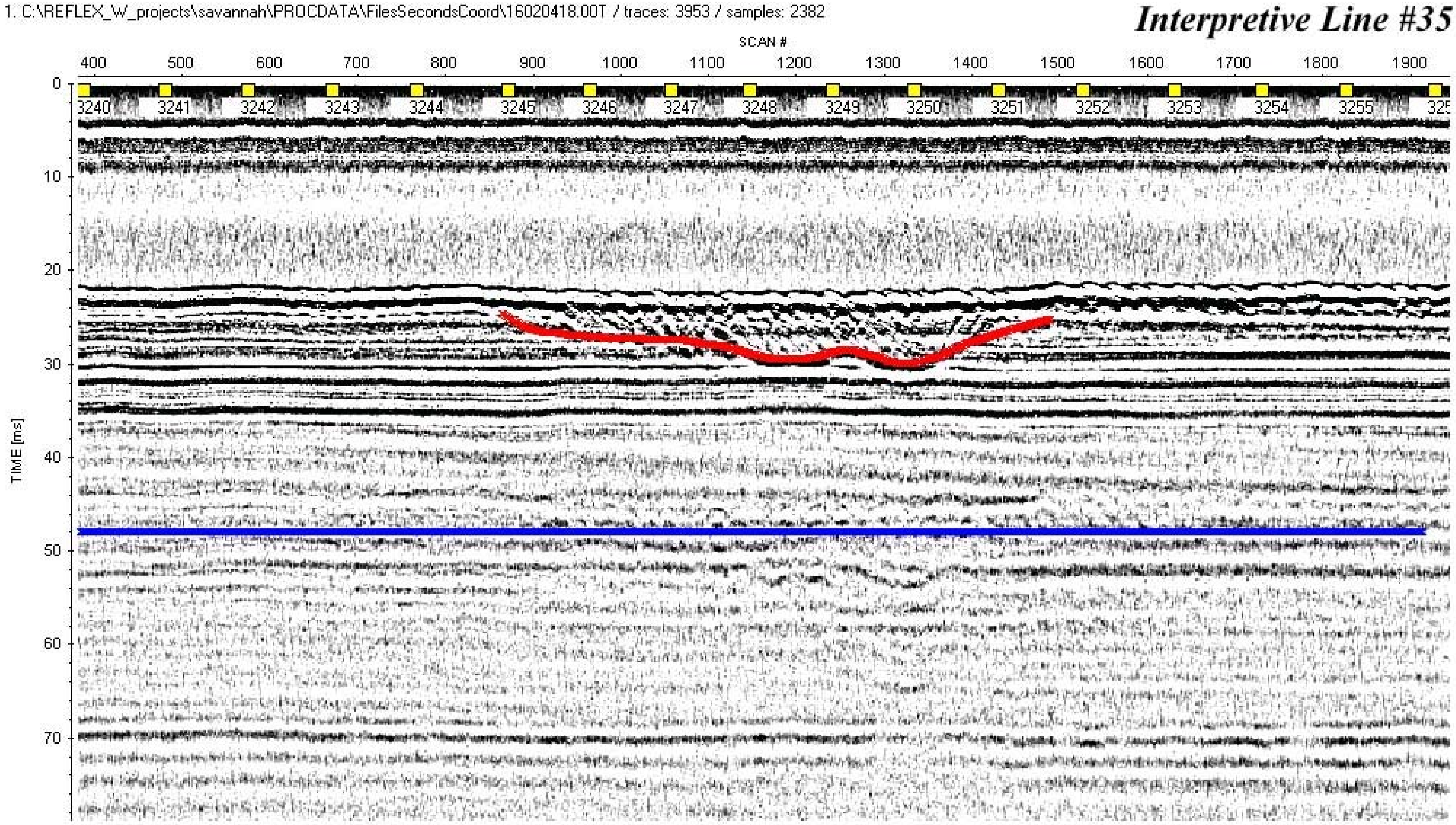
Interpretive Line #34

Interpretive Line #35



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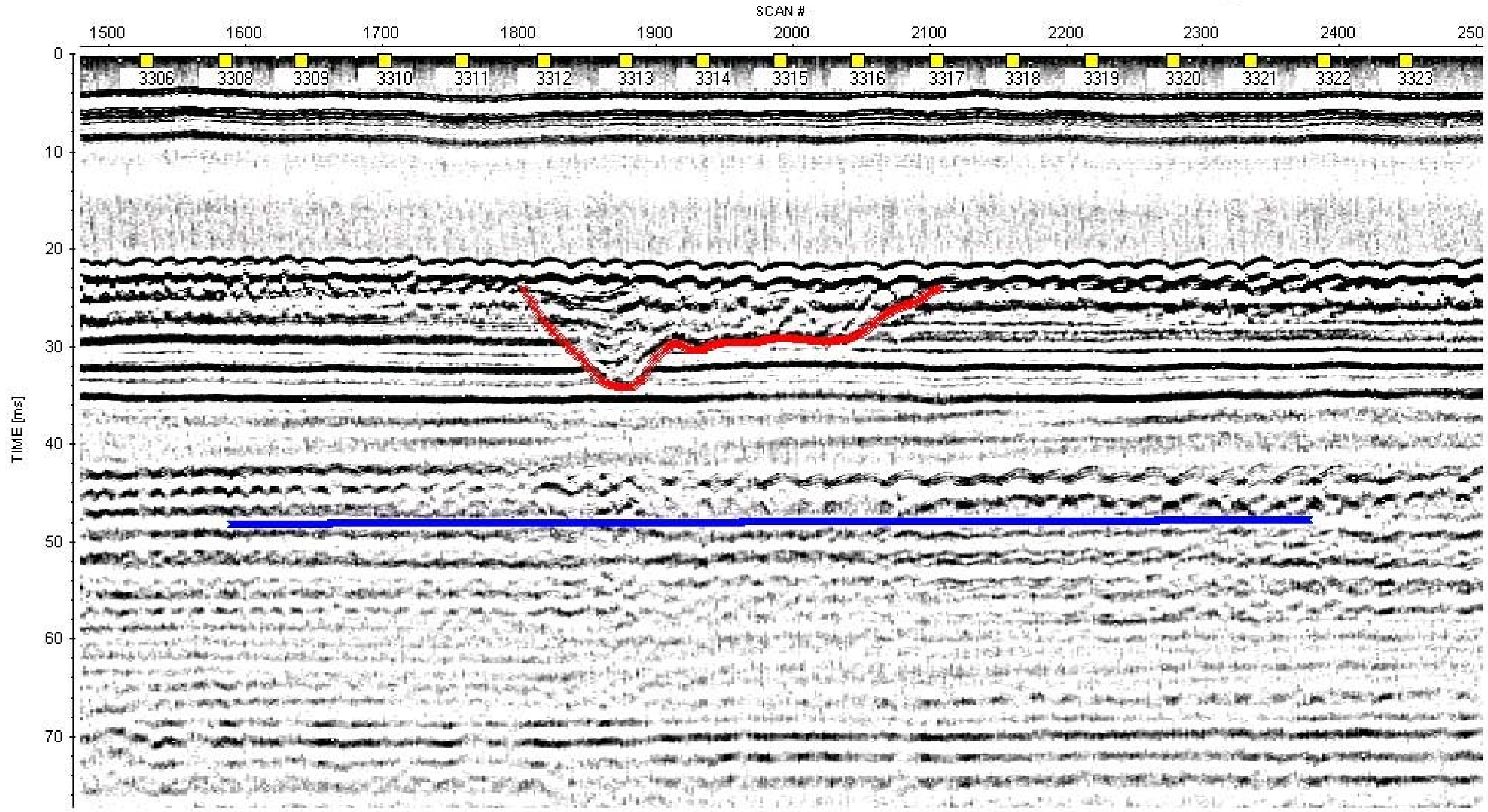

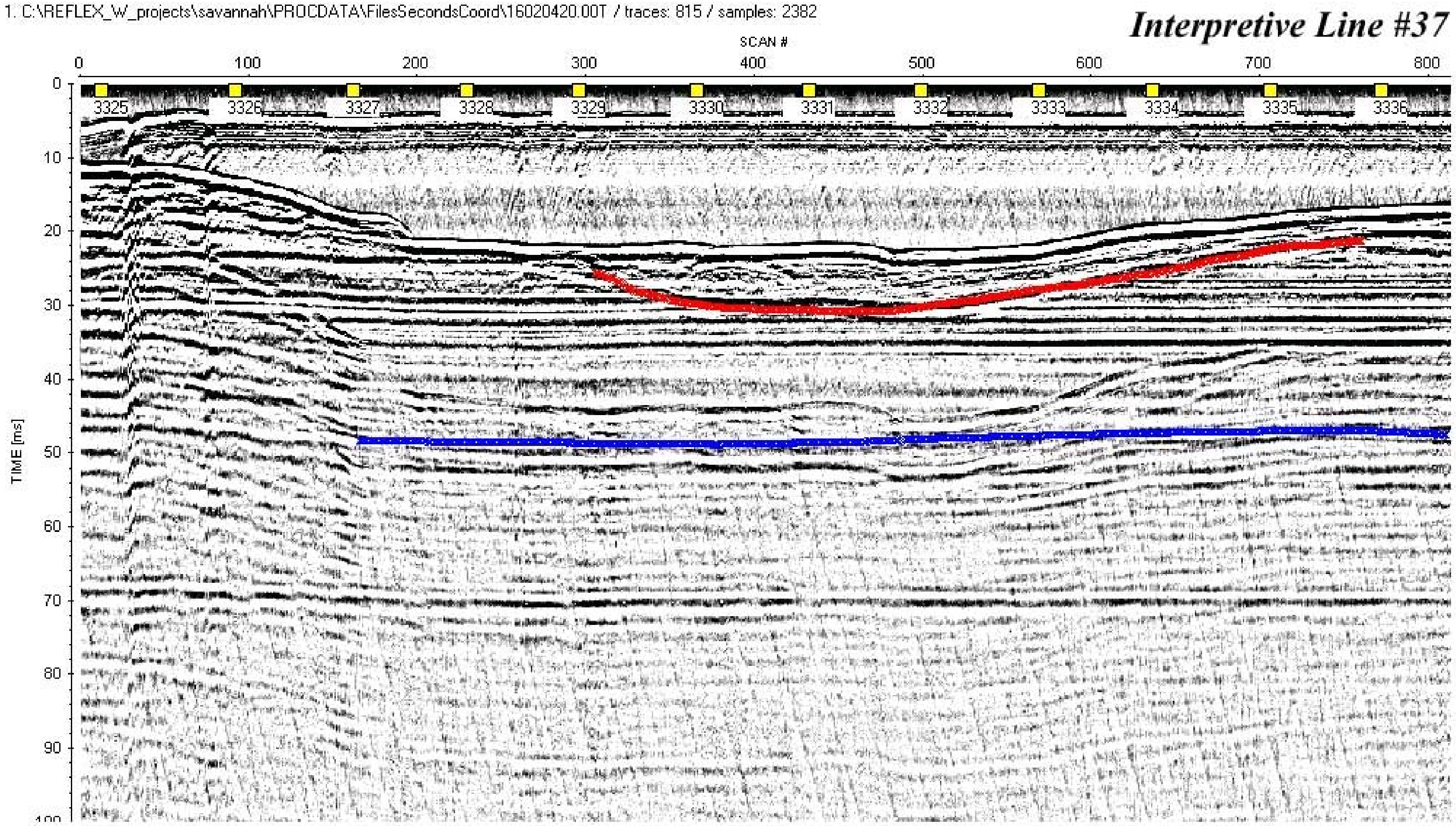
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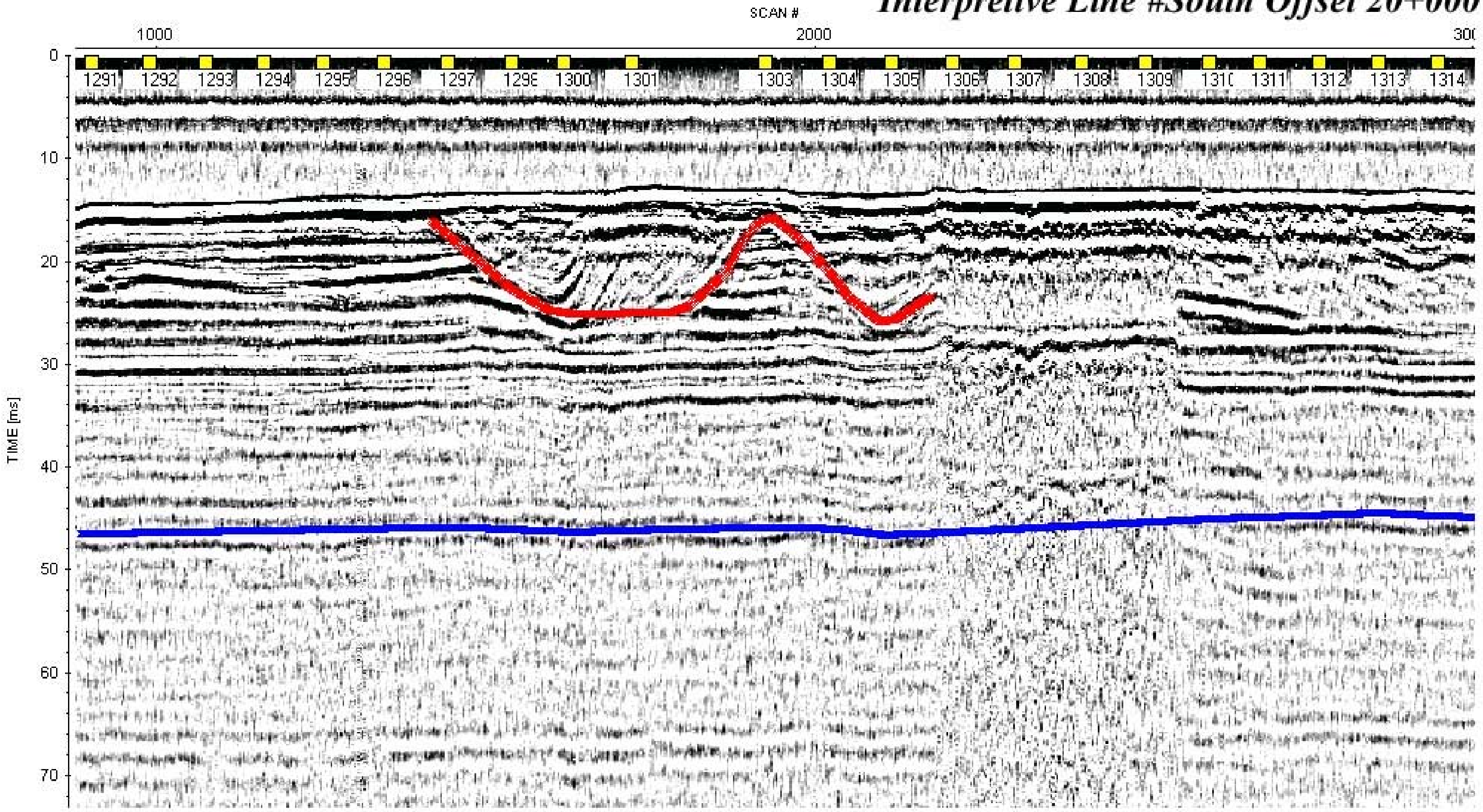
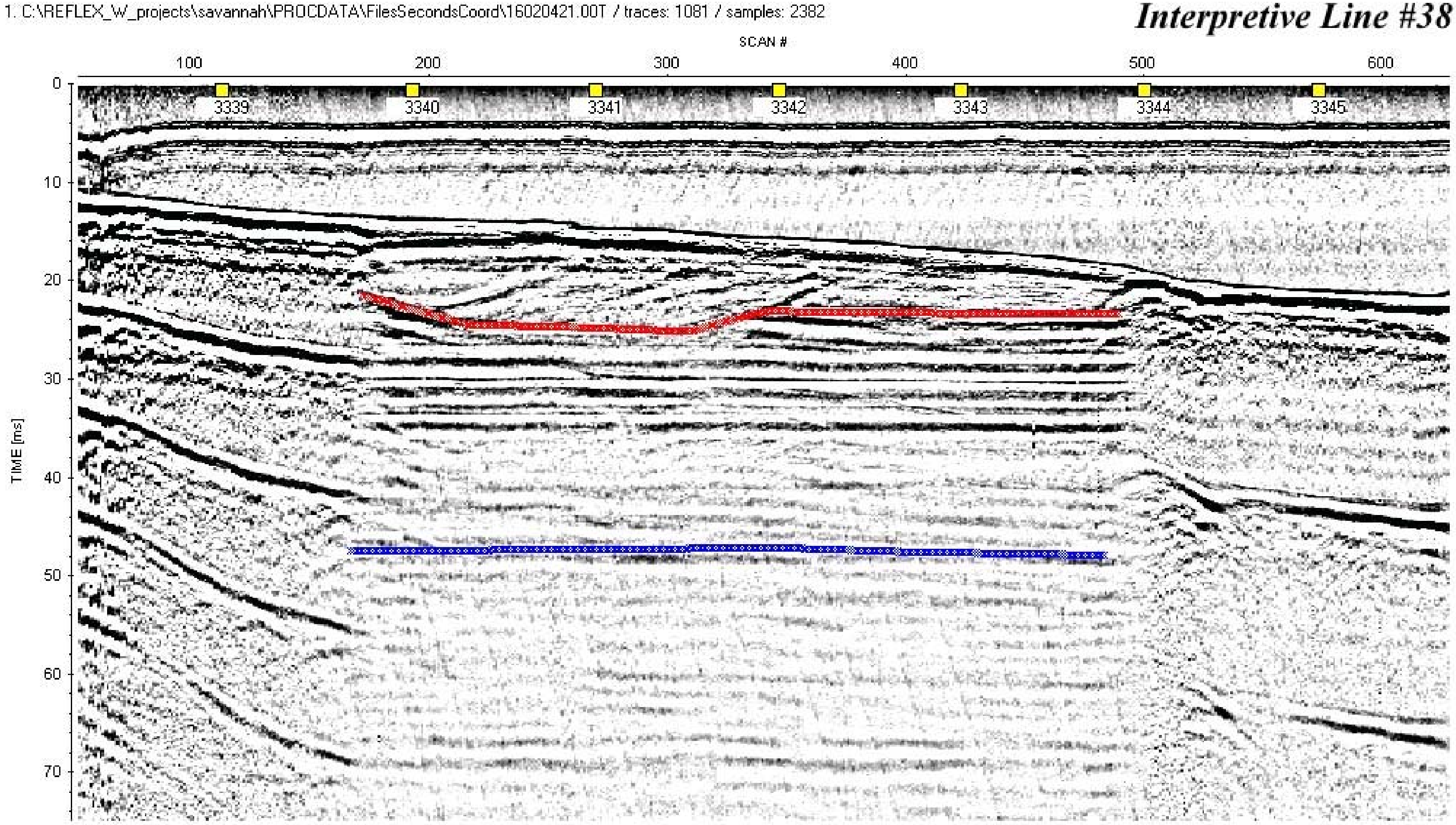
Interpretive Line #37
SCAN #
0
100
200
300
400
500
600
700
800
3325
3326
3327
3328
3329
3330
3331
3332
3333
3334
3335
3336
TIME [ms]
0
10
20
30
40
50
60
70
80
90
100

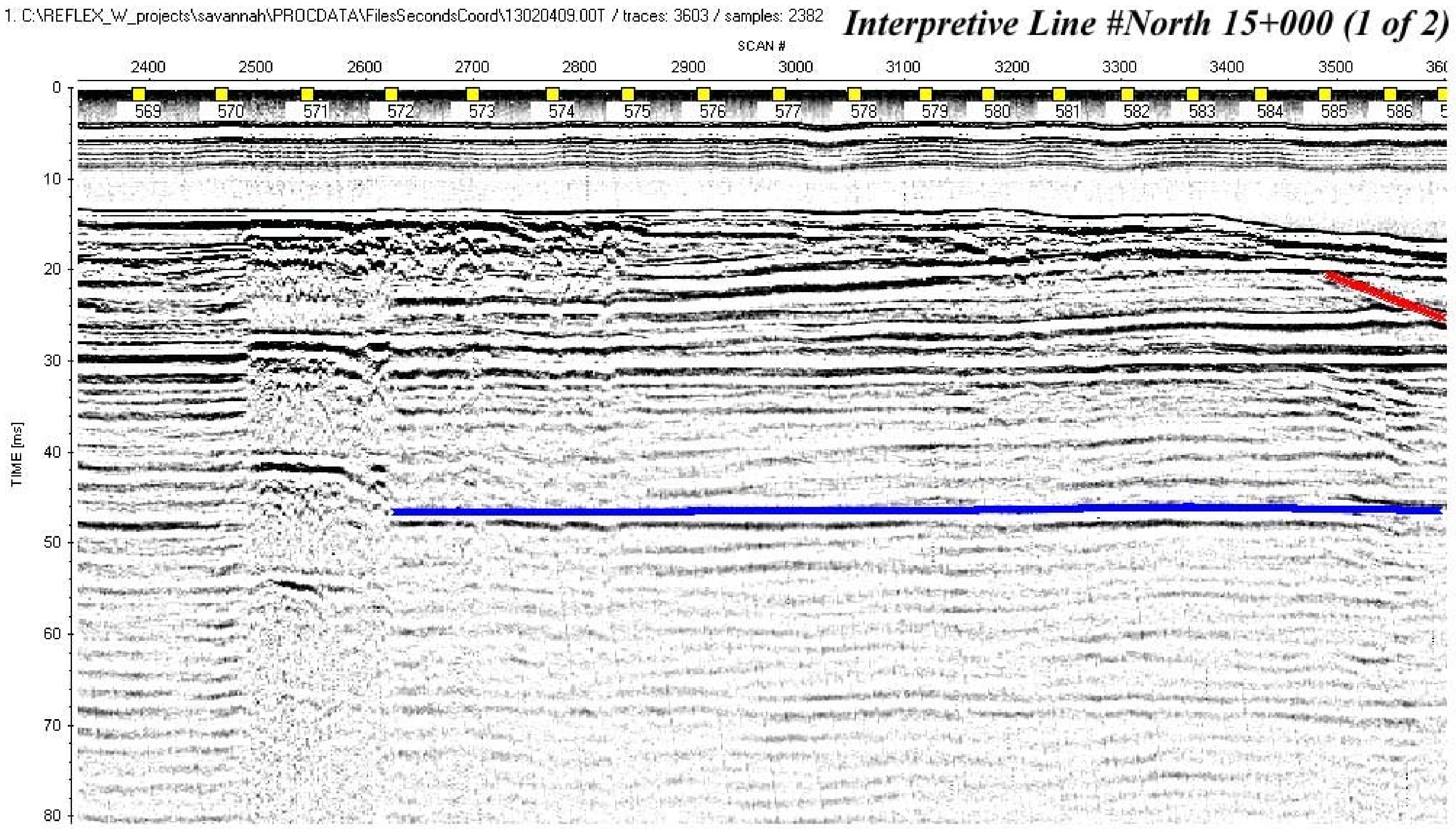
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020402.00T / traces: 4320 / samples: 2382

Interpretive Line #South Offset 20+000



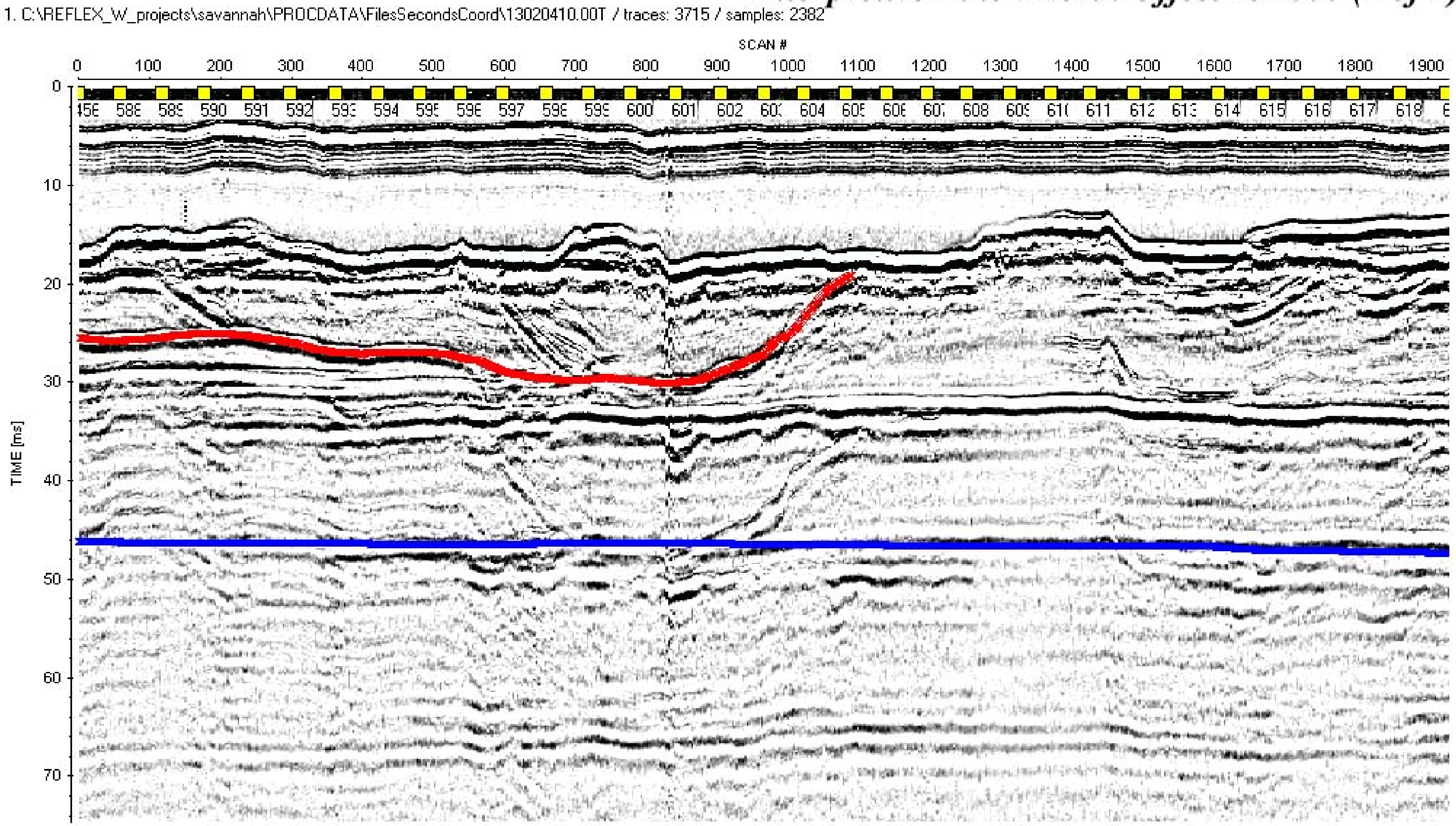
Interpretive Line #38

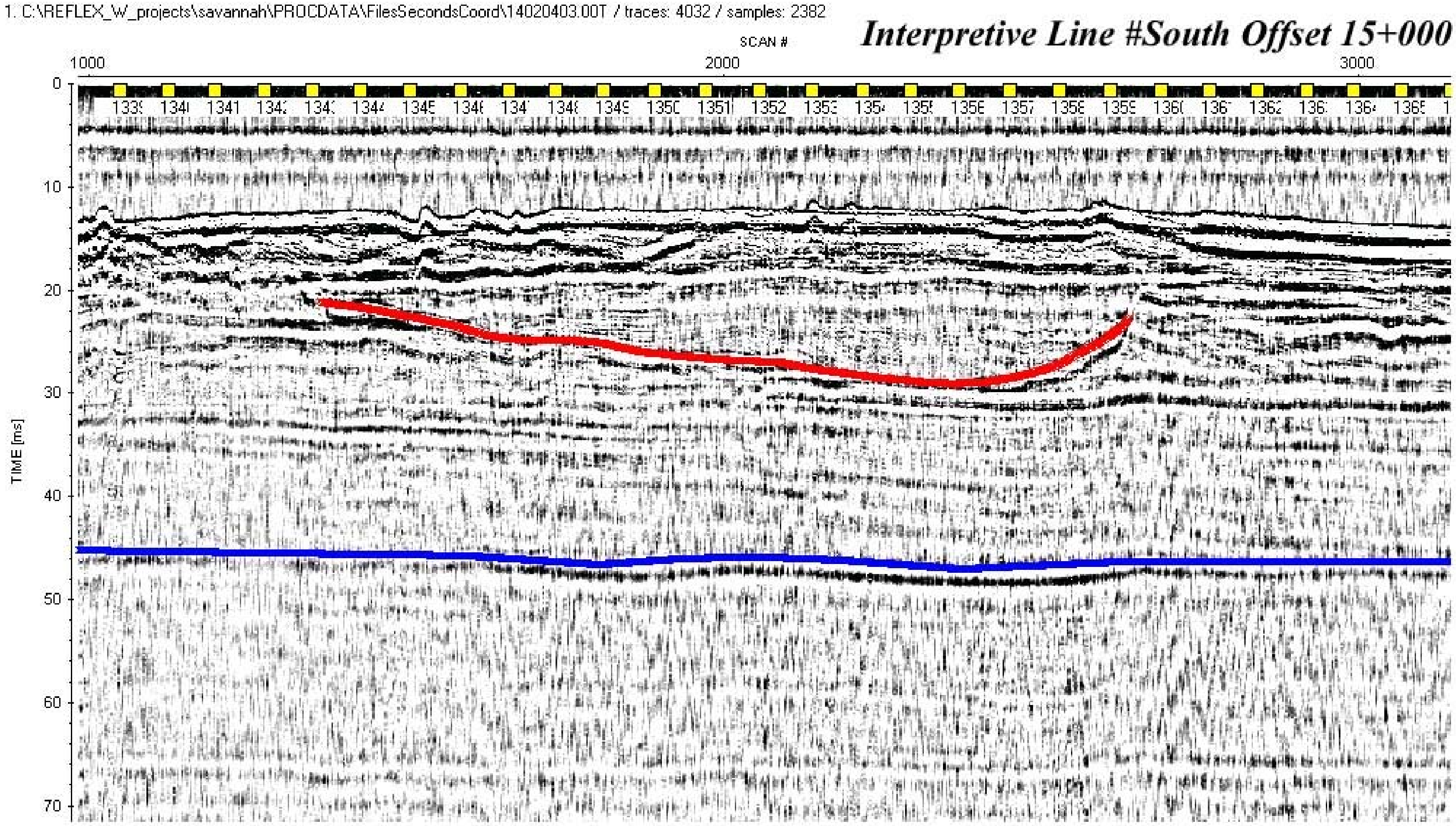




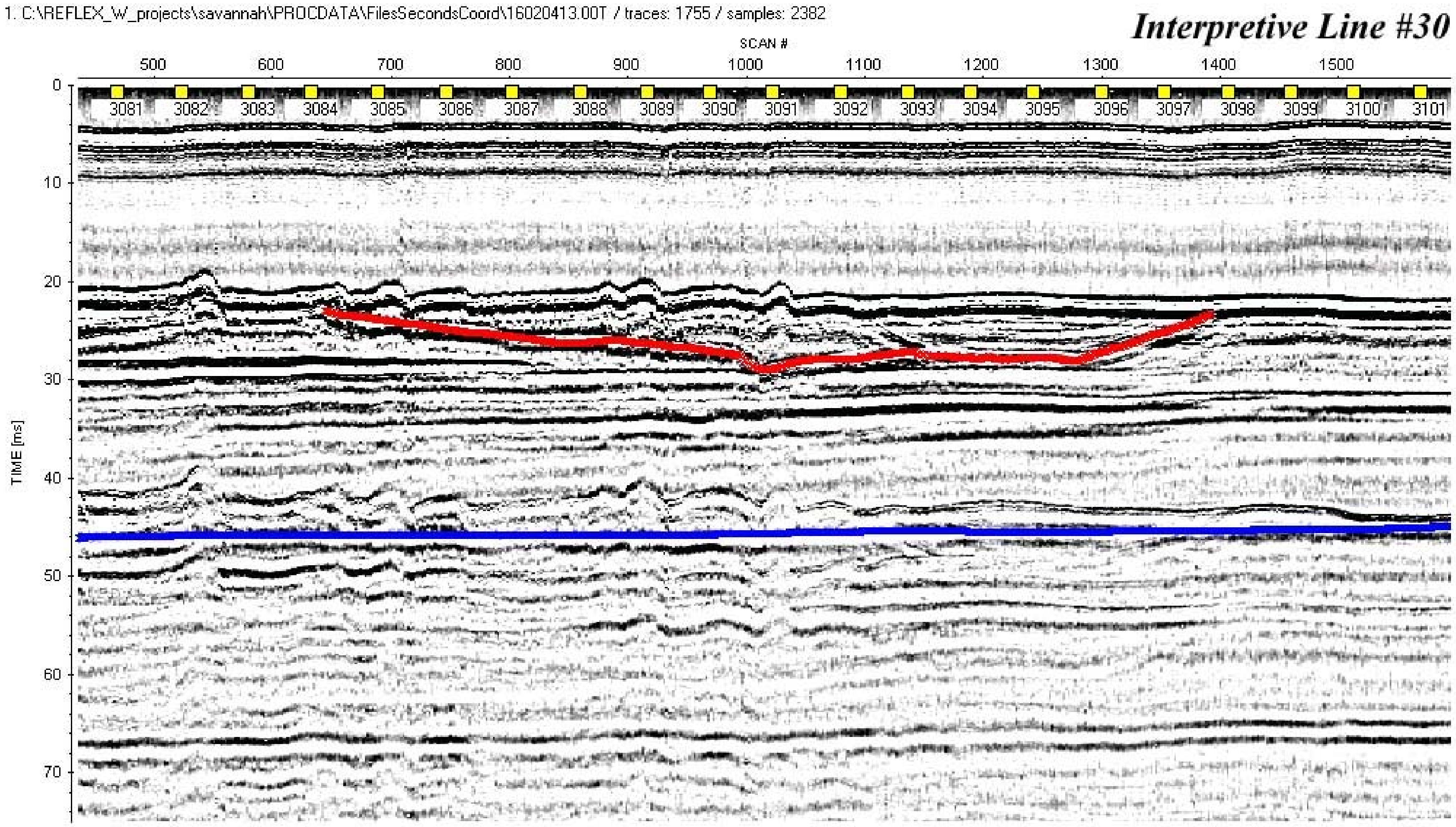
Interpretive Line #North 15+000 (1 of 2)

Interpretive Line #North Offset 15+000 (2 of 2)





Interpretive Line #South Offset 15+000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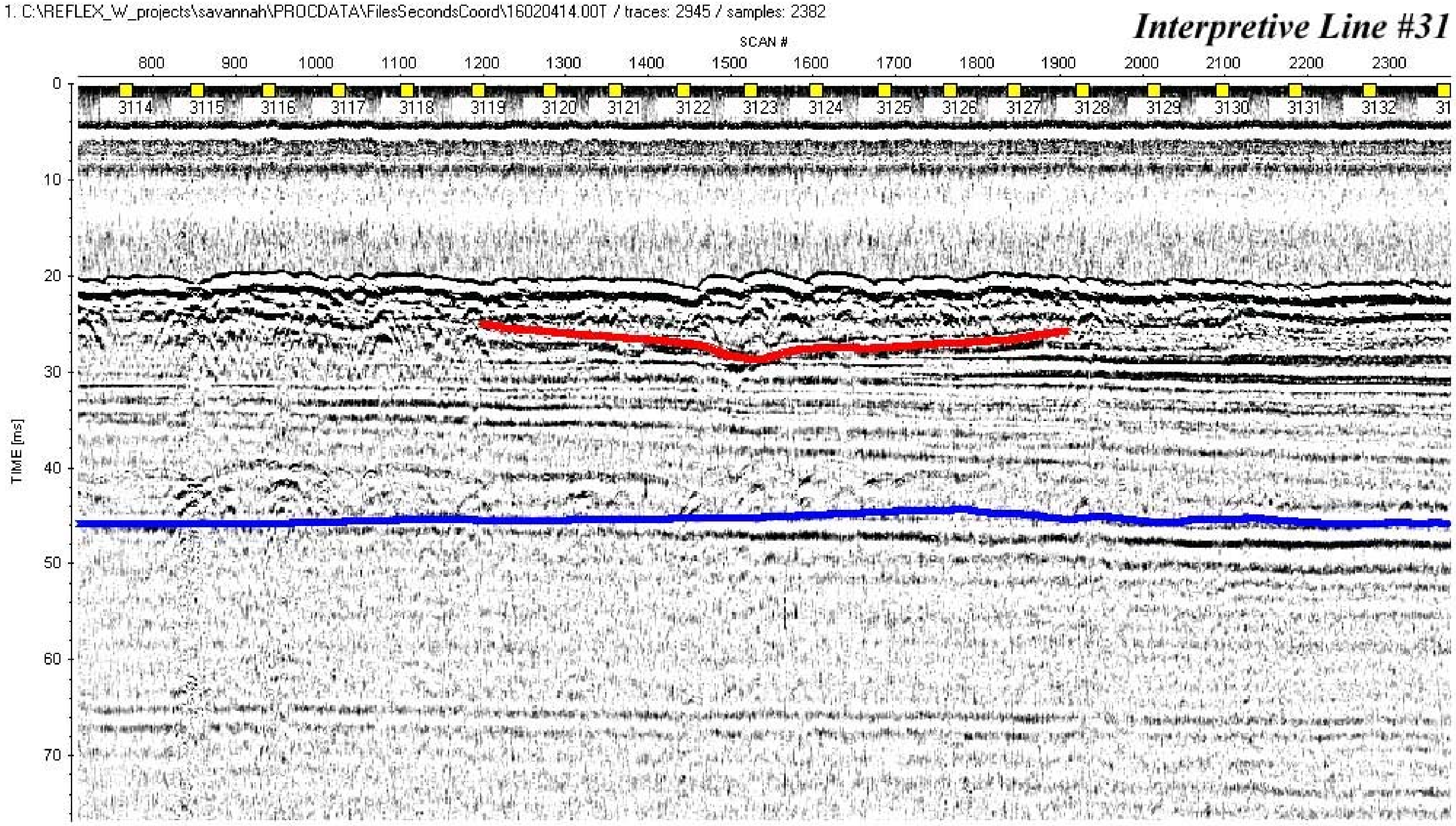
Interpretive Line #30
SCAN #
500
600
700
800
900
1000
1100
1200
1300
1400
1500
3081
3082
3083
3084
3085
3086
3087
3088
3089
3090
3091
3092
3093
3094
3095
3096
3097
3098
3099
3100
3101
TIME [ms]
0
10
20
30
40
50
60
70


Interpretive Line #31

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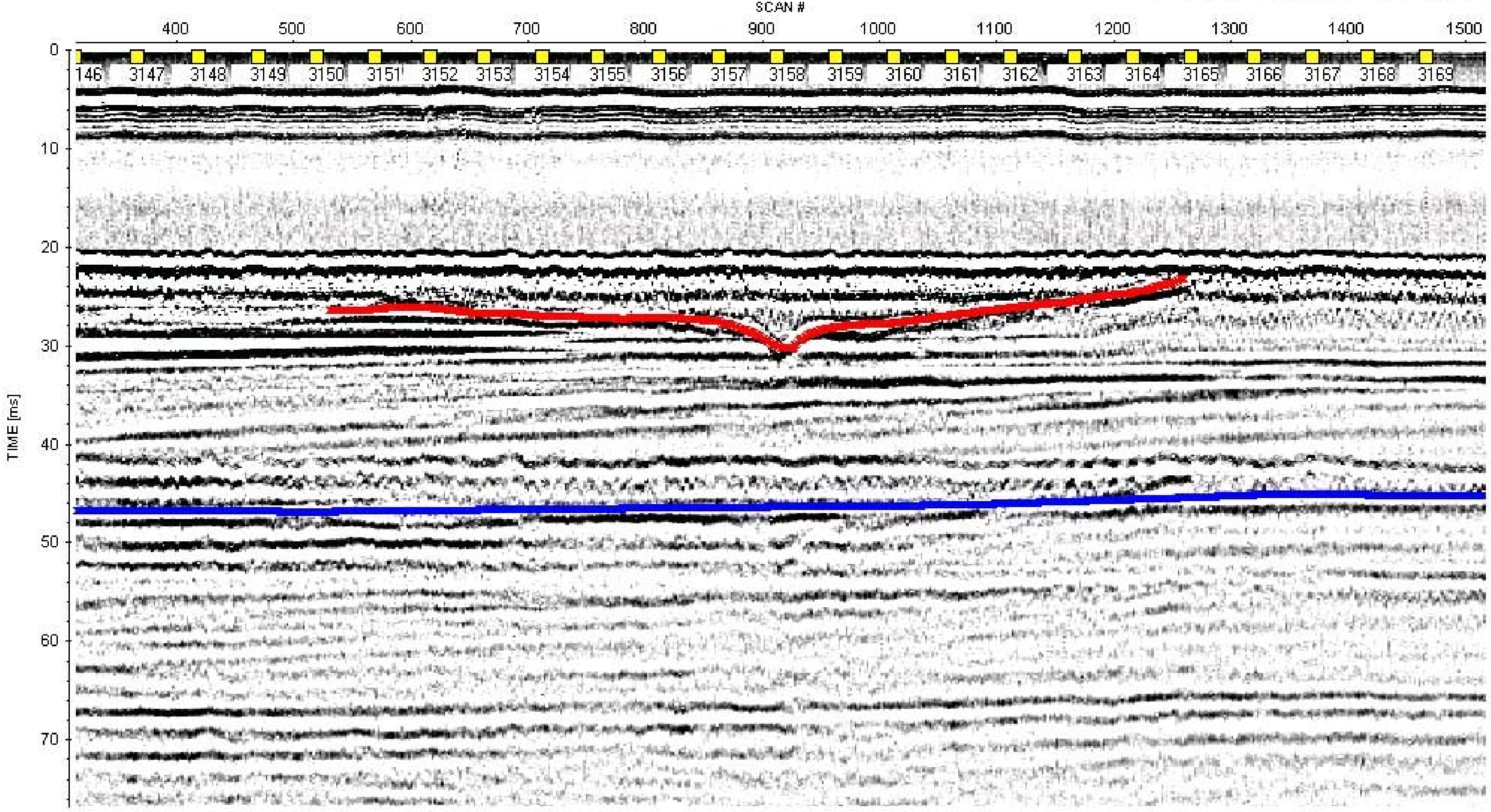
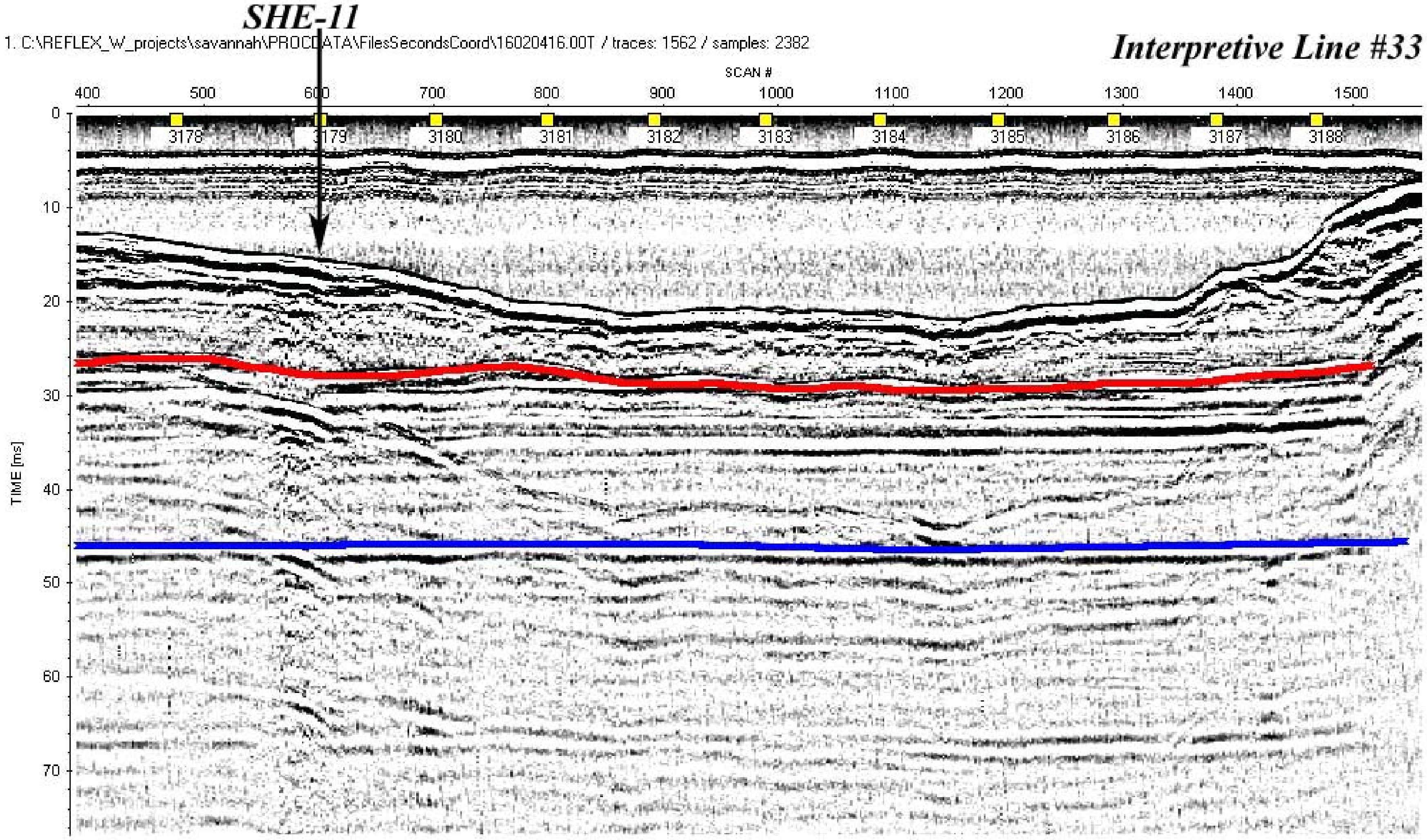
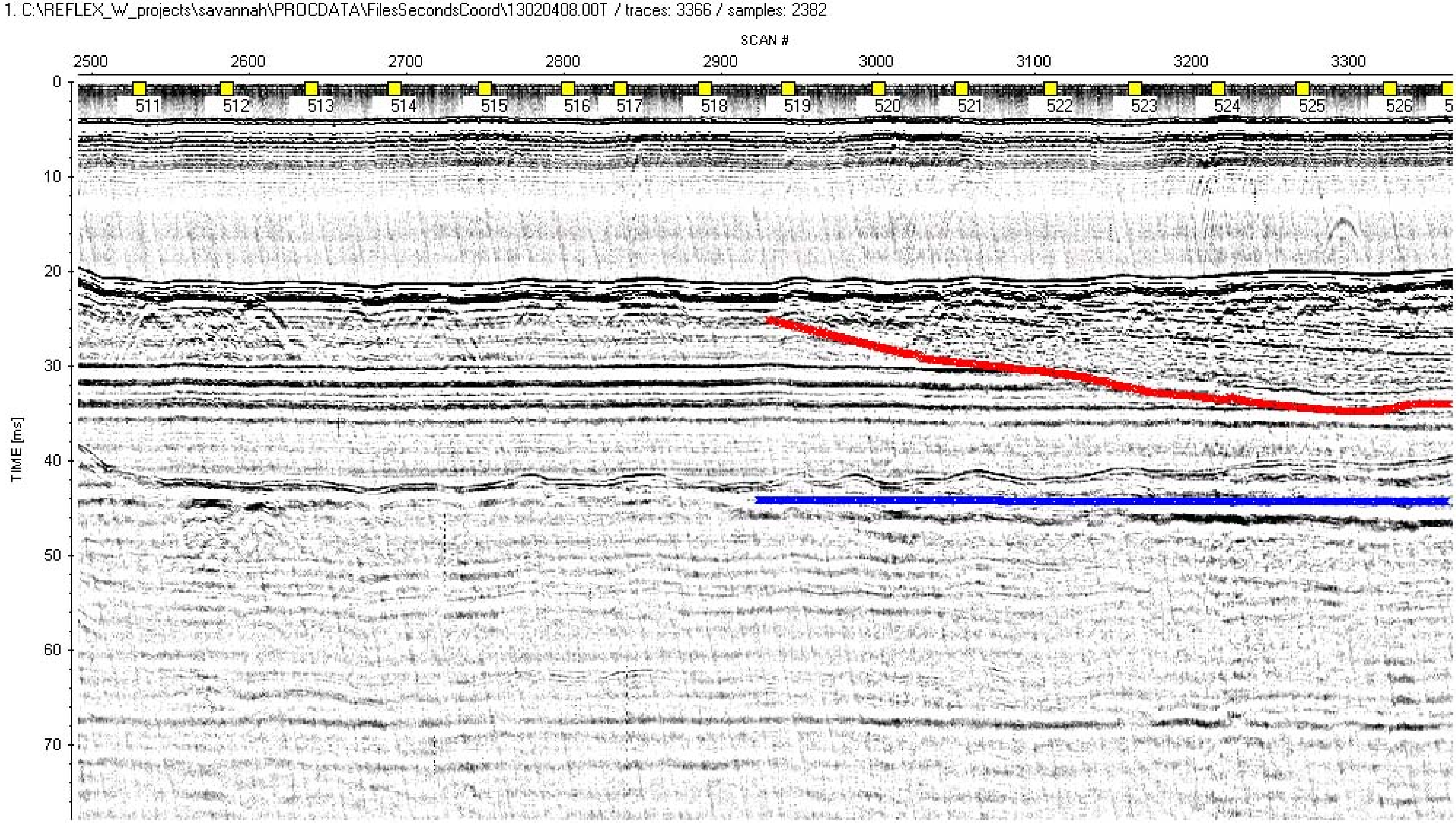
Interpretive Line #32



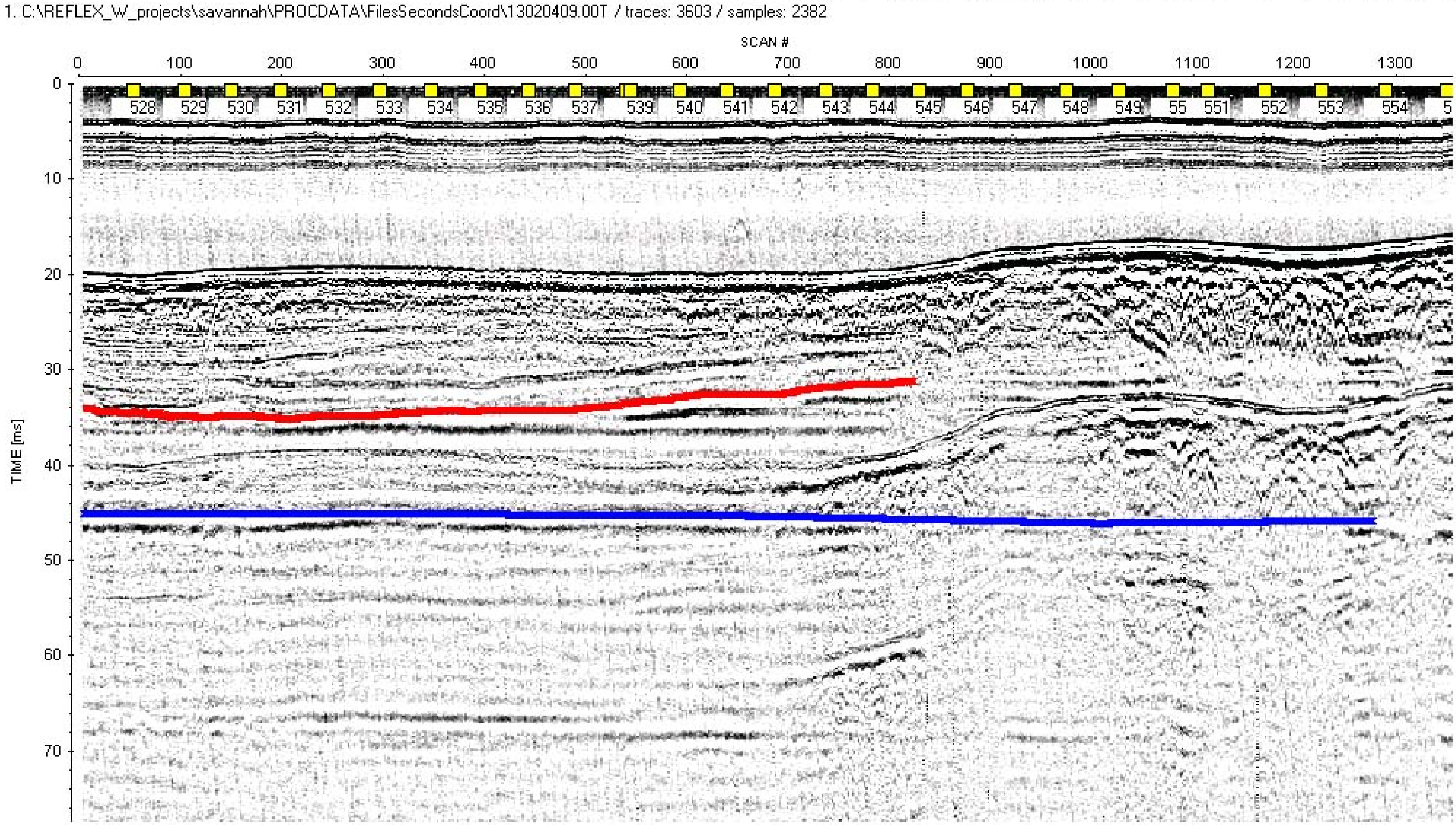
Interpretive Line #33



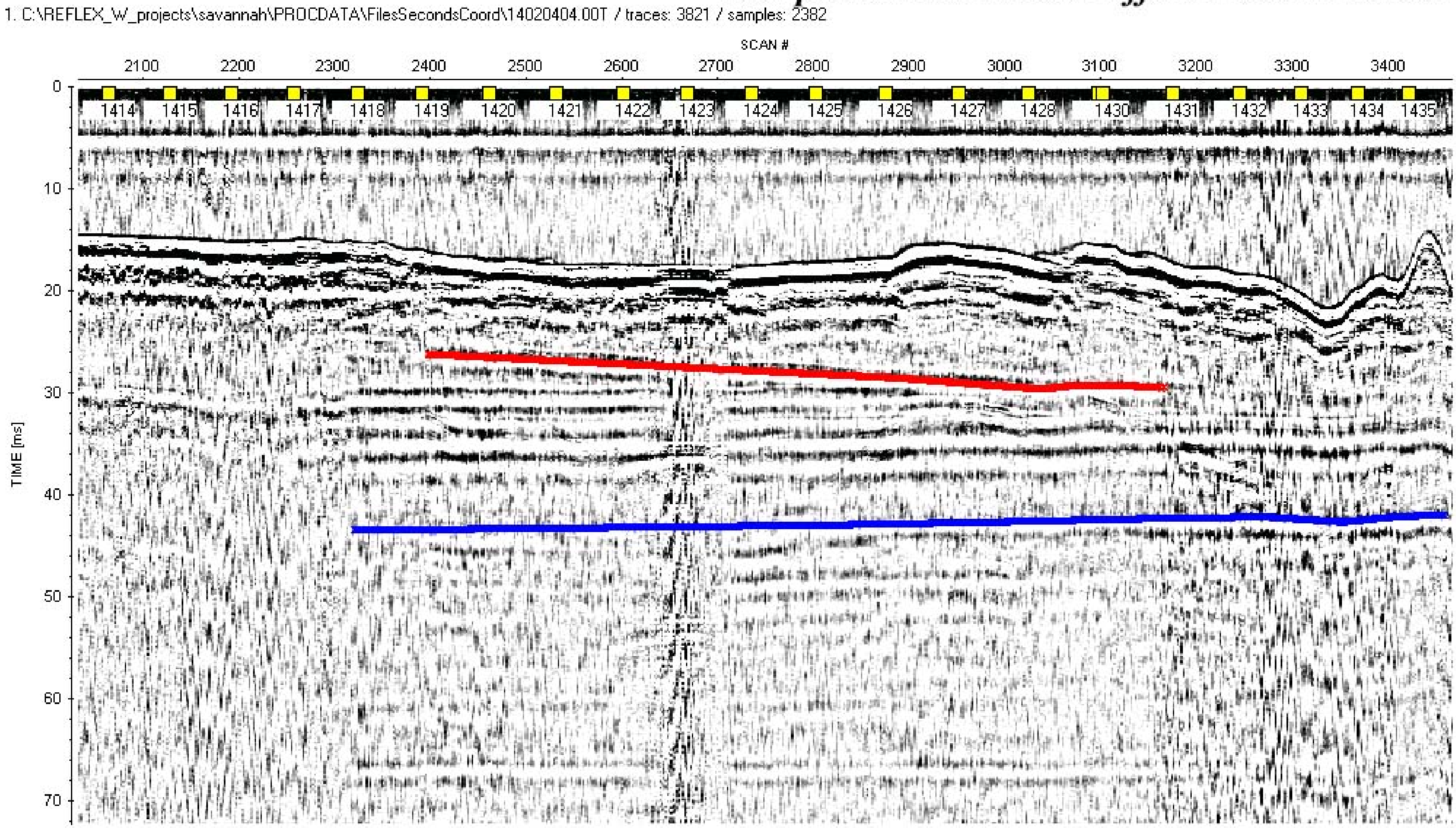
Interpretive Line # North Offset 7+000 to 12+000 (1 of 2)



Interpretive Profile #North Offset 7+000 to 12+000 (2 of 2)



Interpretive Line #South Offset 7+000 to 10+000



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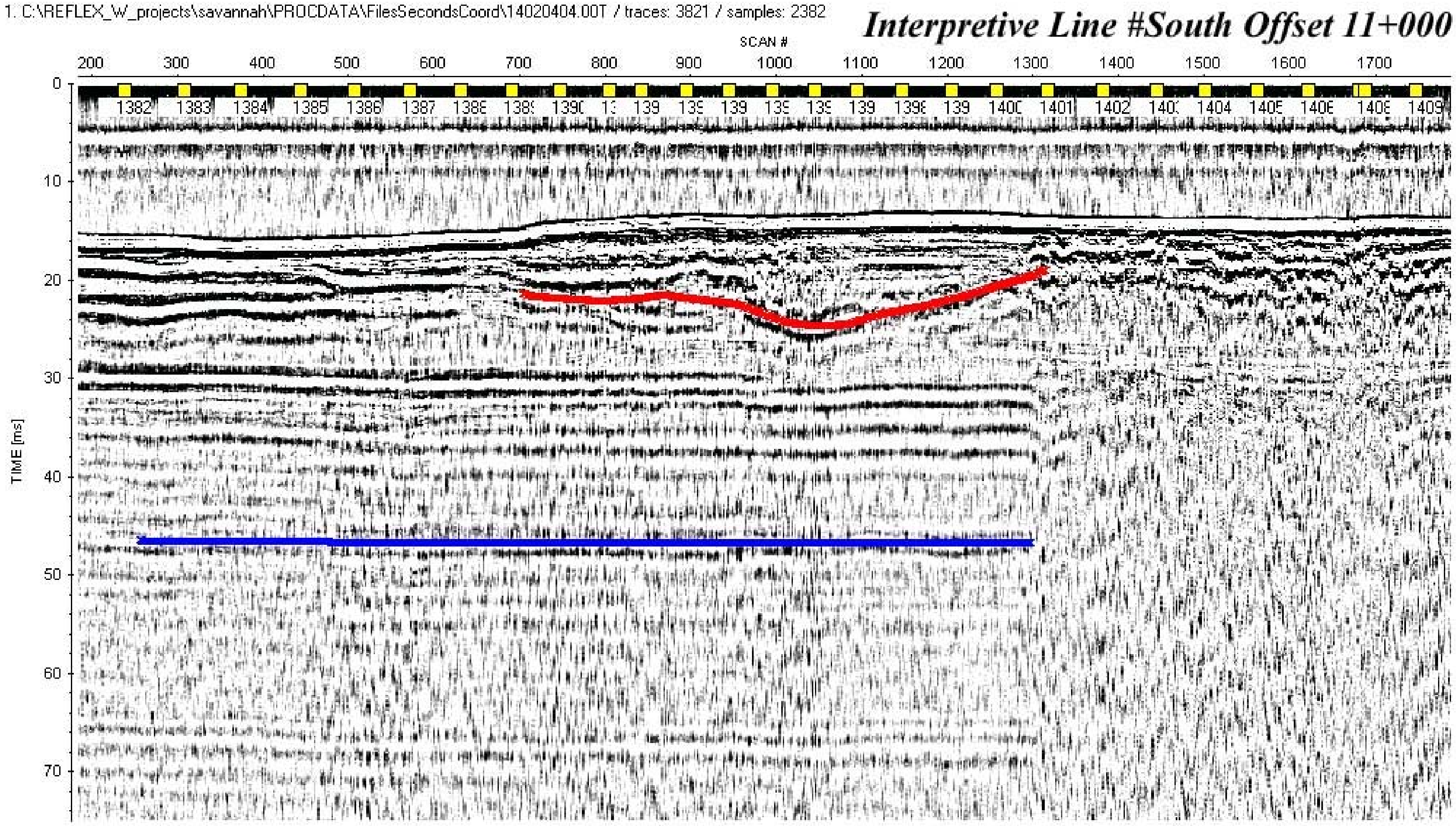
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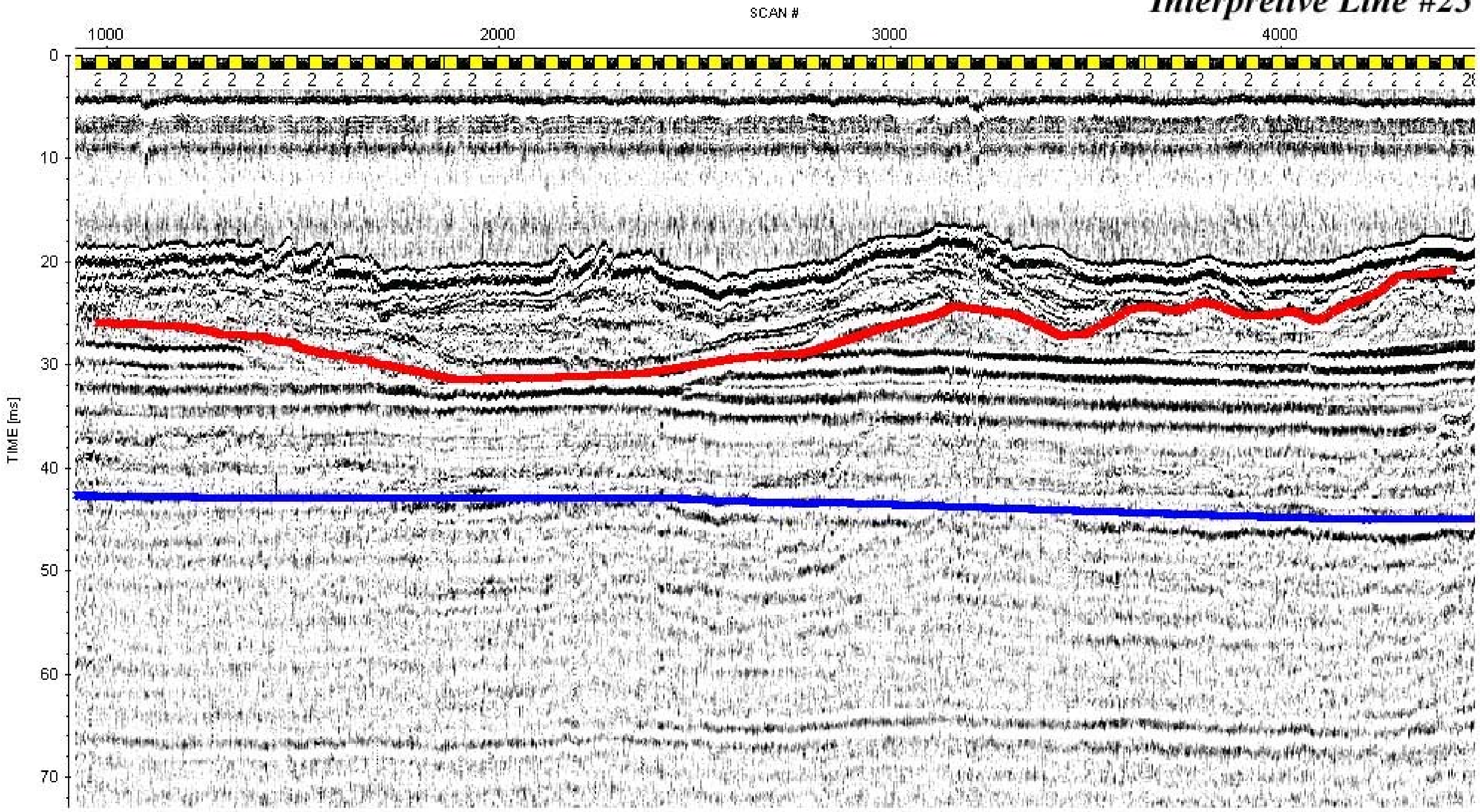
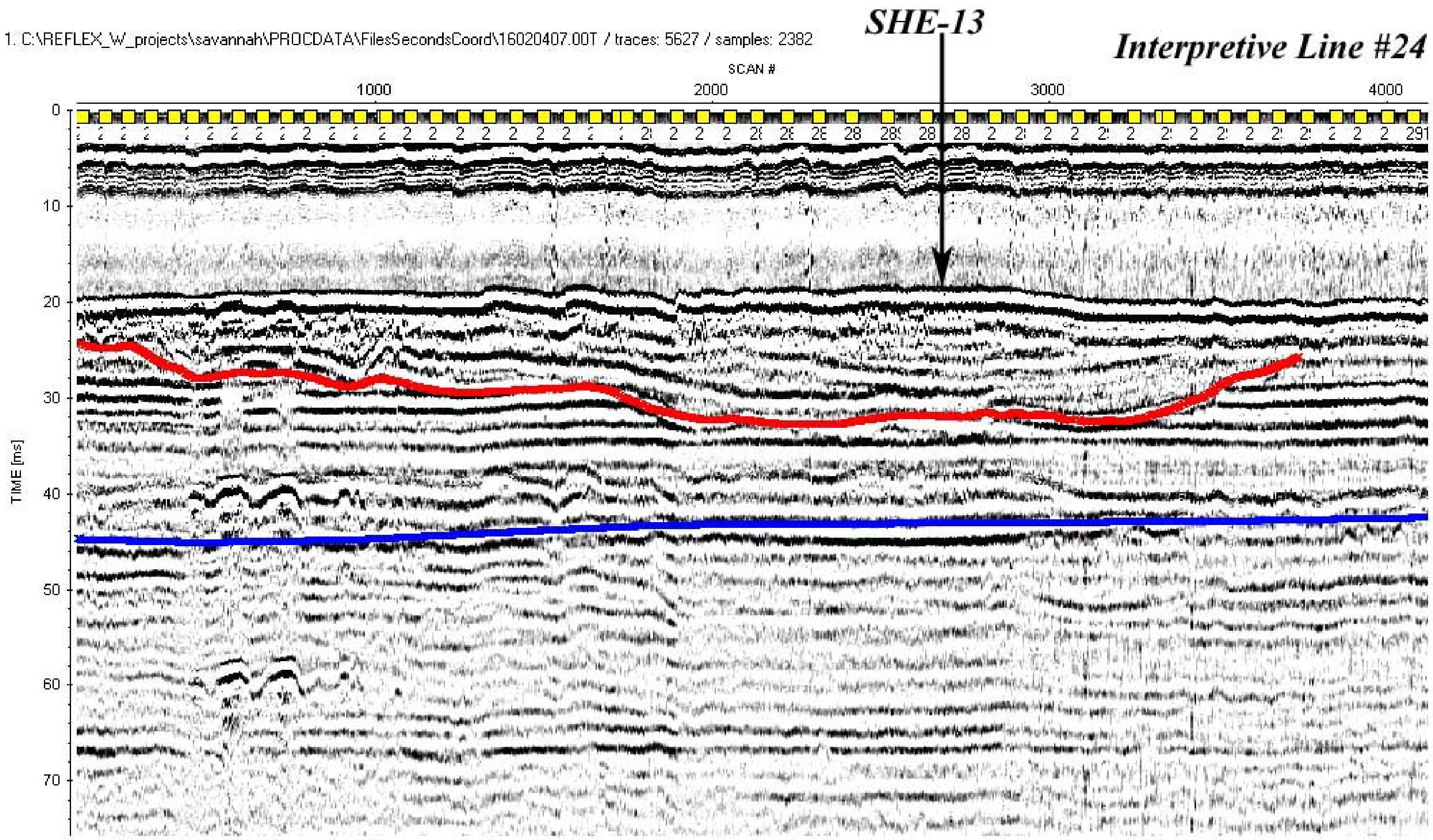
Interpretive Line #South Offset 11+000
SCAN #
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
TIME [ms]
0
10
20
30
40
50
60
70
1382
1383
1384
1385
1386
1387
1401
1402
1404

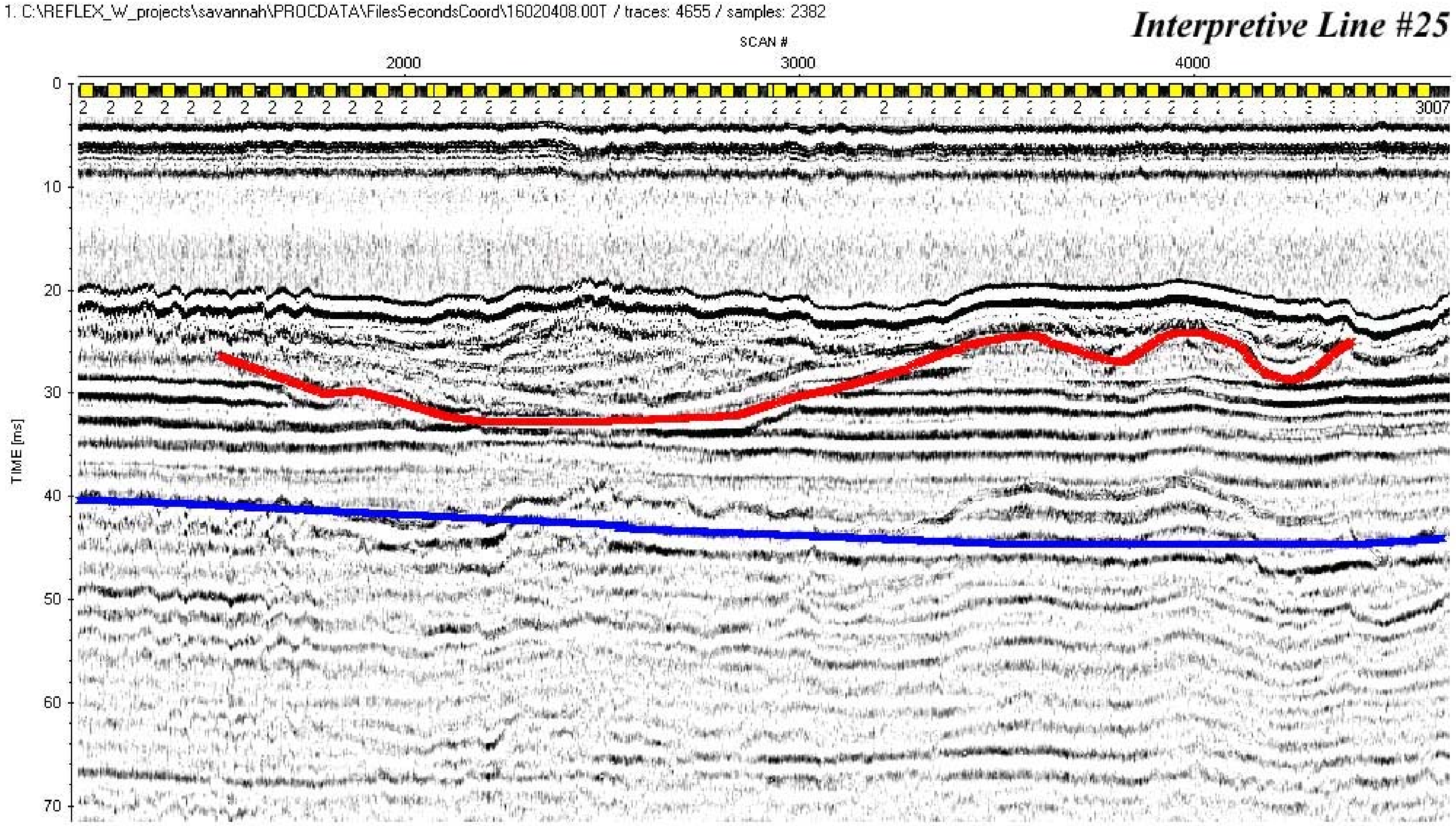
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\16020406.00T / traces: 4662 / samples: 2382

Interpretive Line #23

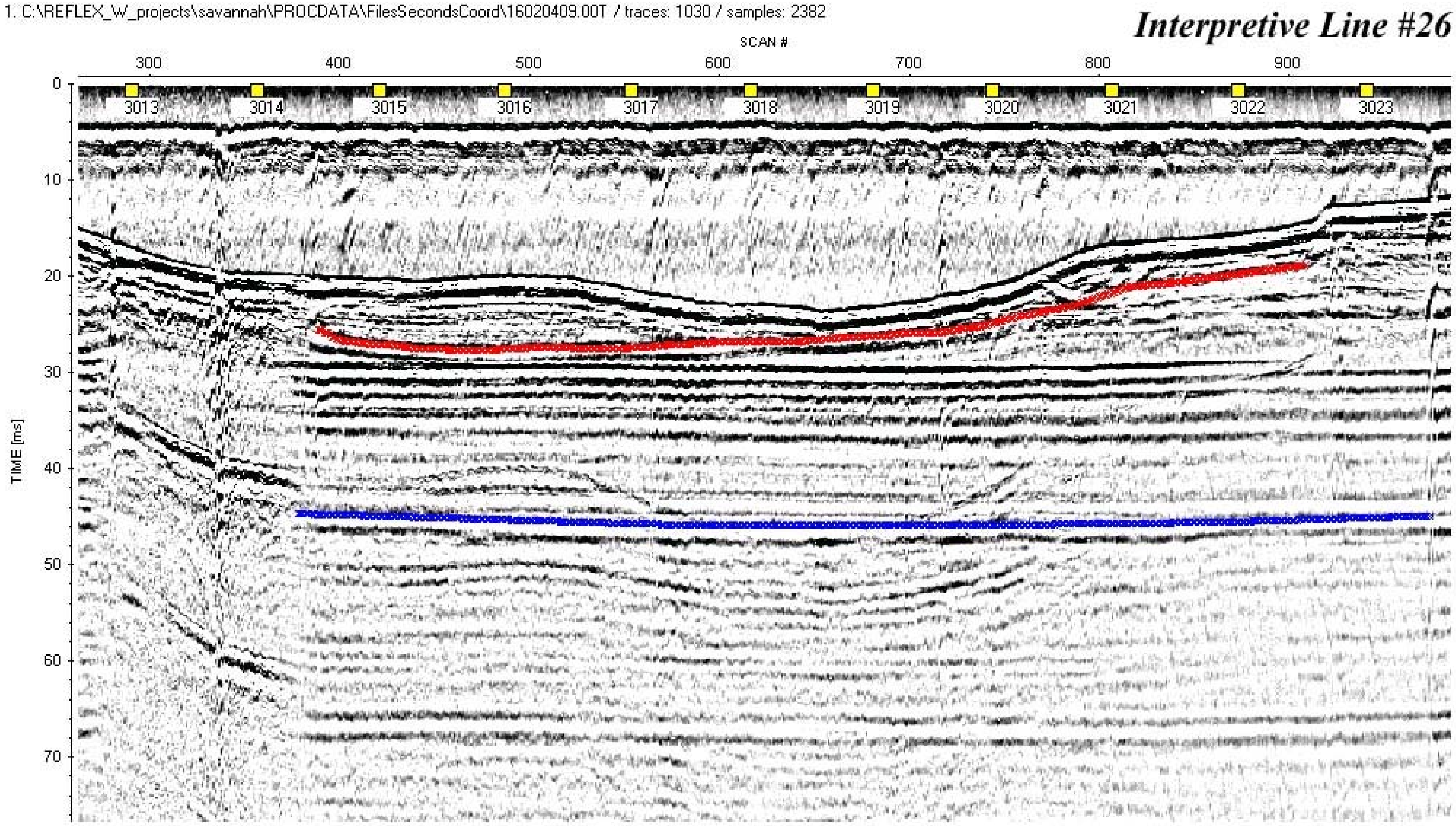



1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\16020407.00T / traces: 5627 / samples: 2382
SHE-13
Interpretive Line #24
SCAN #
1000
2000
3000
4000
TIME [ms]
0
10
20
30
40
50
60
70

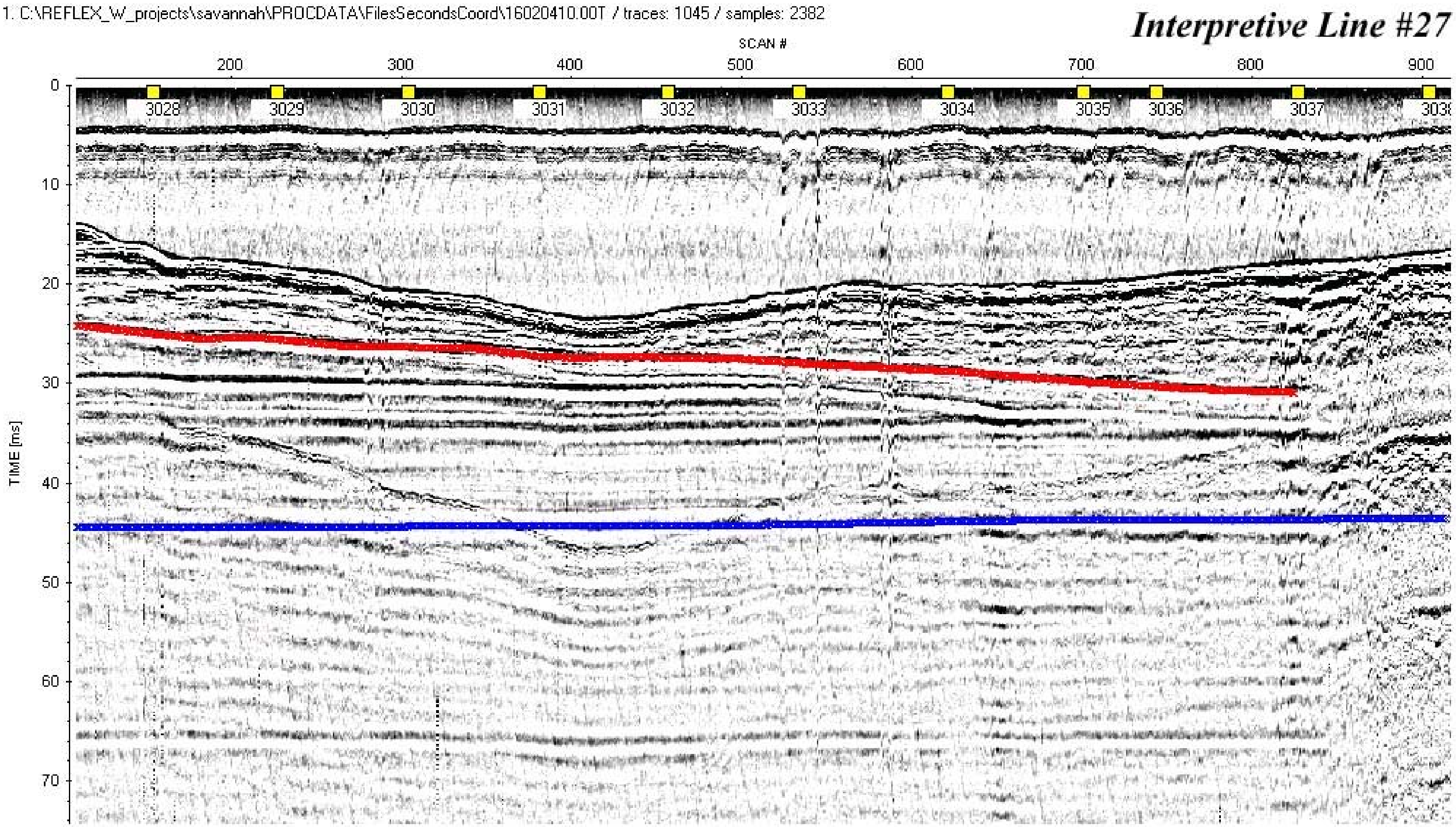
Interpretive Line #25

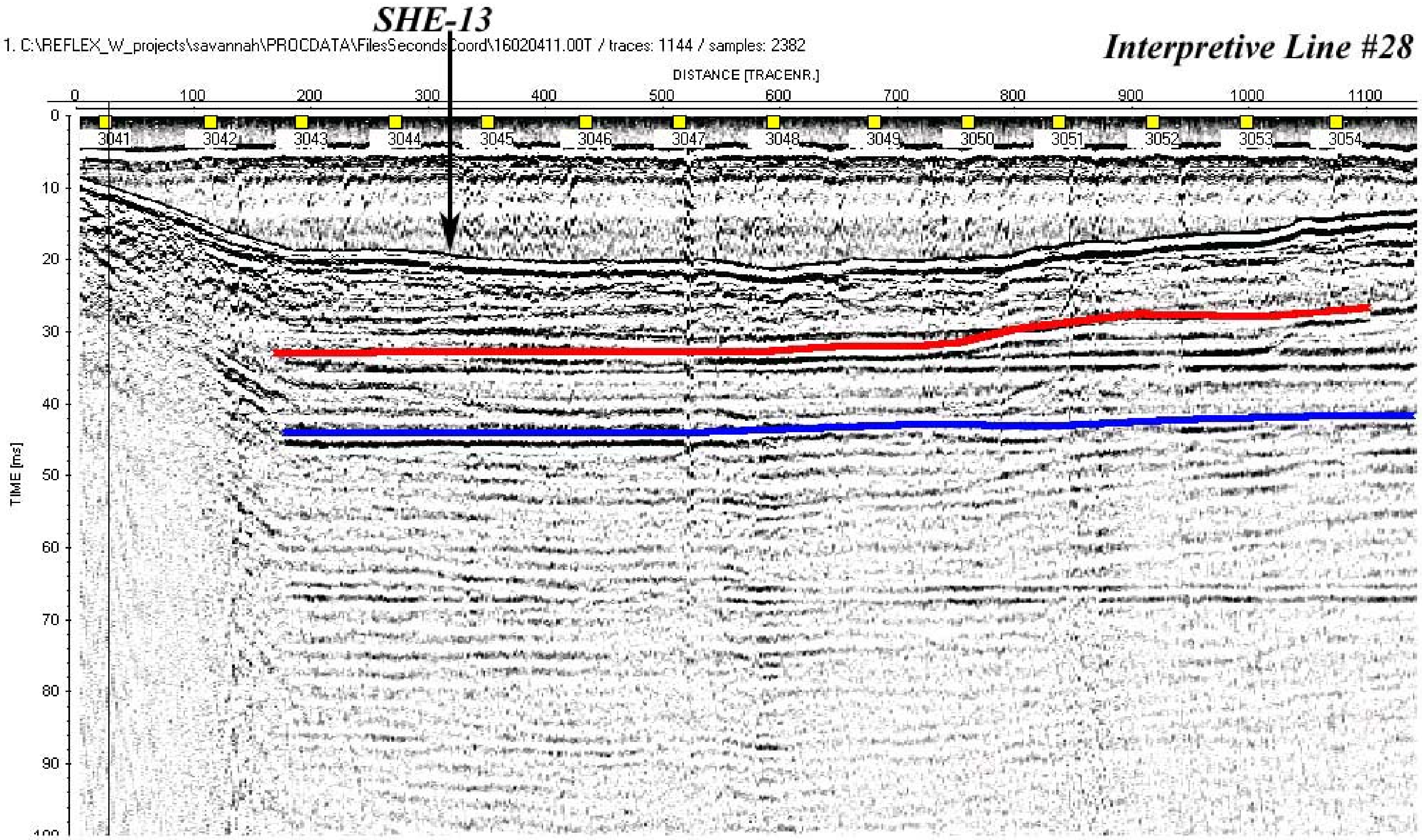


Interpretive Line #26



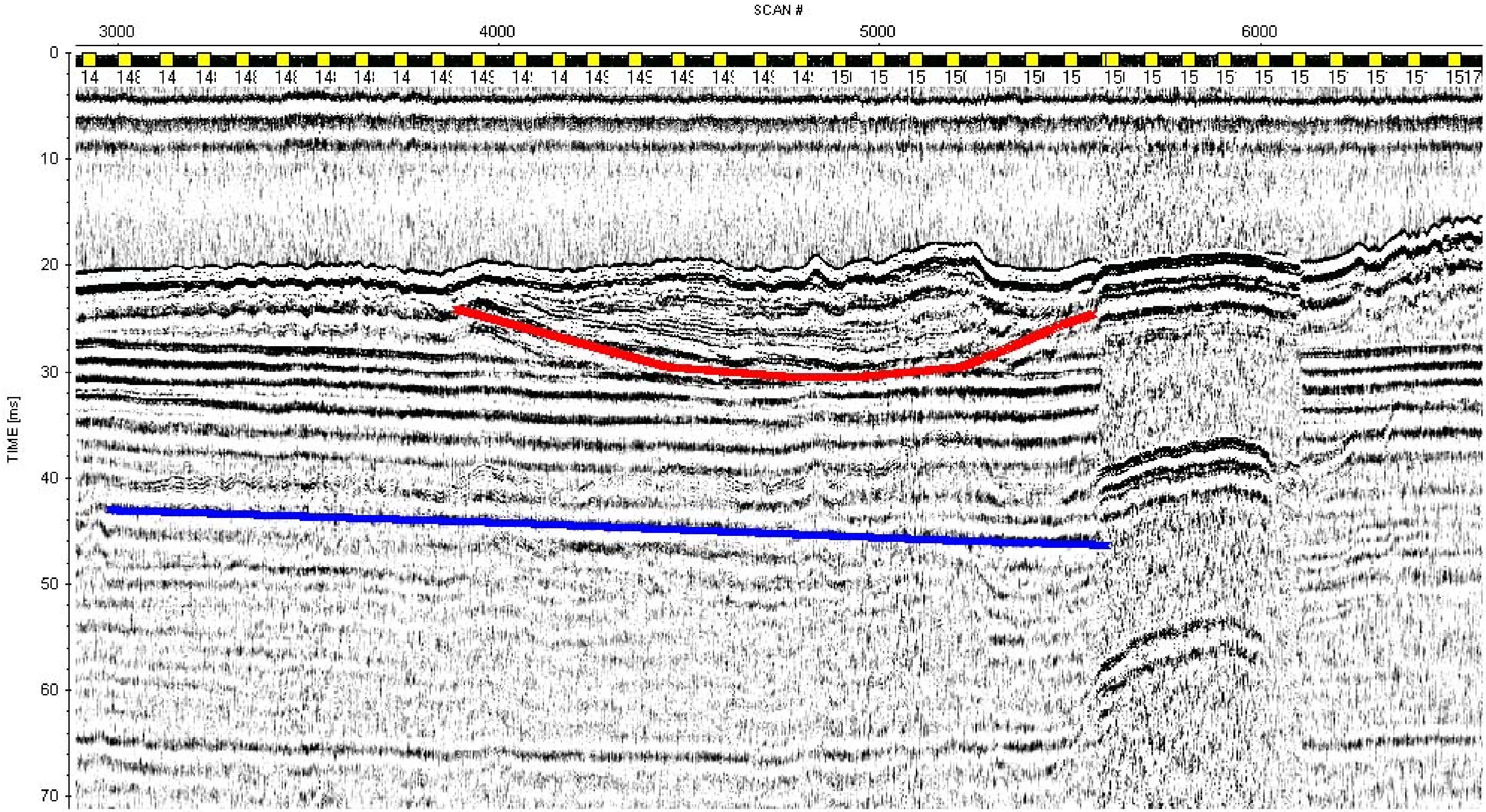
Interpretive Line #27

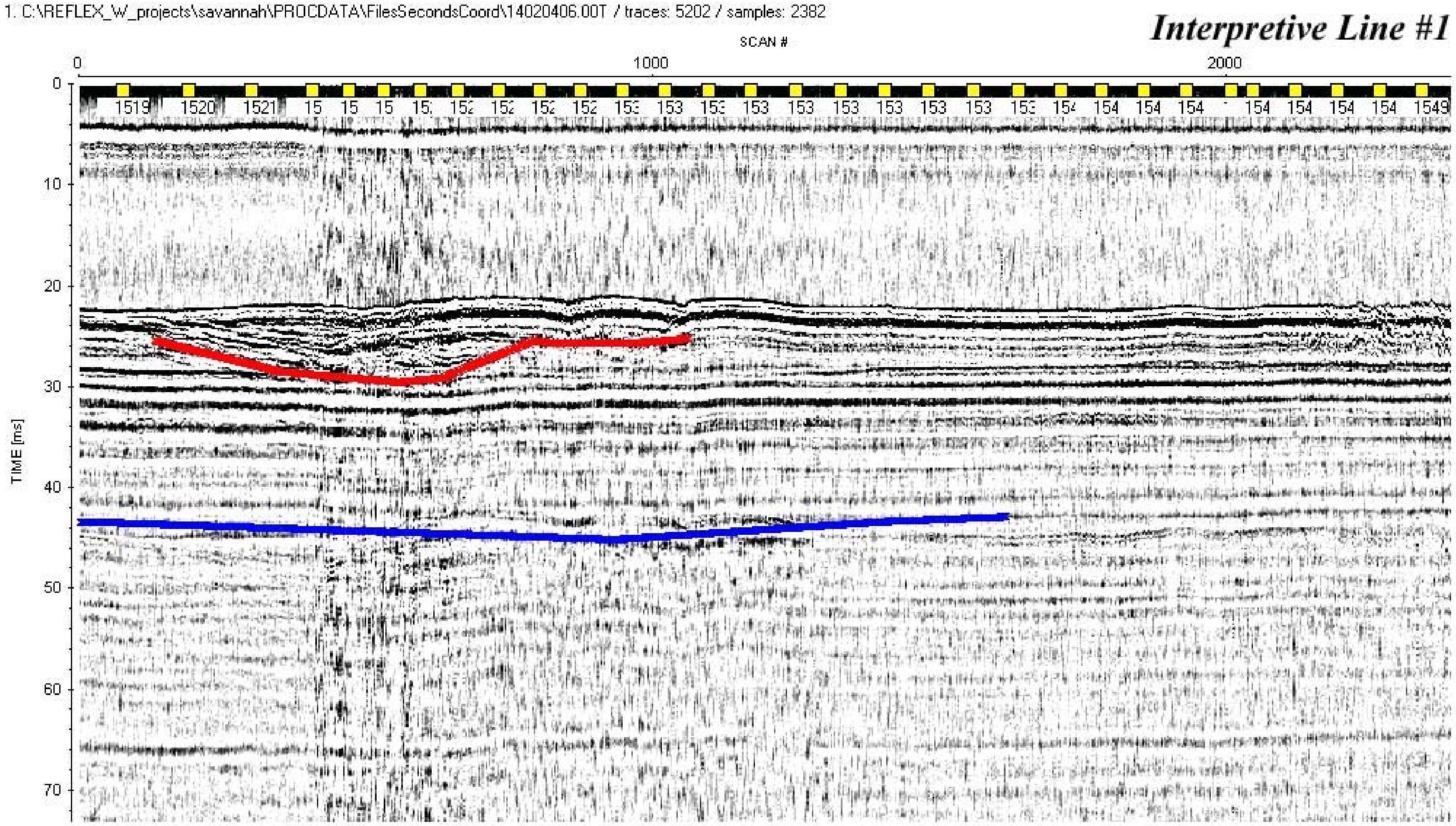



SHE-13
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\16020411.00T / traces: 1144 / samples: 2382
Interpretive Line #28
DISTANCE [TRACENR.]
0
100
200
300
400
500
600
700
800
900
1000
1100
TIME [ms]
0
10
20
30
40
50
60
70
80
90
100
3041
3042
3043
3044
3045
3046
3047
3048
3049
3050
3051
3052
3053
3054

Interpretive Line #South Offset 1+000 to 2+000

1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020405.00T / traces: 6586 / samples: 2382

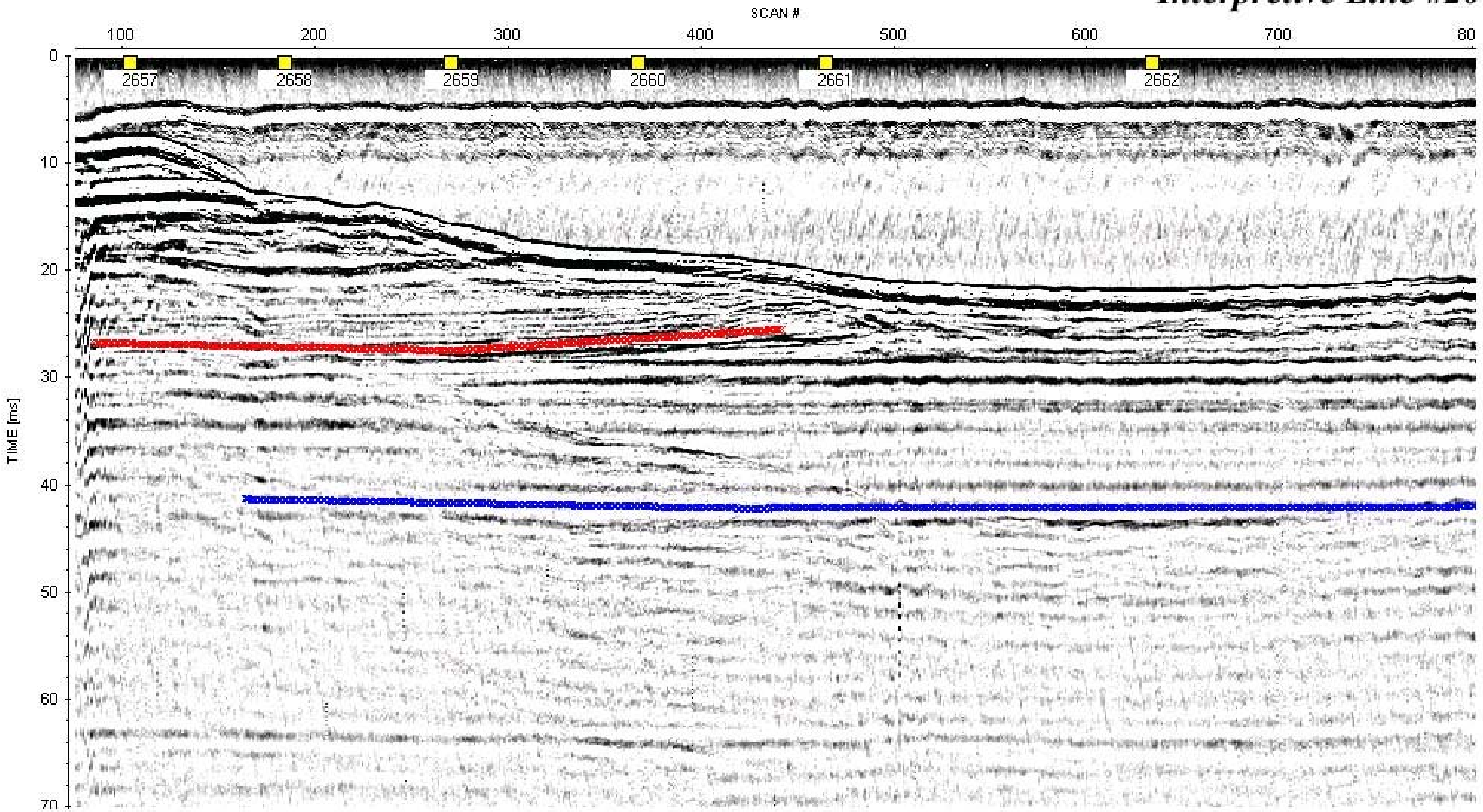


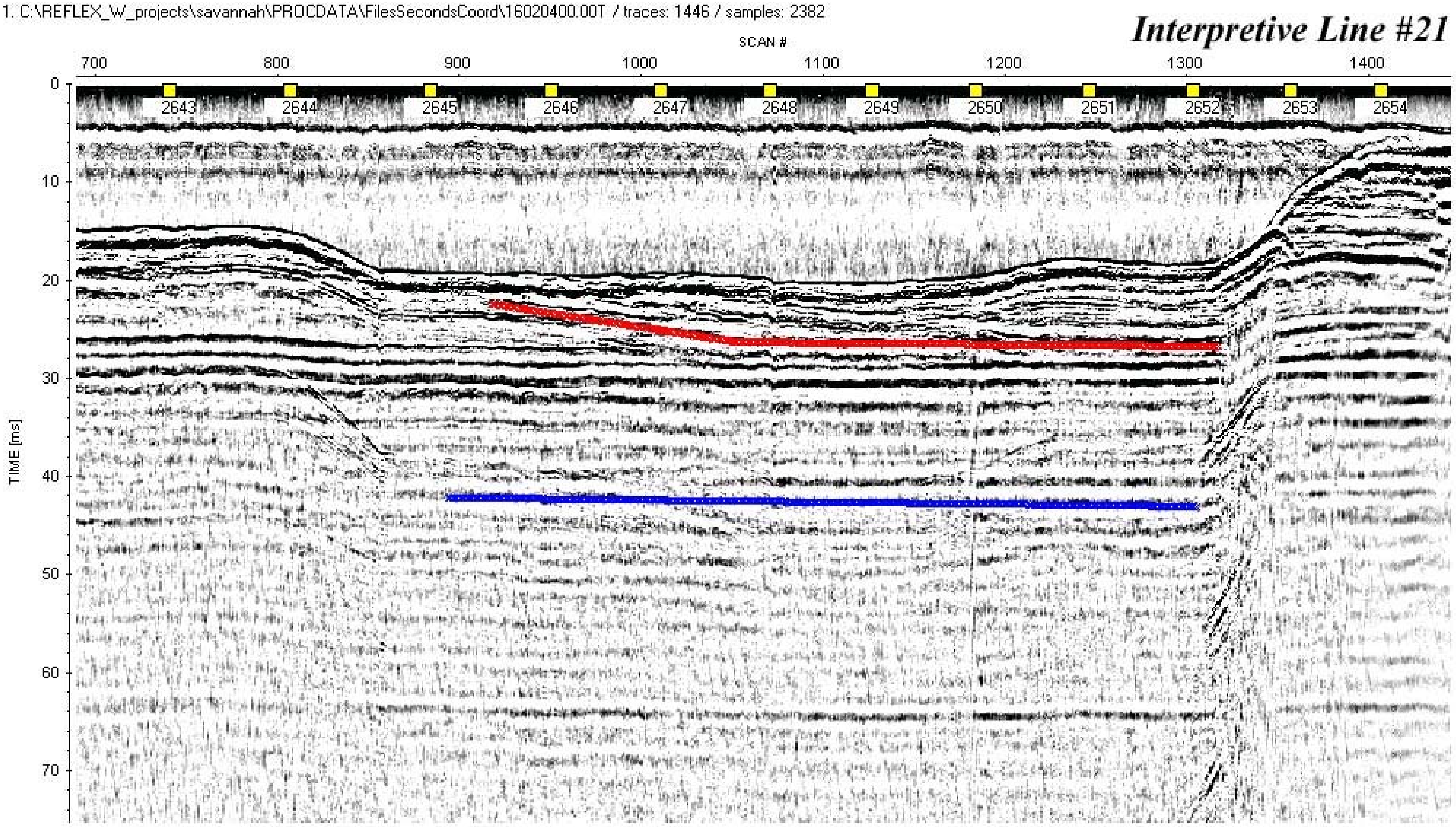


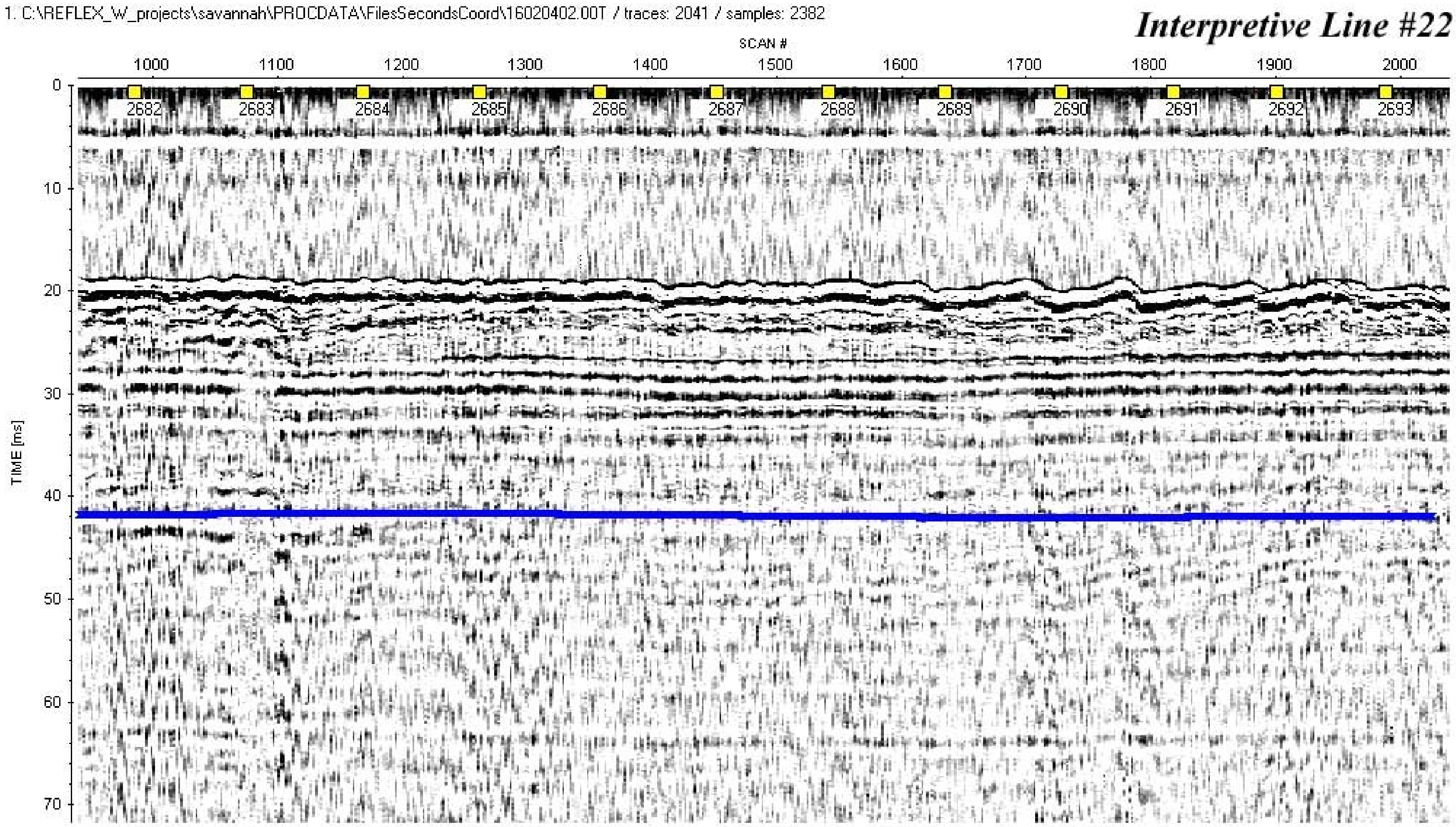
Interpretive Line #1

1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\16020401.00T / traces: 1573 / samples: 2382

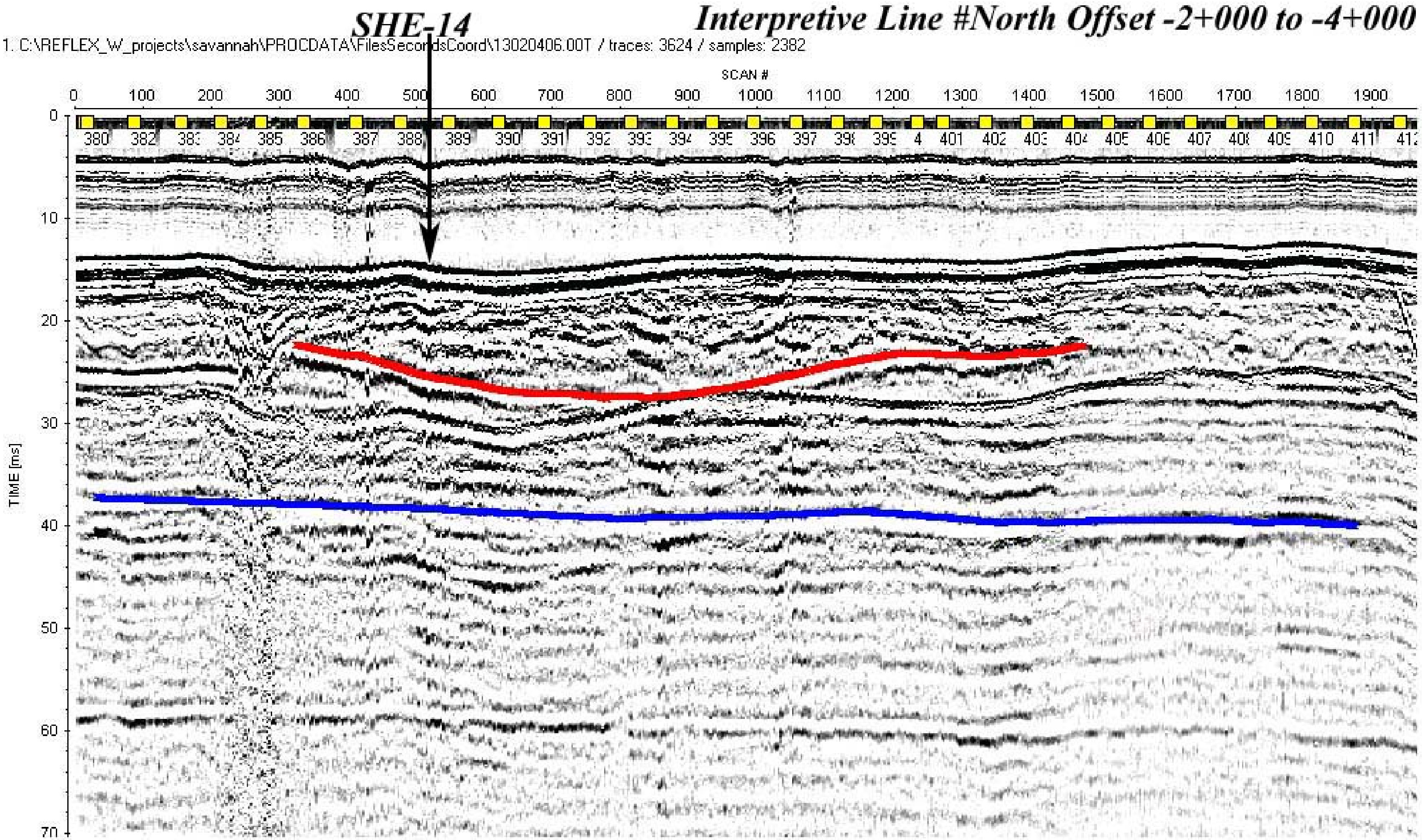
Interpretive Line #20



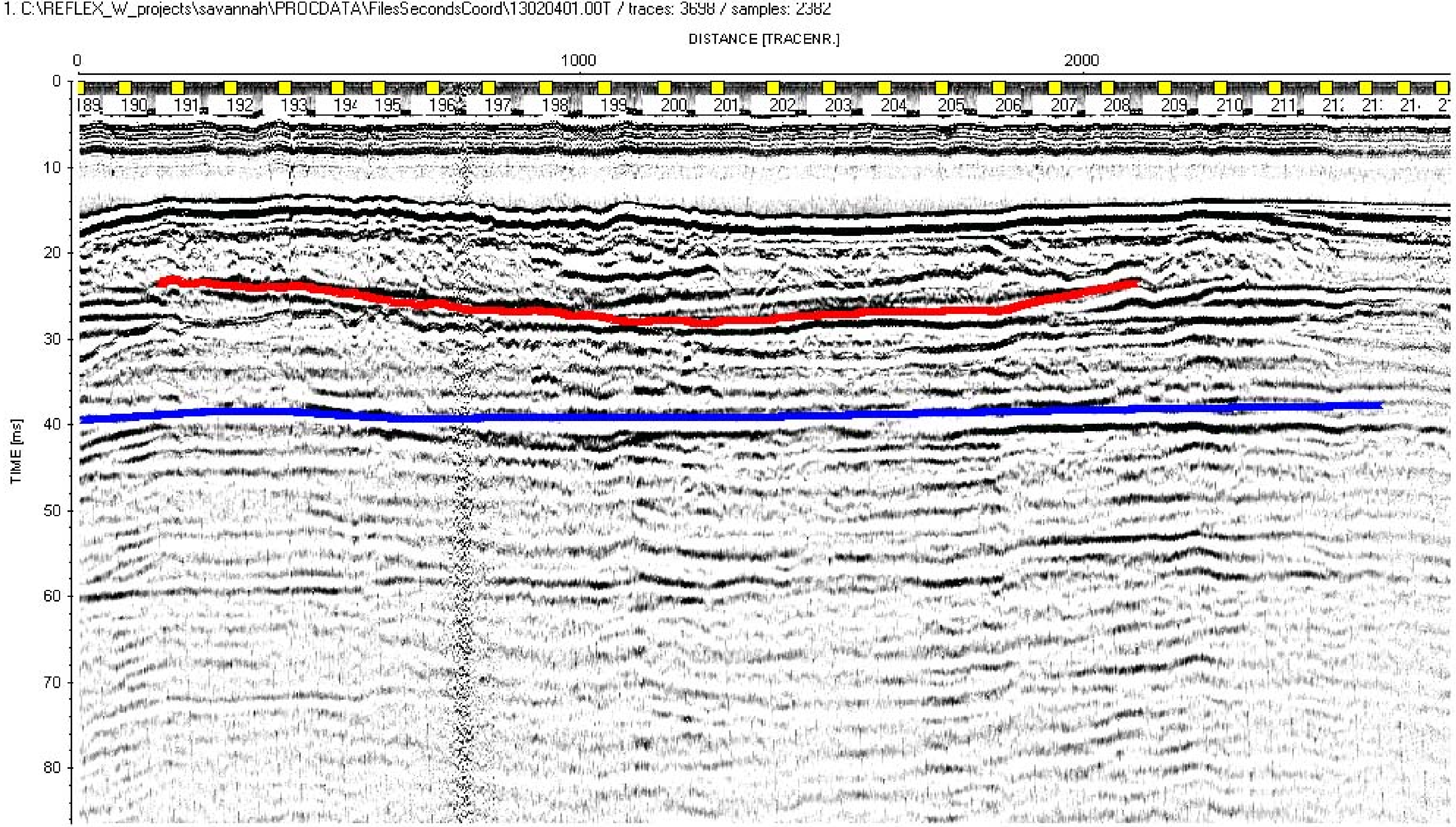

1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\16020400.00T / traces: 1446 / samples: 2382
Interpretive Line #21
SCAN #
700
800
900
1000
1100
1200
1300
1400
2643
2644
2645
2646
2647
2648
2649
2650
2651
2652
2653
2654
TIME [ms]
0
10
20
30
40
50
60
70



Interpretive Line #22

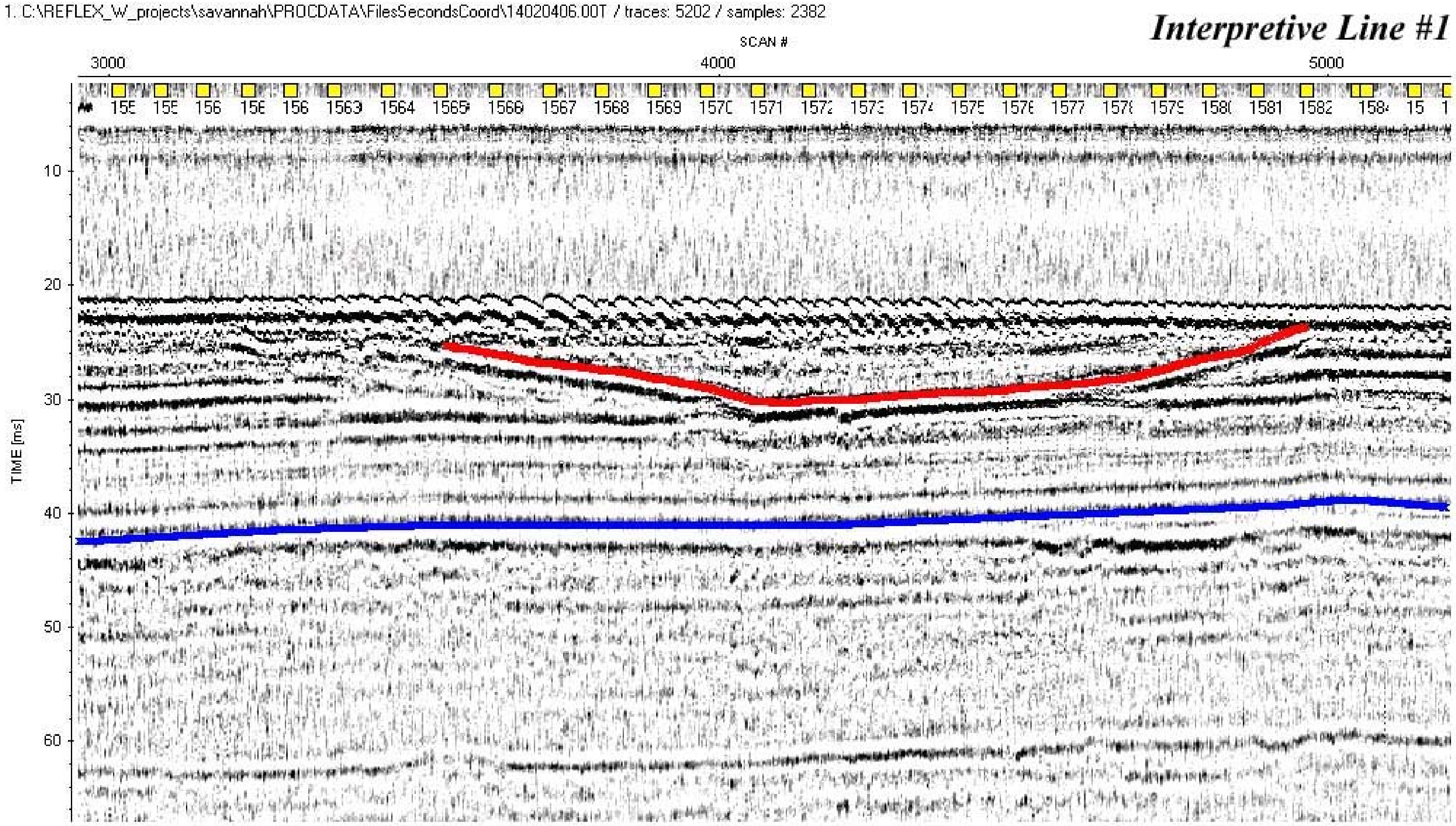

SHE-14
Interpretive Line #North Offset -2+000 to -4+000
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\13020406.00T / traces: 3624 / samples: 2382
SCAN #
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
380
382
384
385
386
387
388
389
390
391
392
394
395
396
397
4
401
402
405
407
410
411
TIME [ms]
0
10
20
30
40
50
60
70

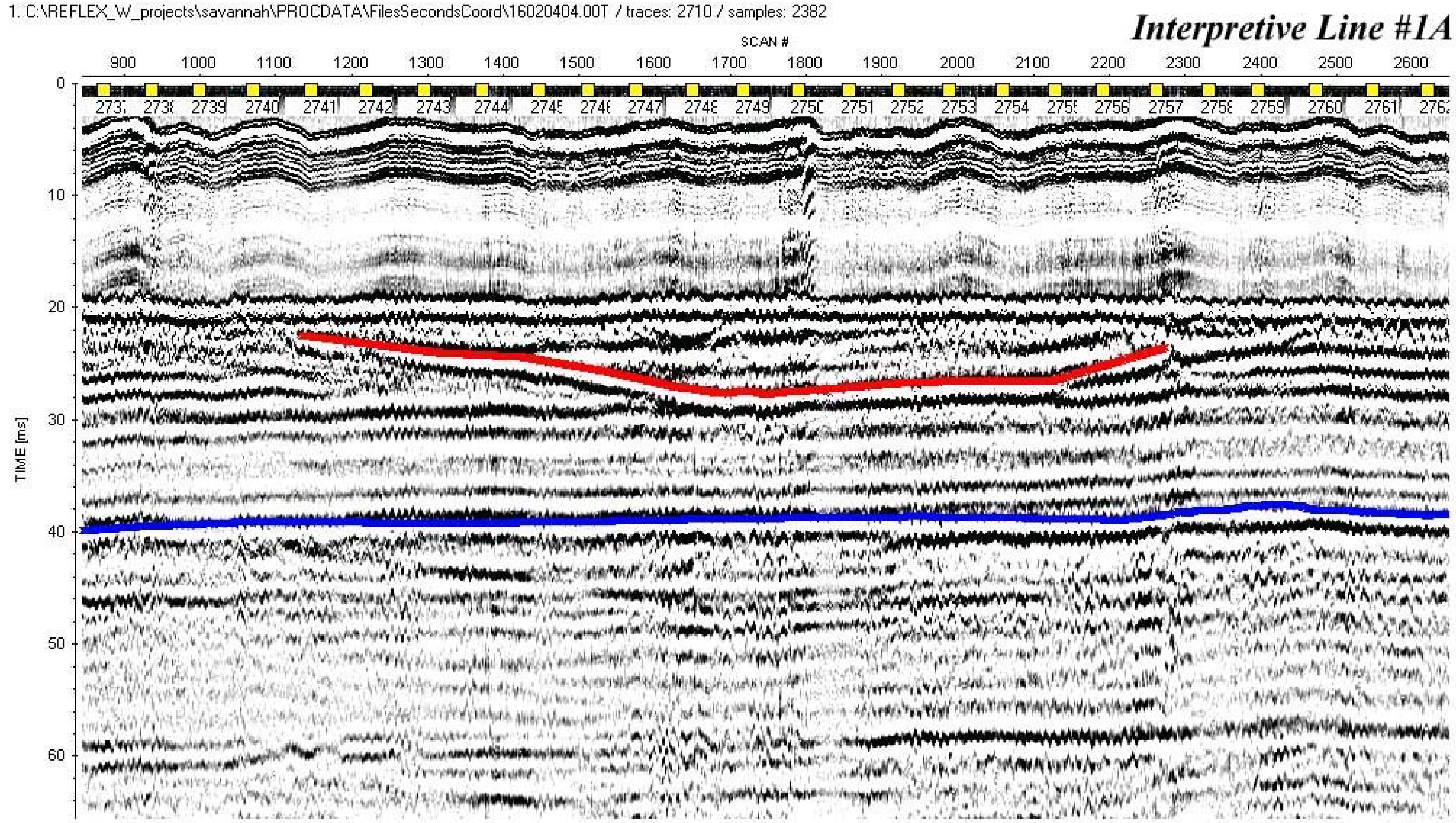
Interpretive Line #South Offset -2+000 to -4+000



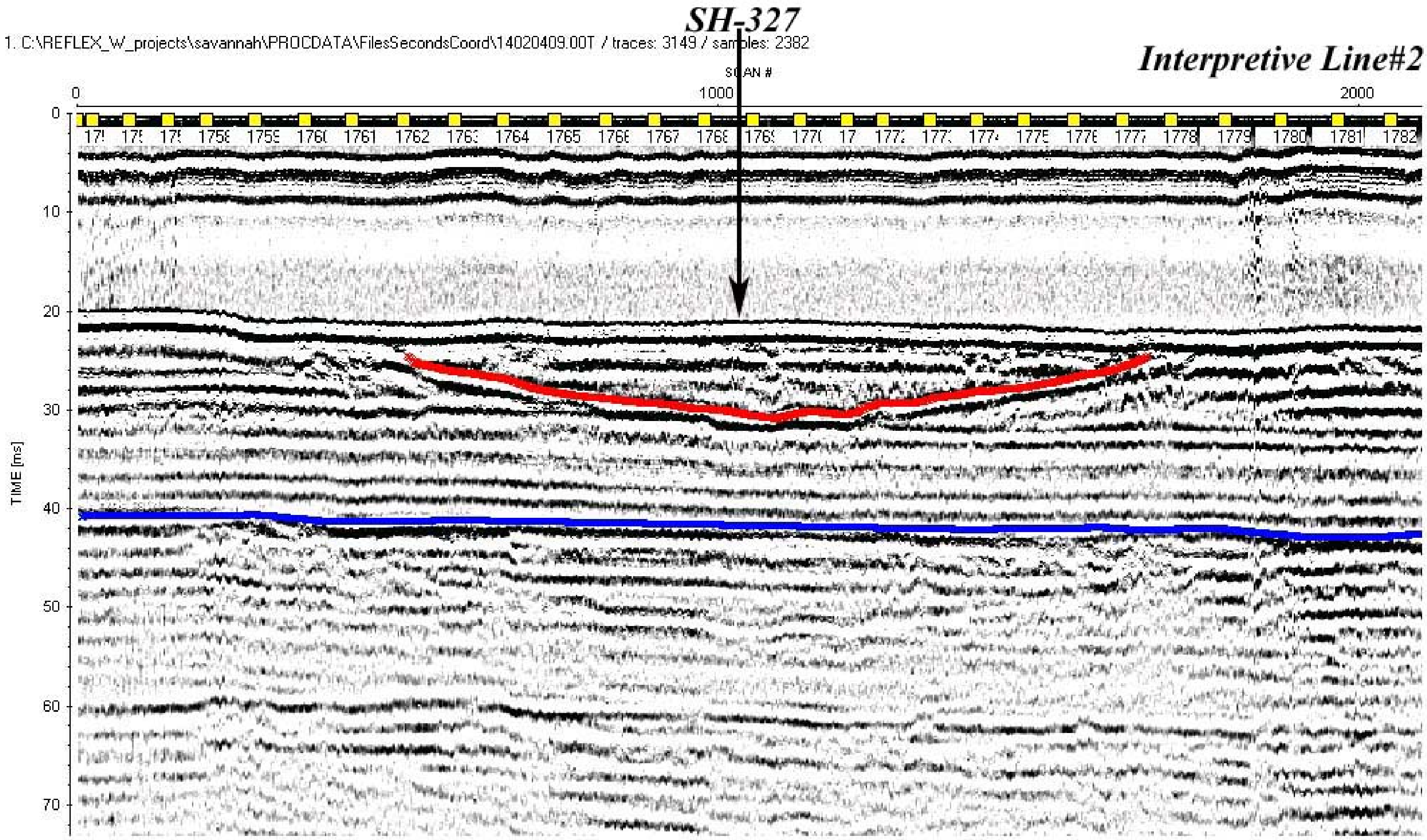
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\13020401.00T / traces: 3698 / samples: 2382

Interpretive Line #1

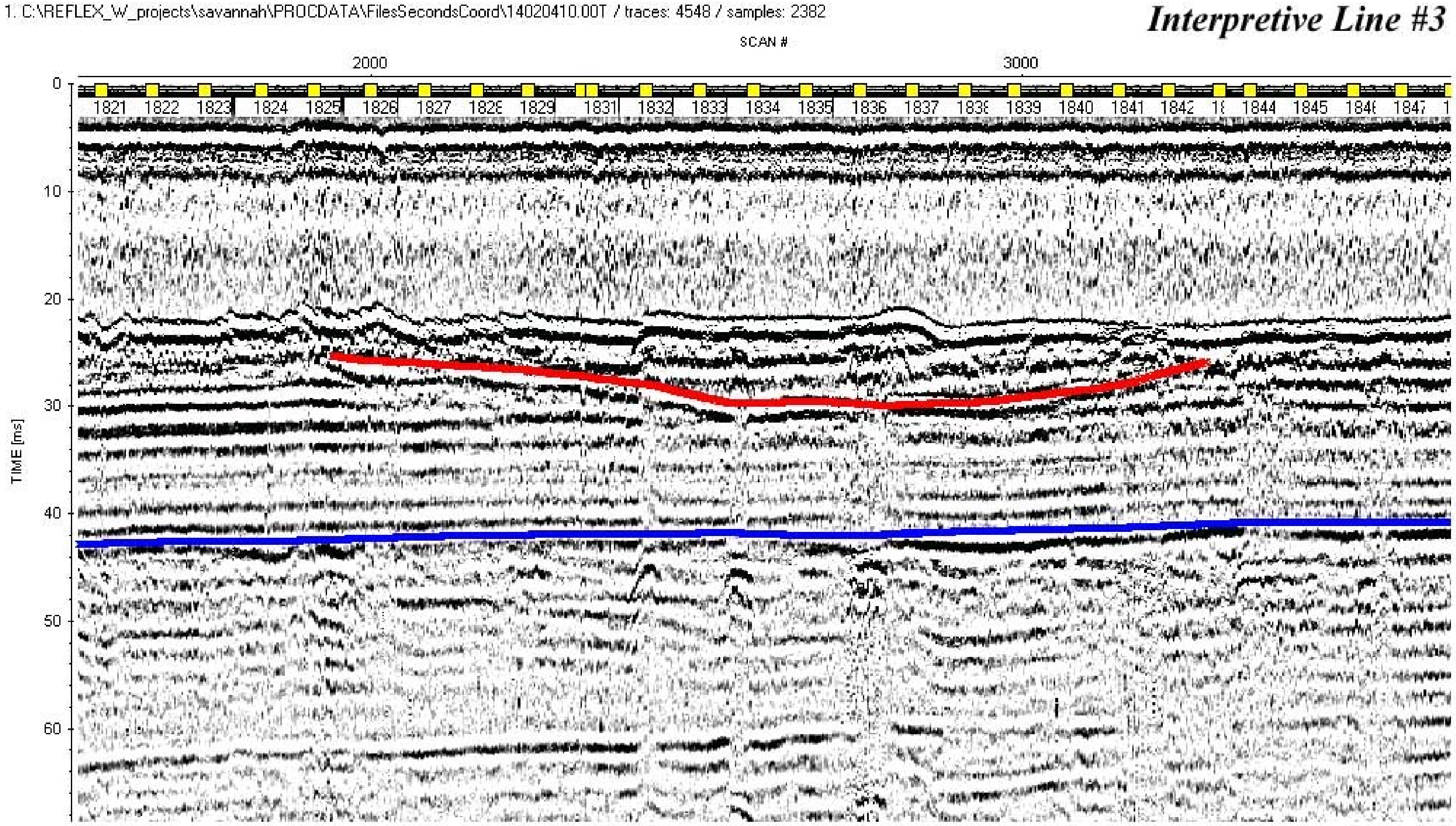




Interpretive Line #1A

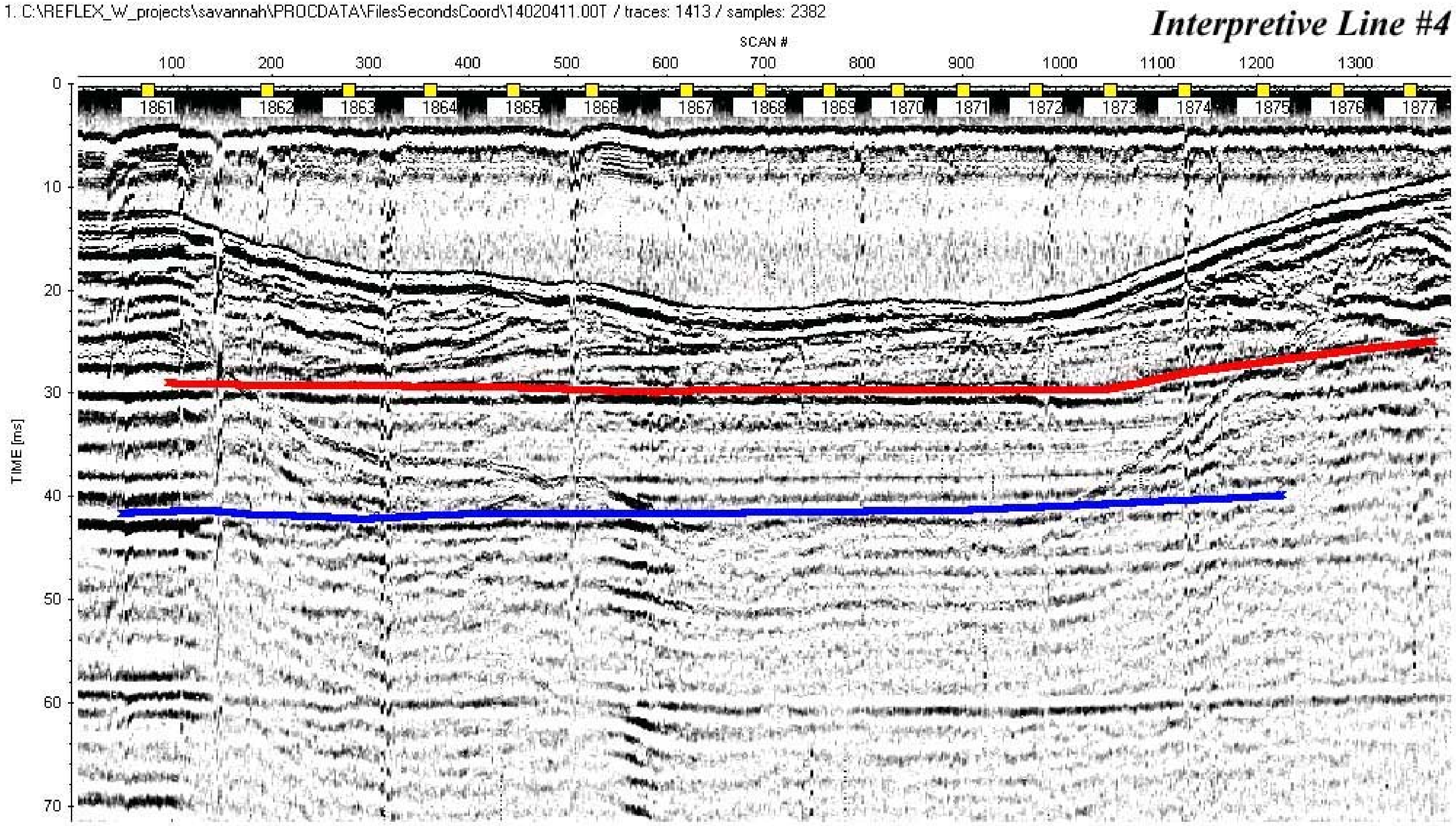

SH-327
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020409.00T / traces: 3149 / samples: 2382
Interpretive Line#2
SCAN #
0
1000
2000
1761
1762
1764
1765
1767
1775
1778
1779
1780
1781
1782
TIME [ms]
0
10
20
30
40
50
60
70

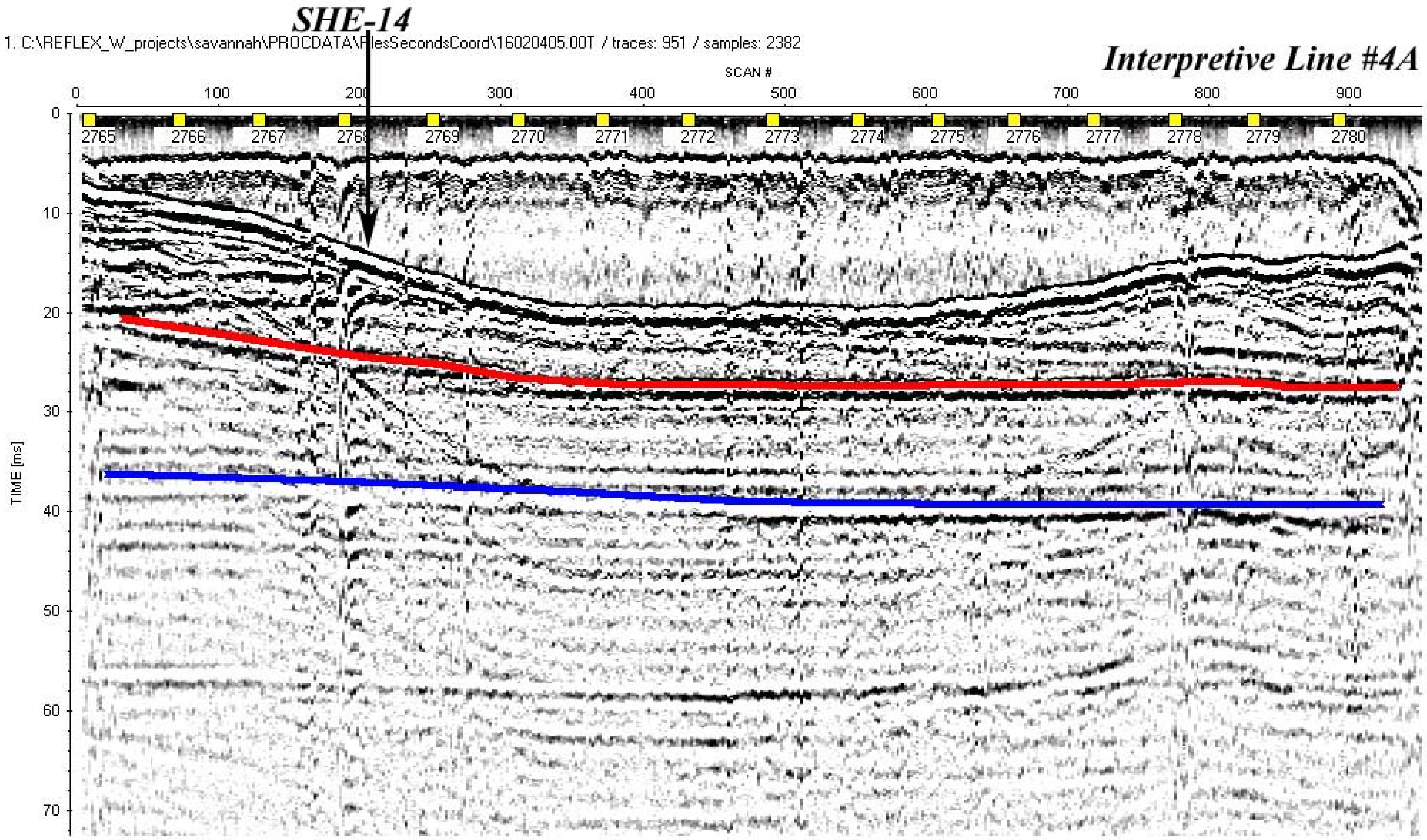
Interpretive Line #3



1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020410.00T / traces: 4548 / samples: 2382

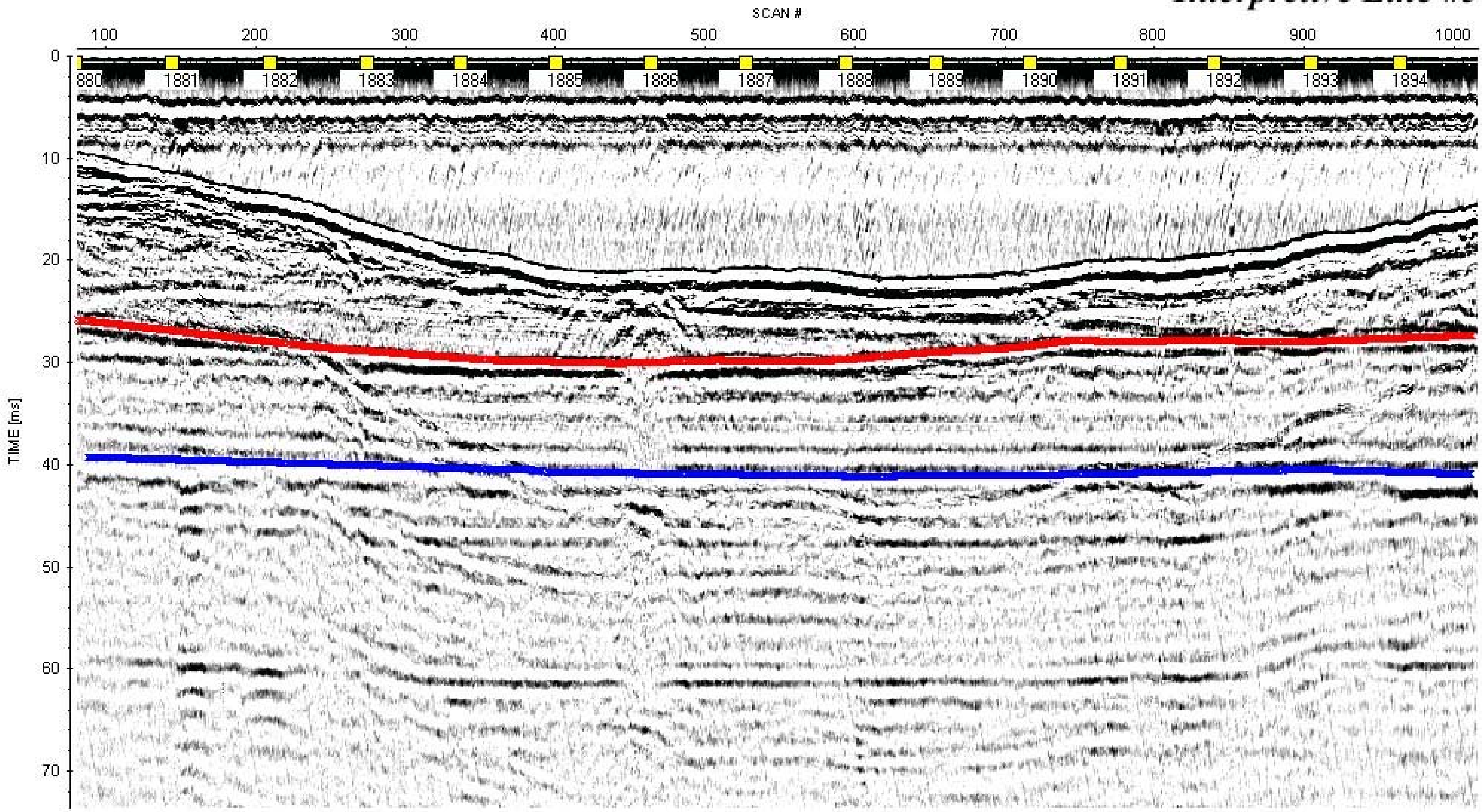
Interpretive Line #4



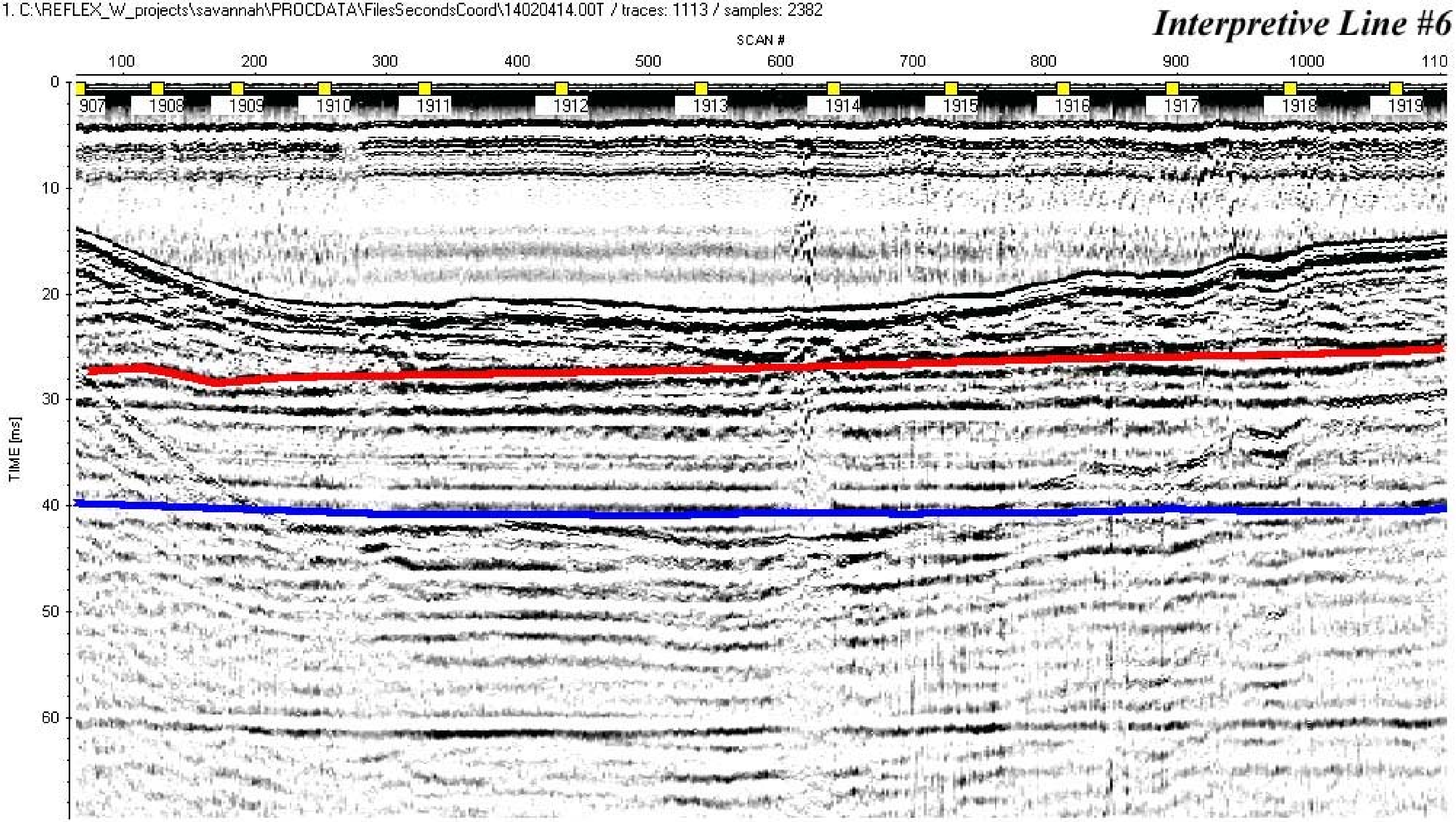

SHE-14
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\16020405.00T / traces: 951 / samples: 2382
Interpretive Line #4A
SCAN #
0
100
200
300
400
500
600
700
800
900
2765
2766
2767
2768
2769
2770
2771
2772
2773
2774
2775
2776
2777
2778
2779
2780
TIME [ms]
0
10
20
30
40
50
60
70

1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020412.00T / traces: 1018 / samples: 2382

Interpretive Line #5

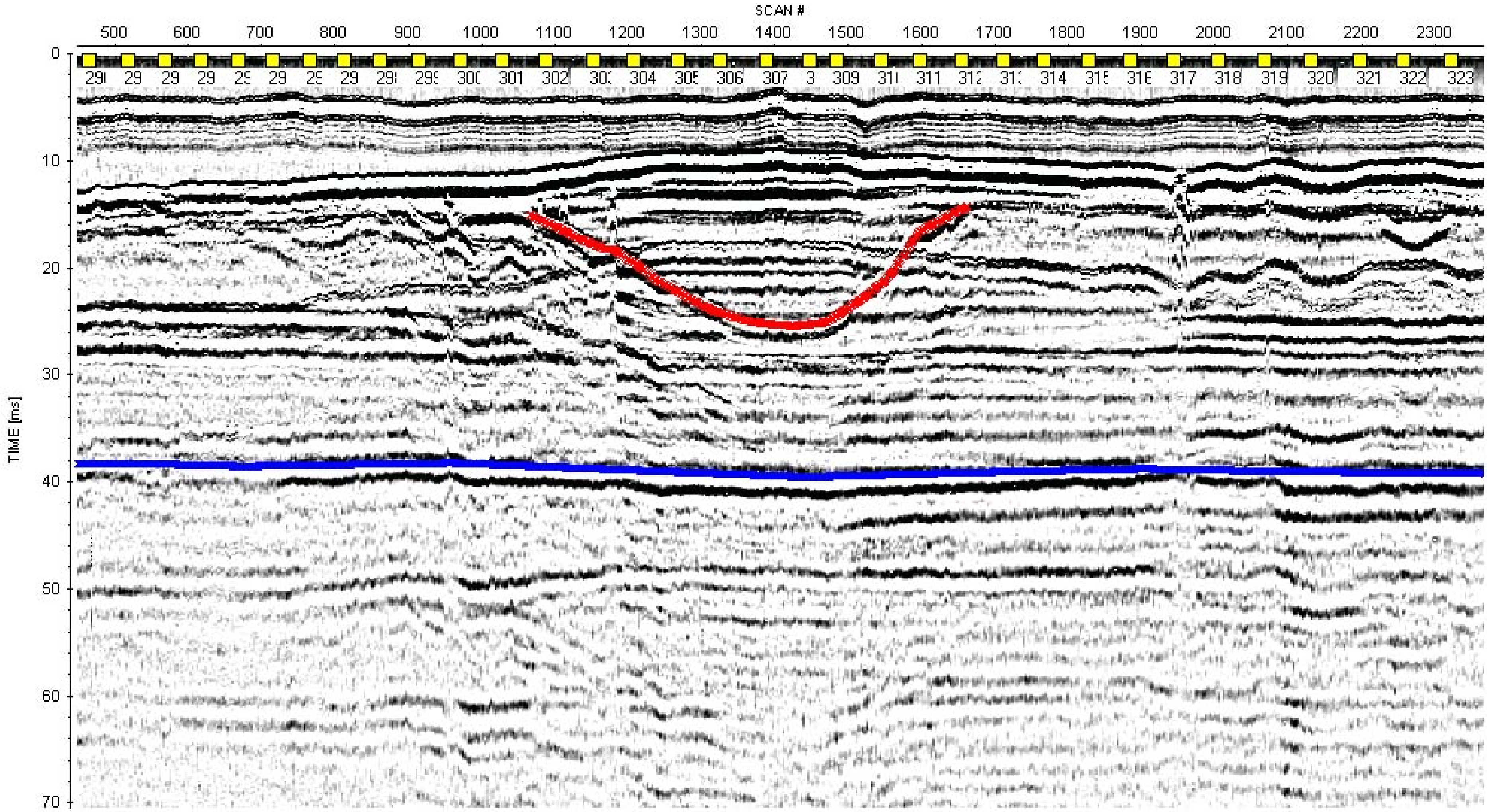


Interpretive Line #6

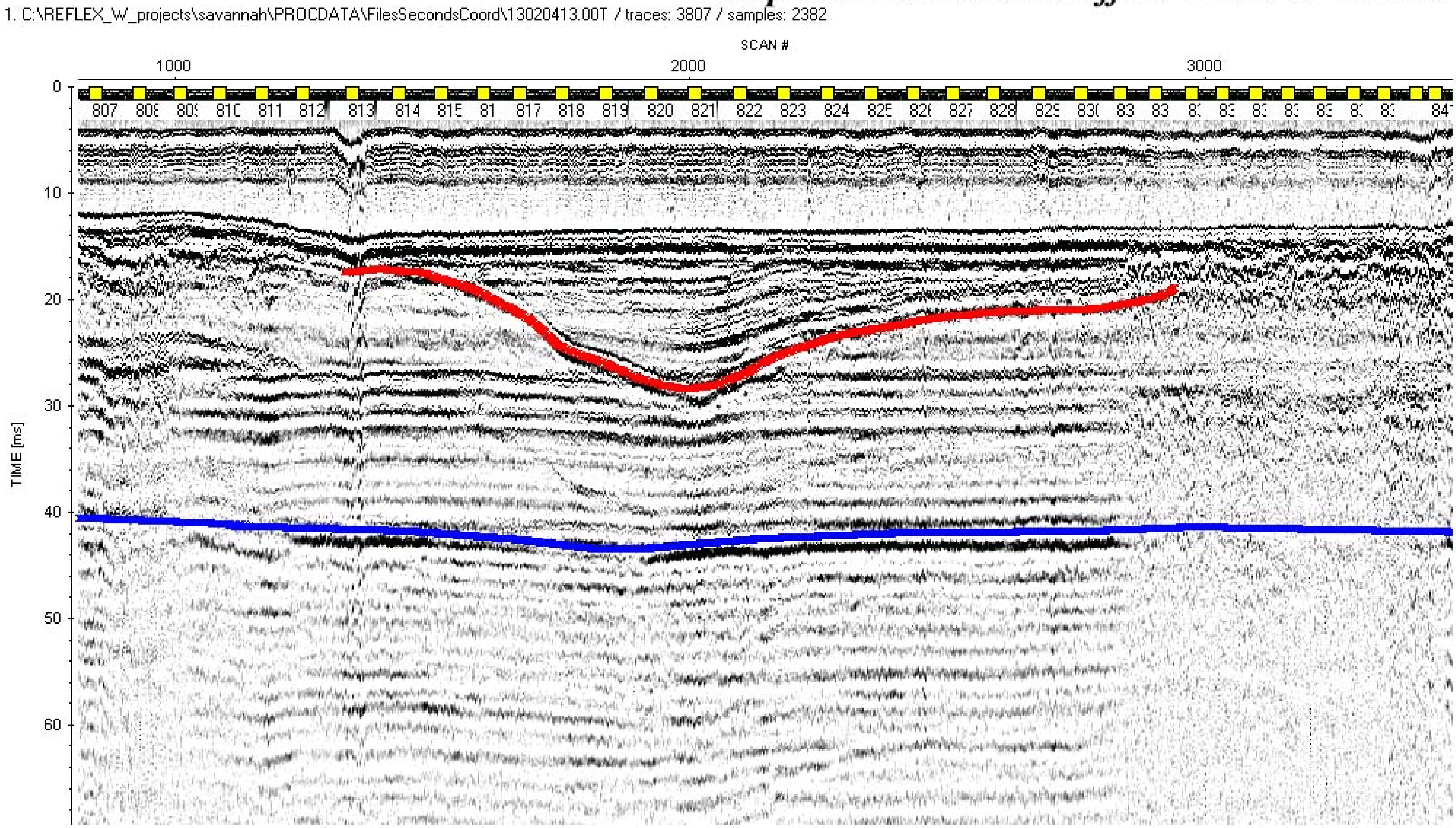


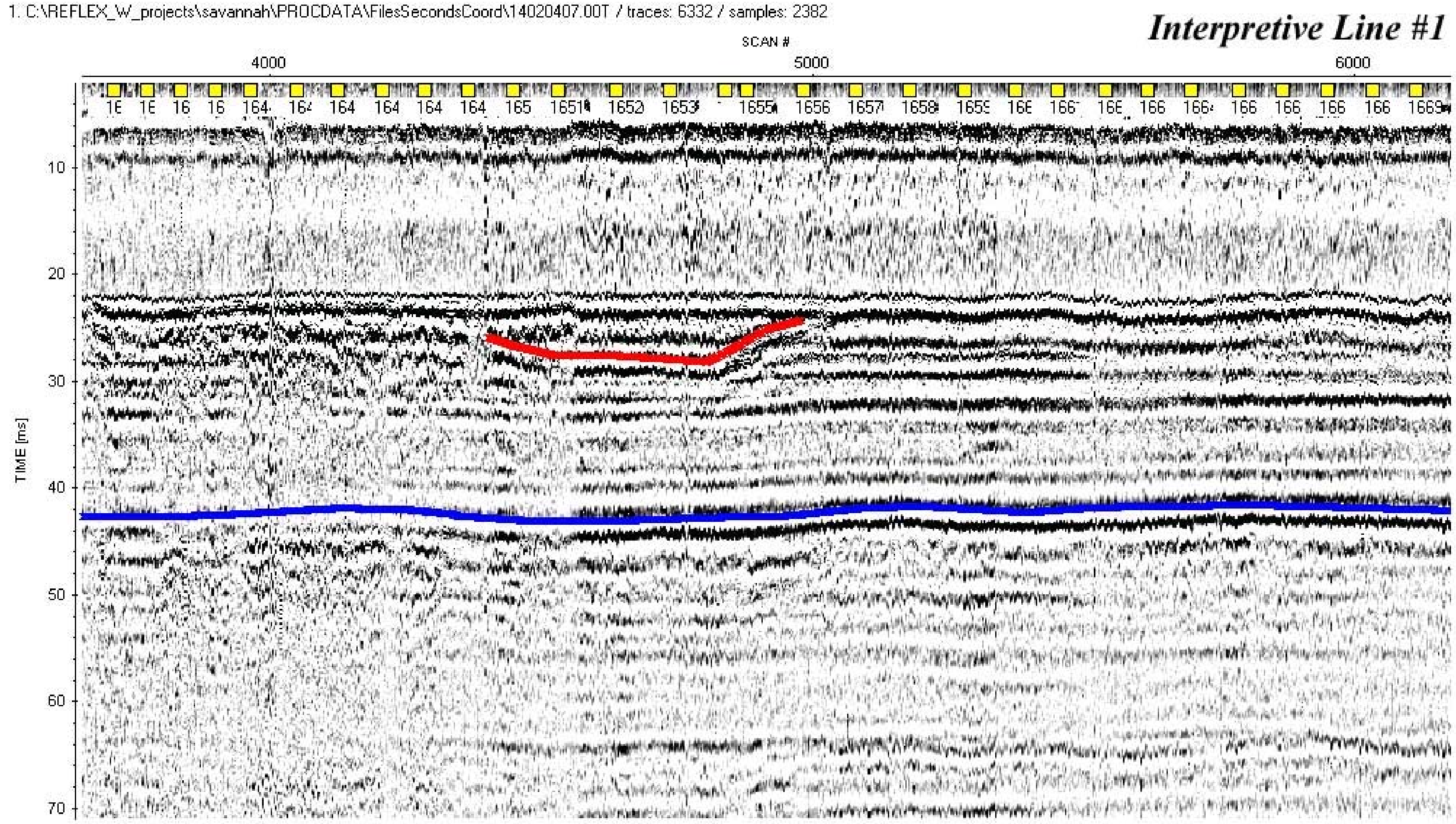
Interpretive Line #North Offset -9+000 to -13+000

1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\13020404.00T / traces: 2881 / samples: 2382



Interpretive Line #South Offset -9+000 to -13+000



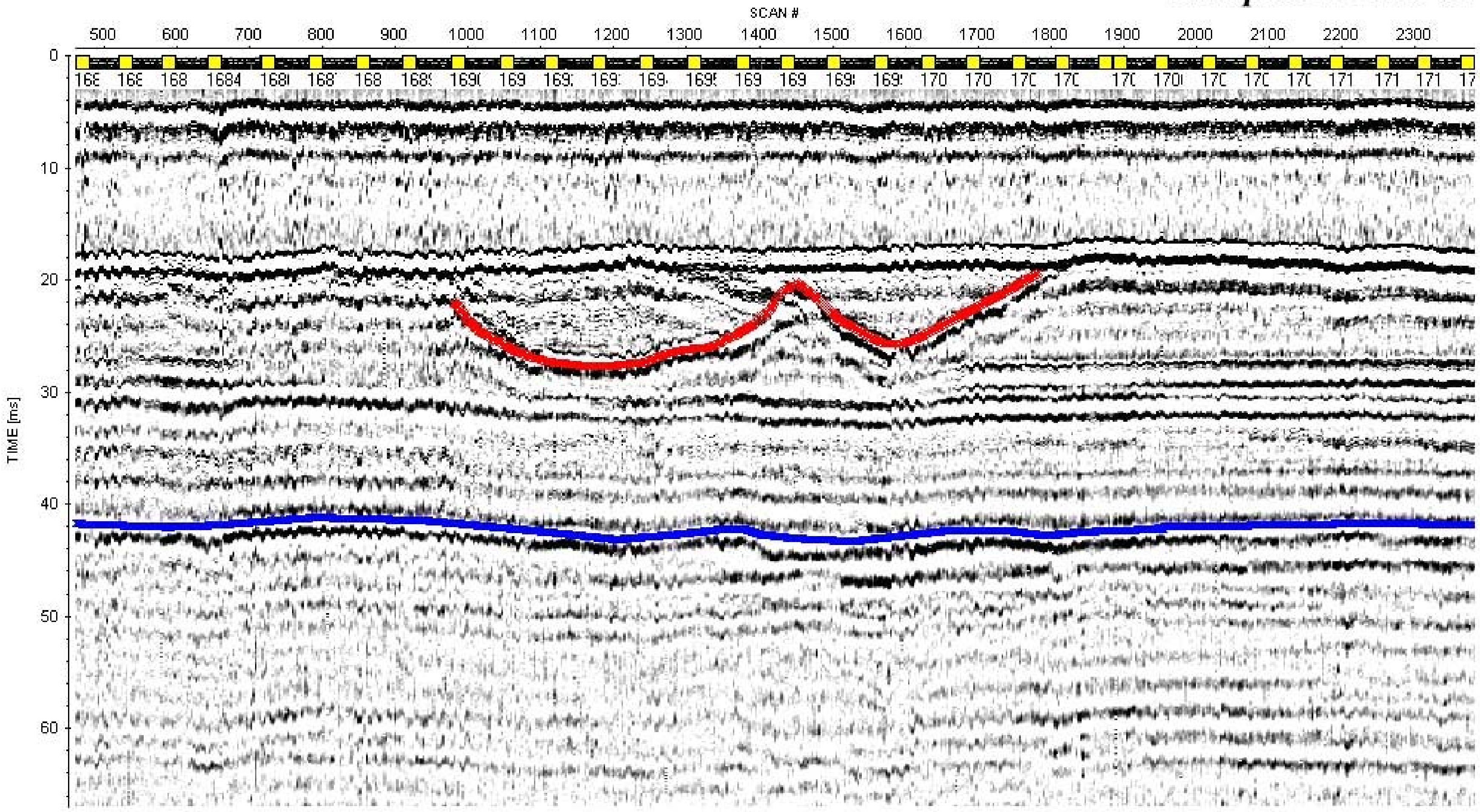


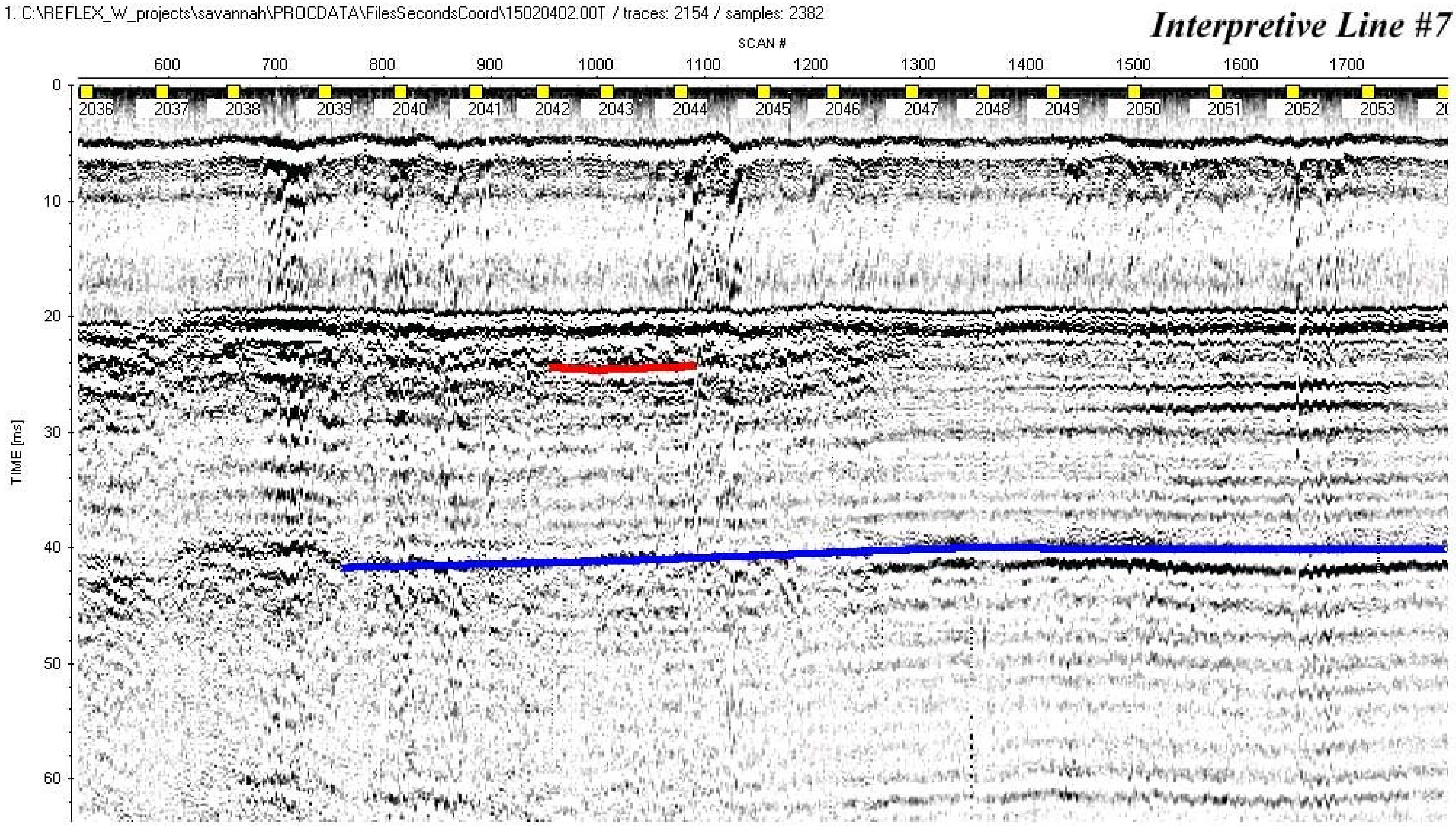
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020407.00T / traces: 6332 / samples: 2382

Interpretive Line #1

Interpretive Line #2

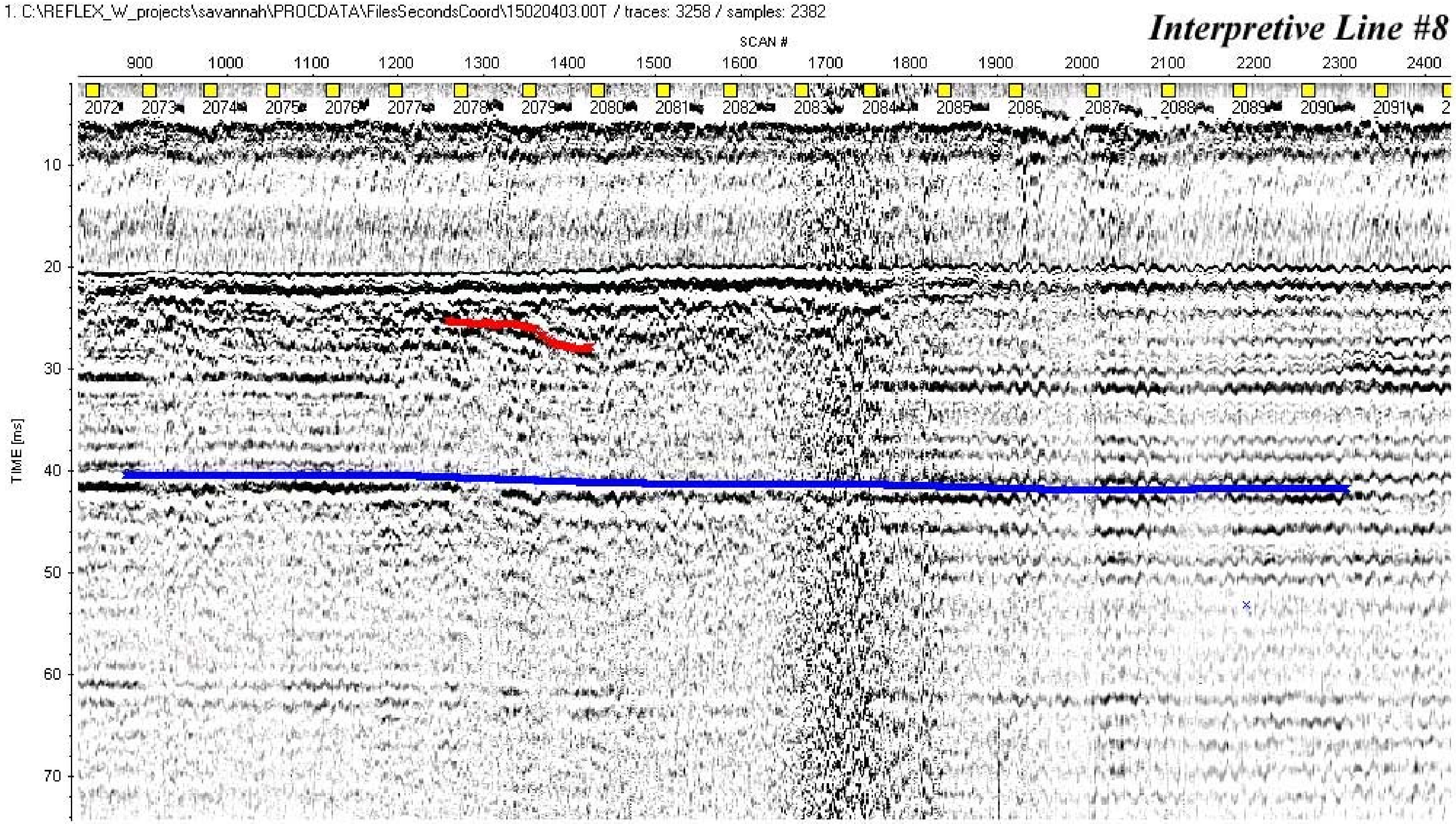
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\14020408.00T / traces: 4811 / samples: 2382





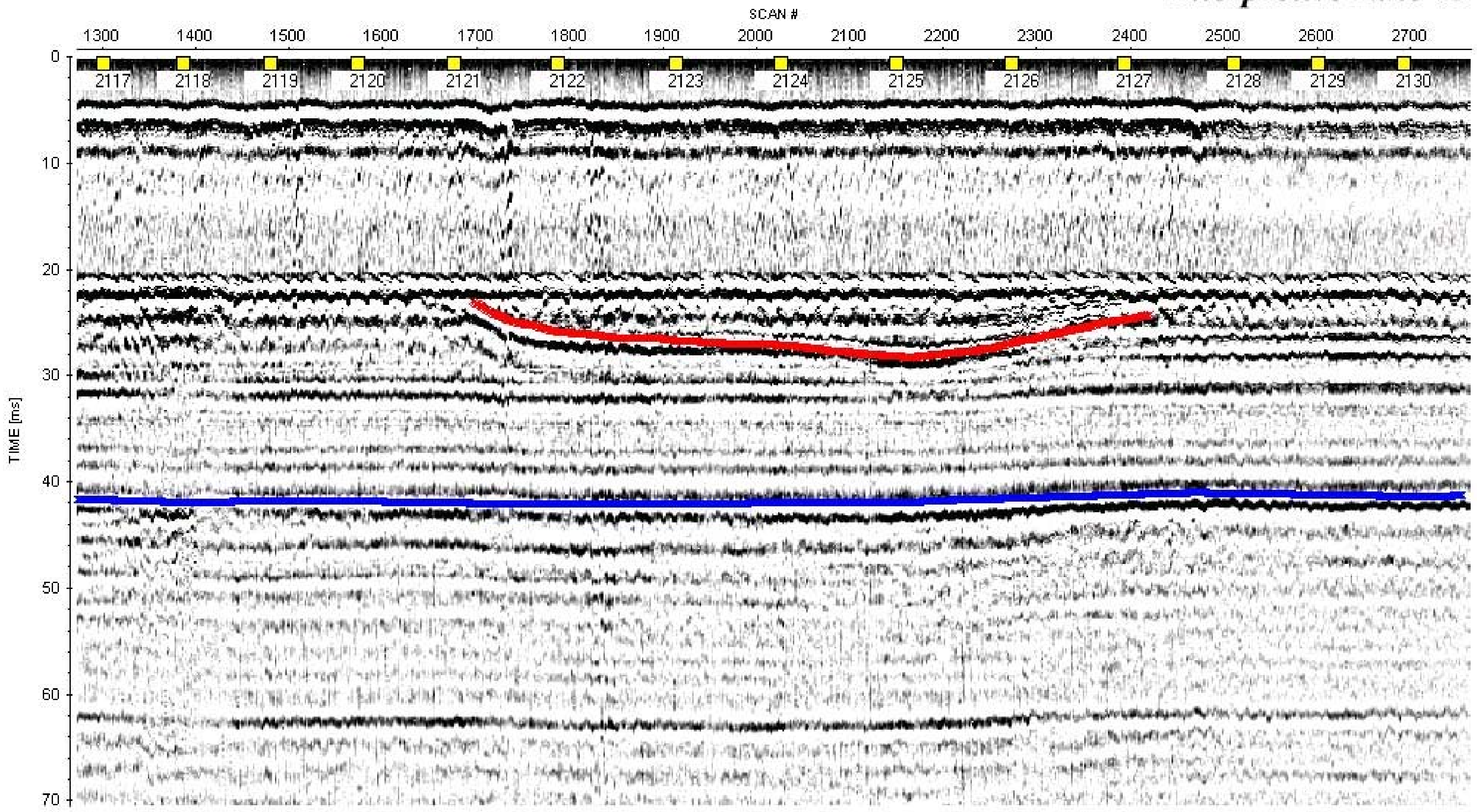
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\15020402.00T / traces: 2154 / samples: 2382

Interpretive Line #7

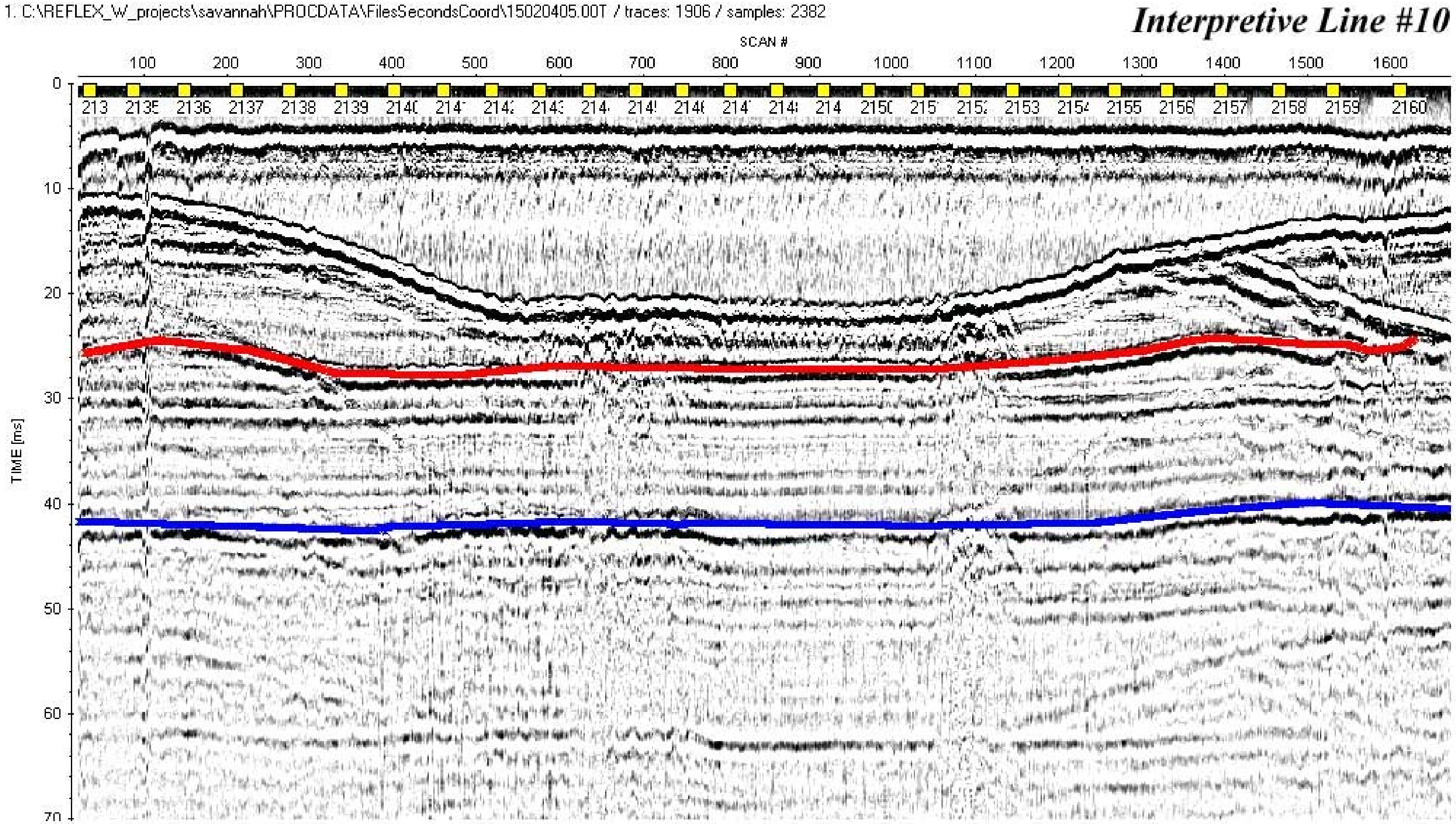

1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\15020403.00T / traces: 3258 / samples: 2382
Interpretive Line #8
SCAN #
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
TIME [ms]
10
20
30
40
50
60
70

Interpretive Line #9

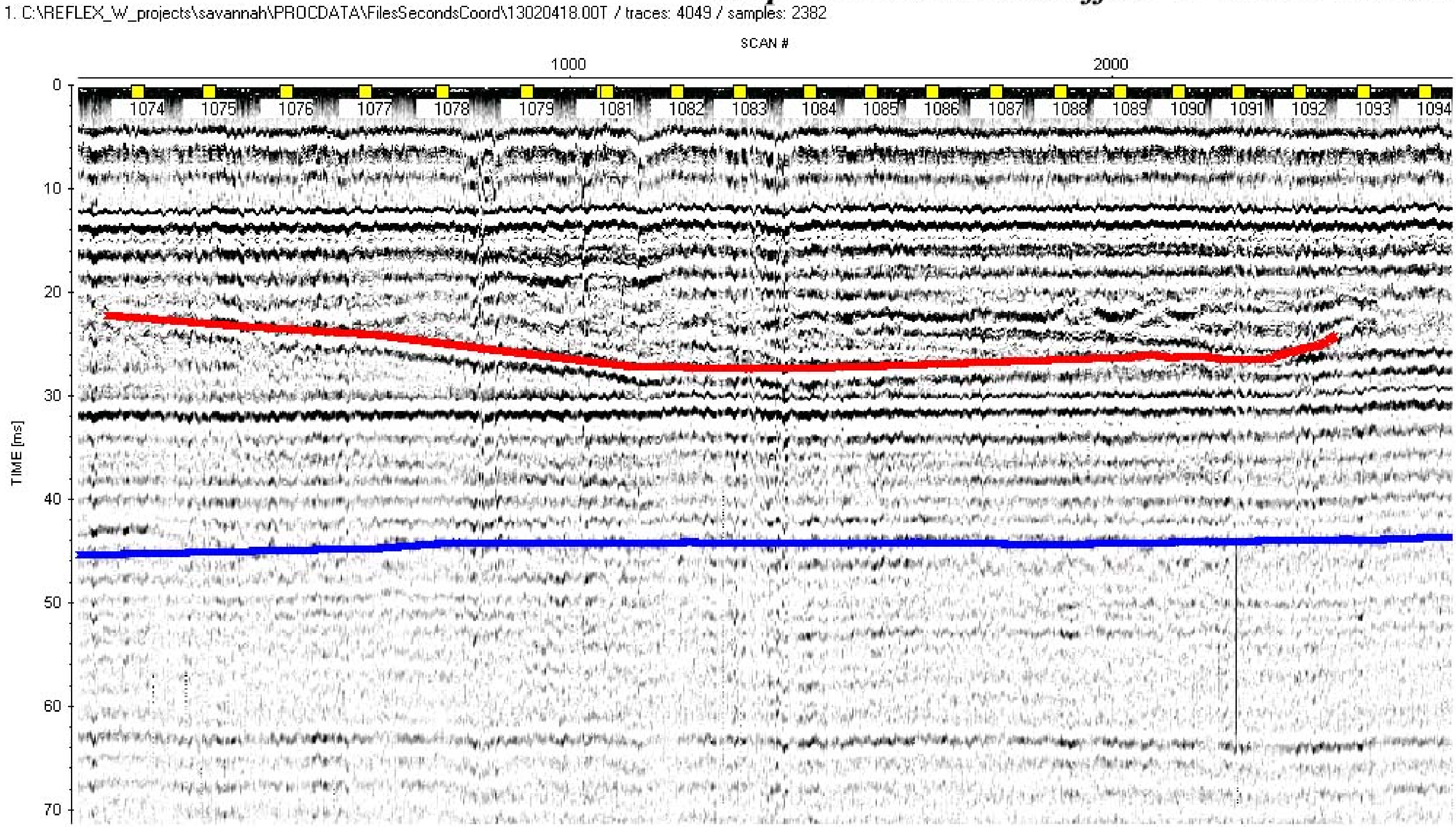
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\15020404.00T / traces: 2767 / samples: 2382



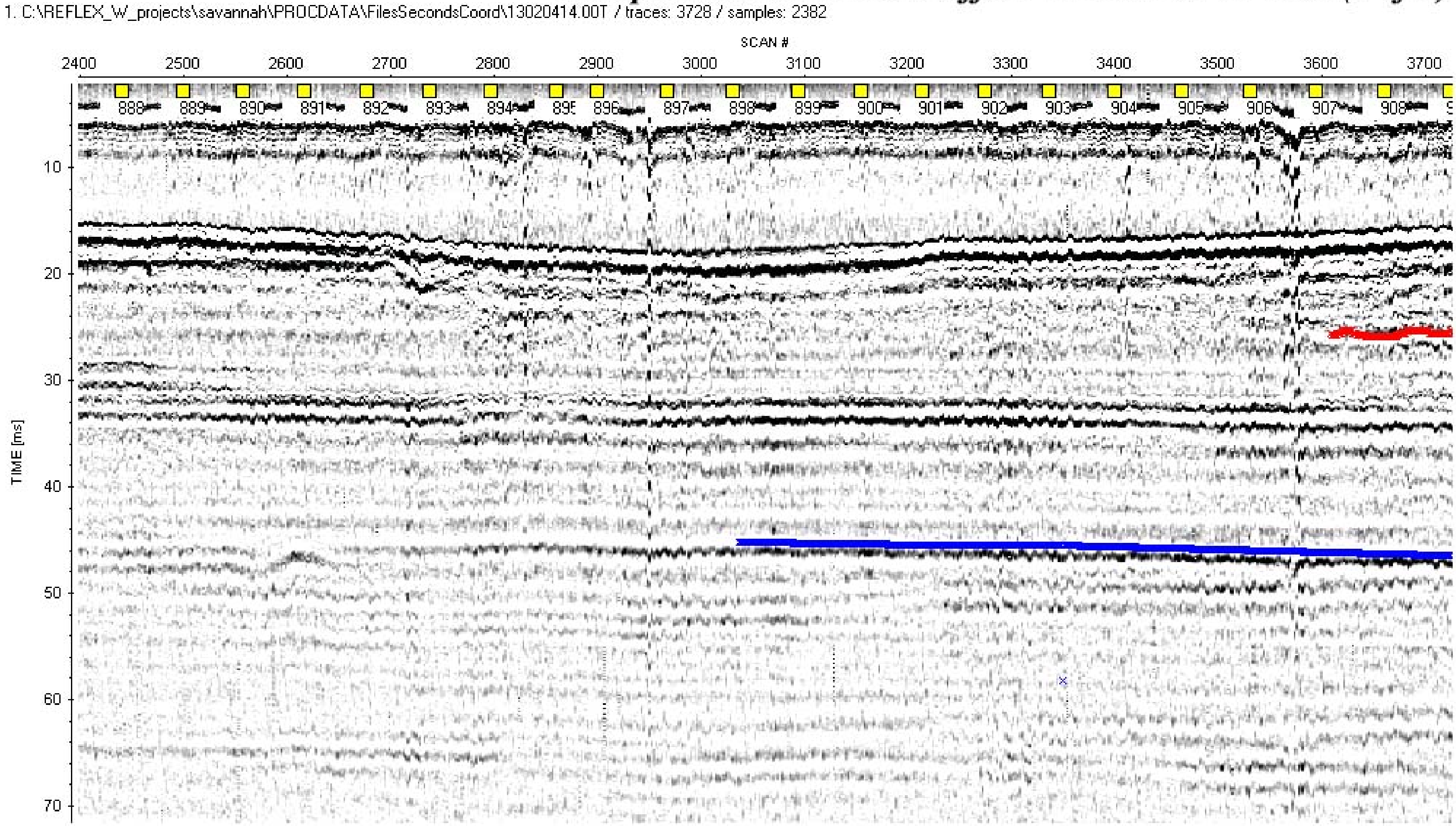
Interpretive Line #10



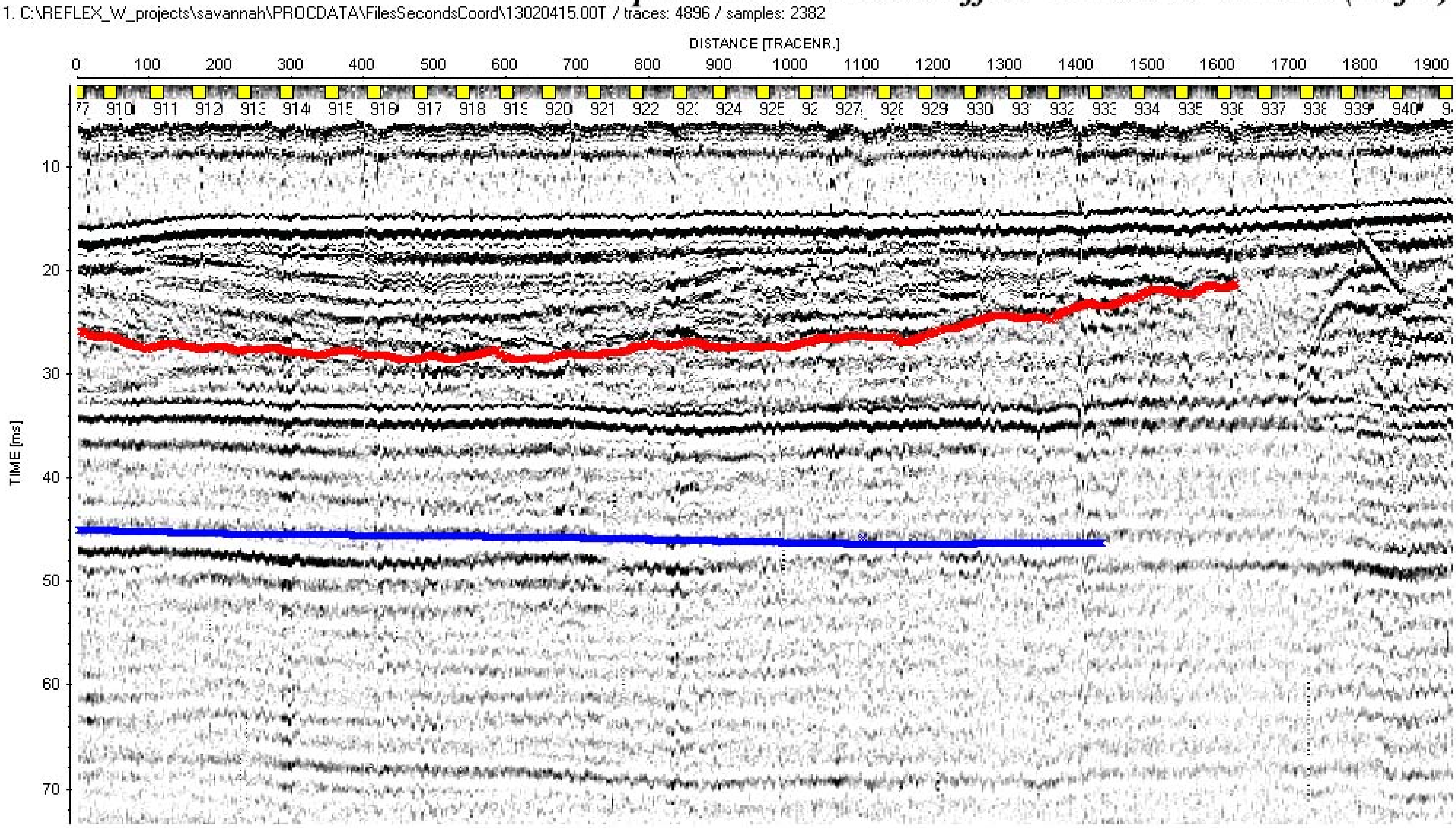
Interpretive line #North Offset -19+000 to -23+000



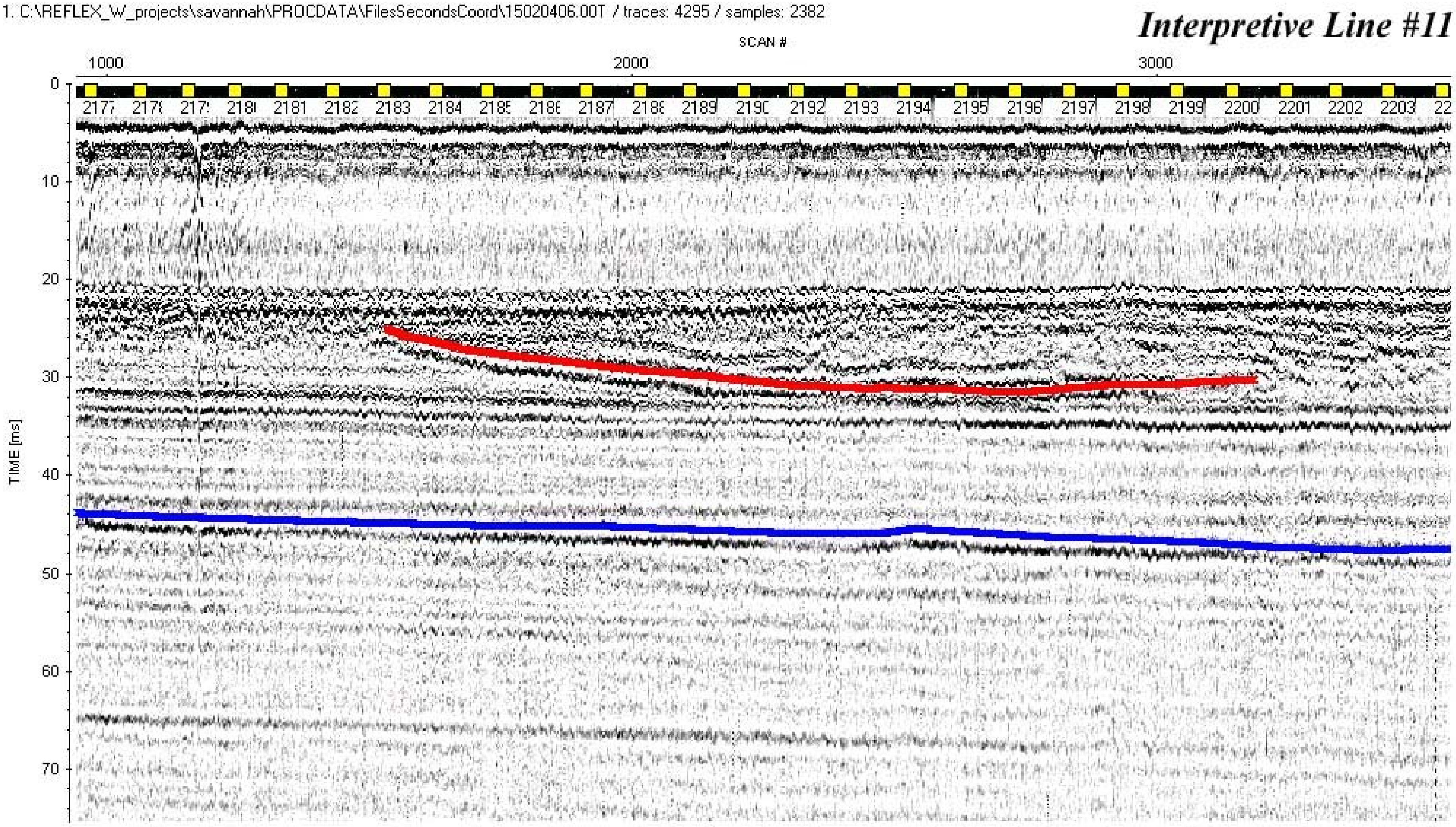
Interpretive Line #South Offset -19+000 to -23+000 (1 of 2)



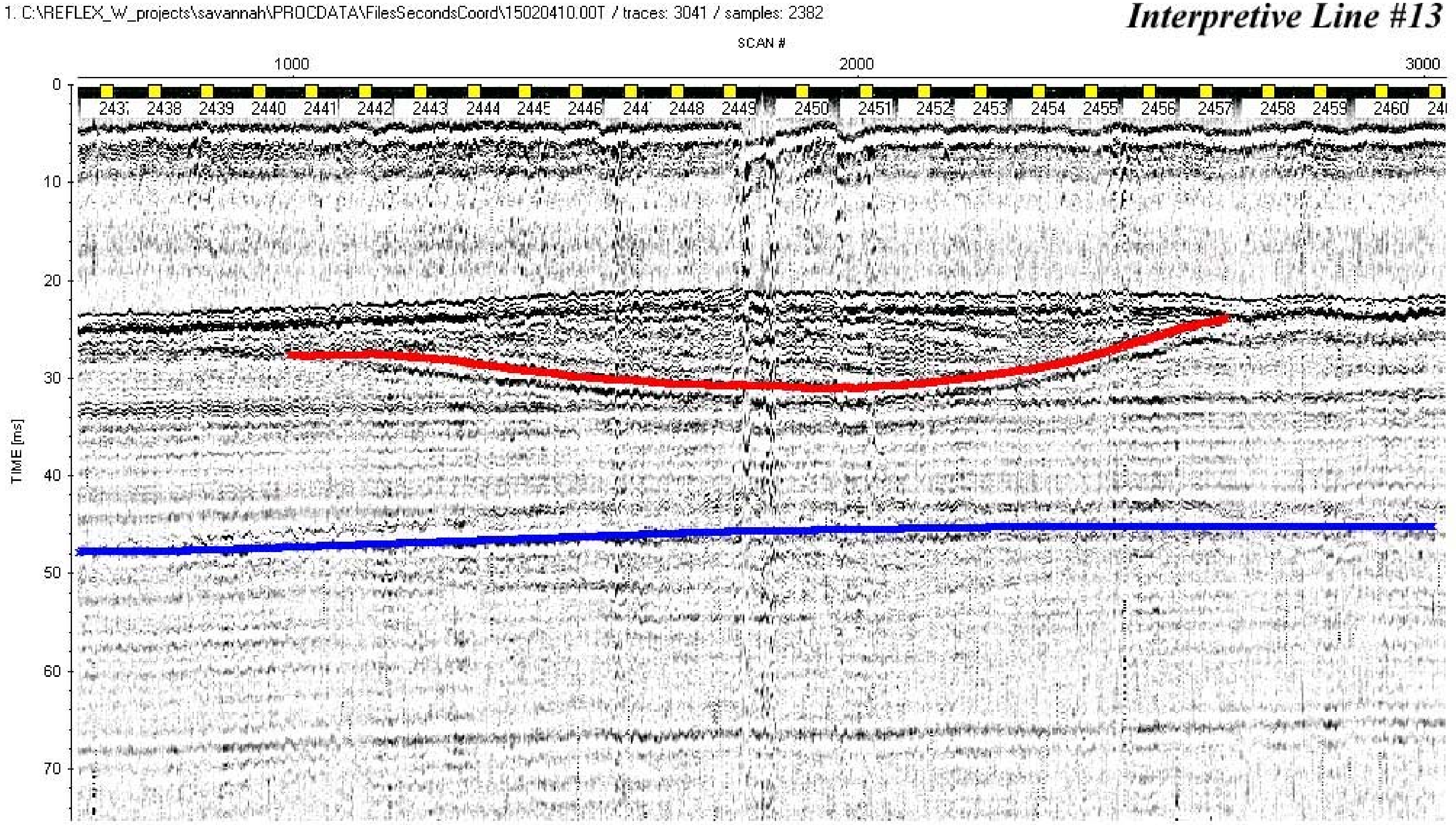
Interpretive Line #South Offset -19+000 to -23+000 (2 of 2)

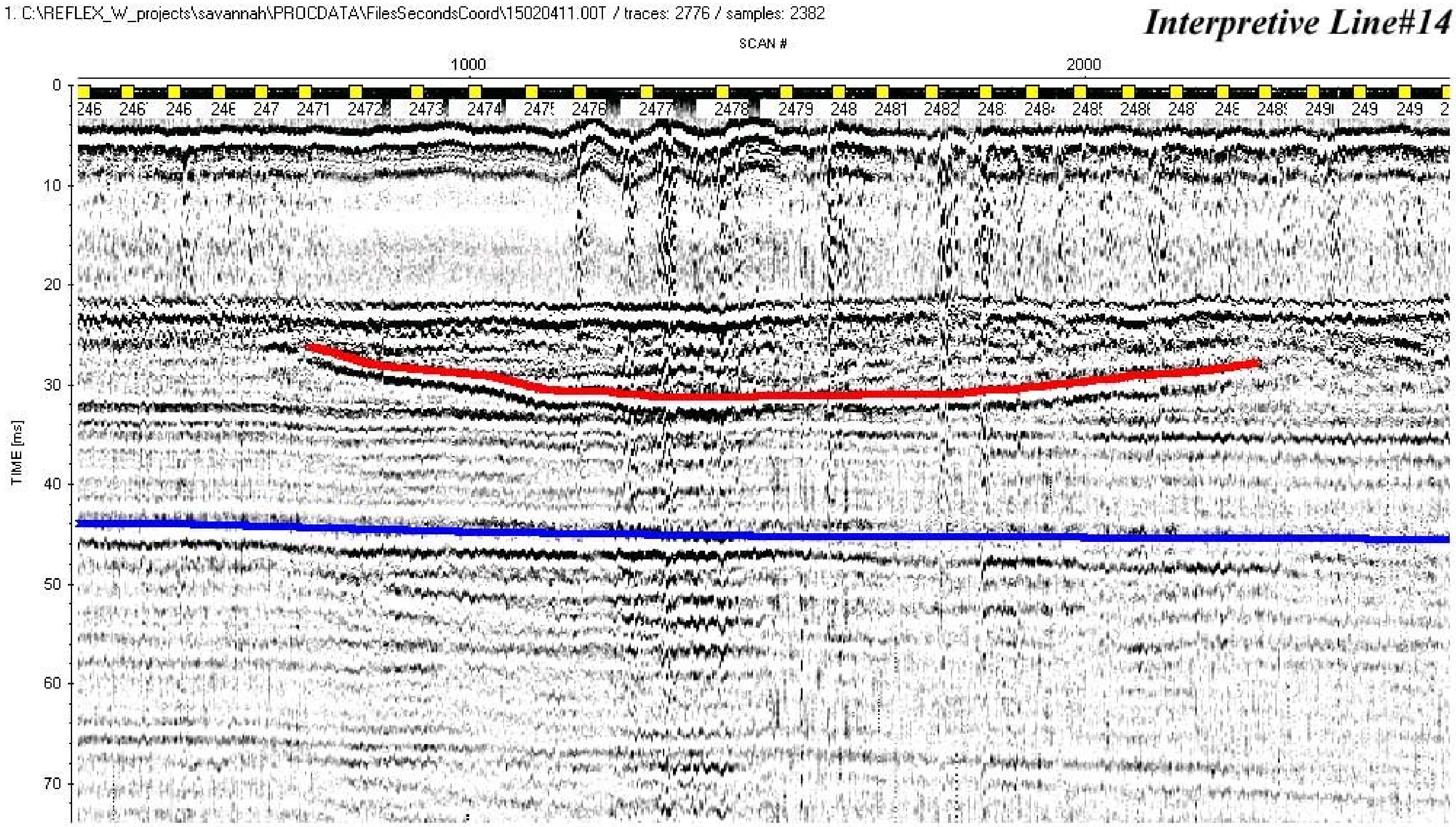


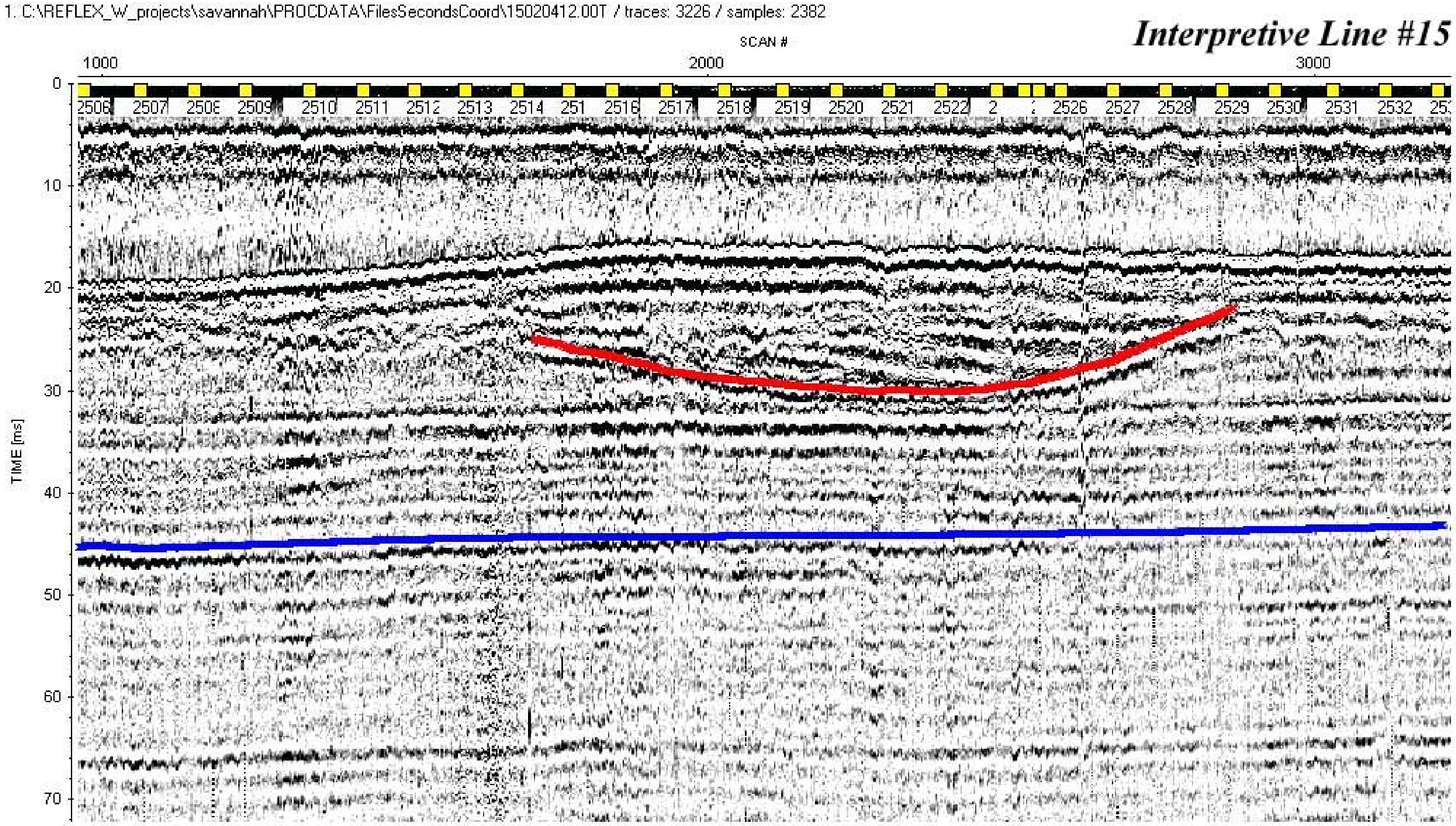
Interpretive Line #11



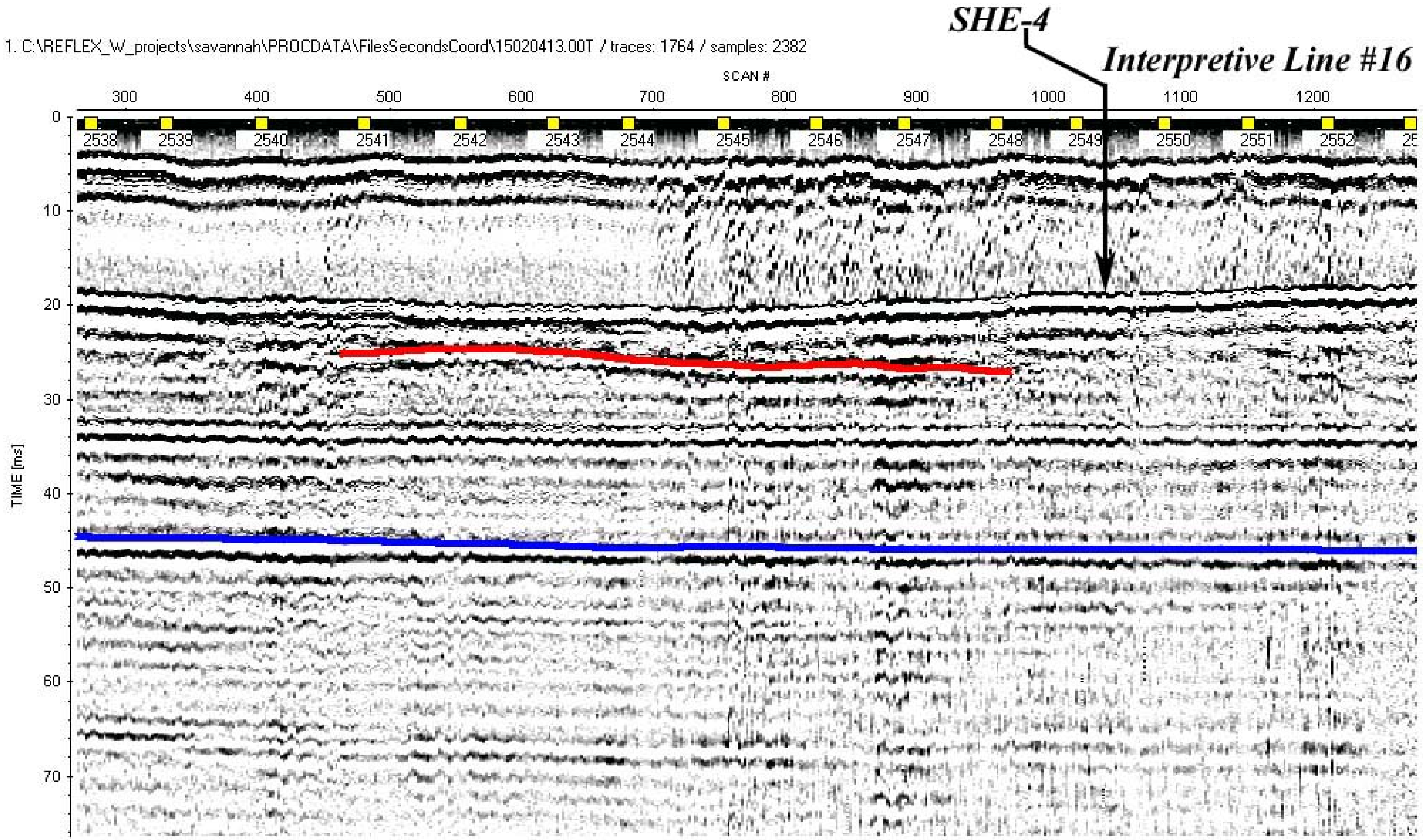
Interpretive Line #13

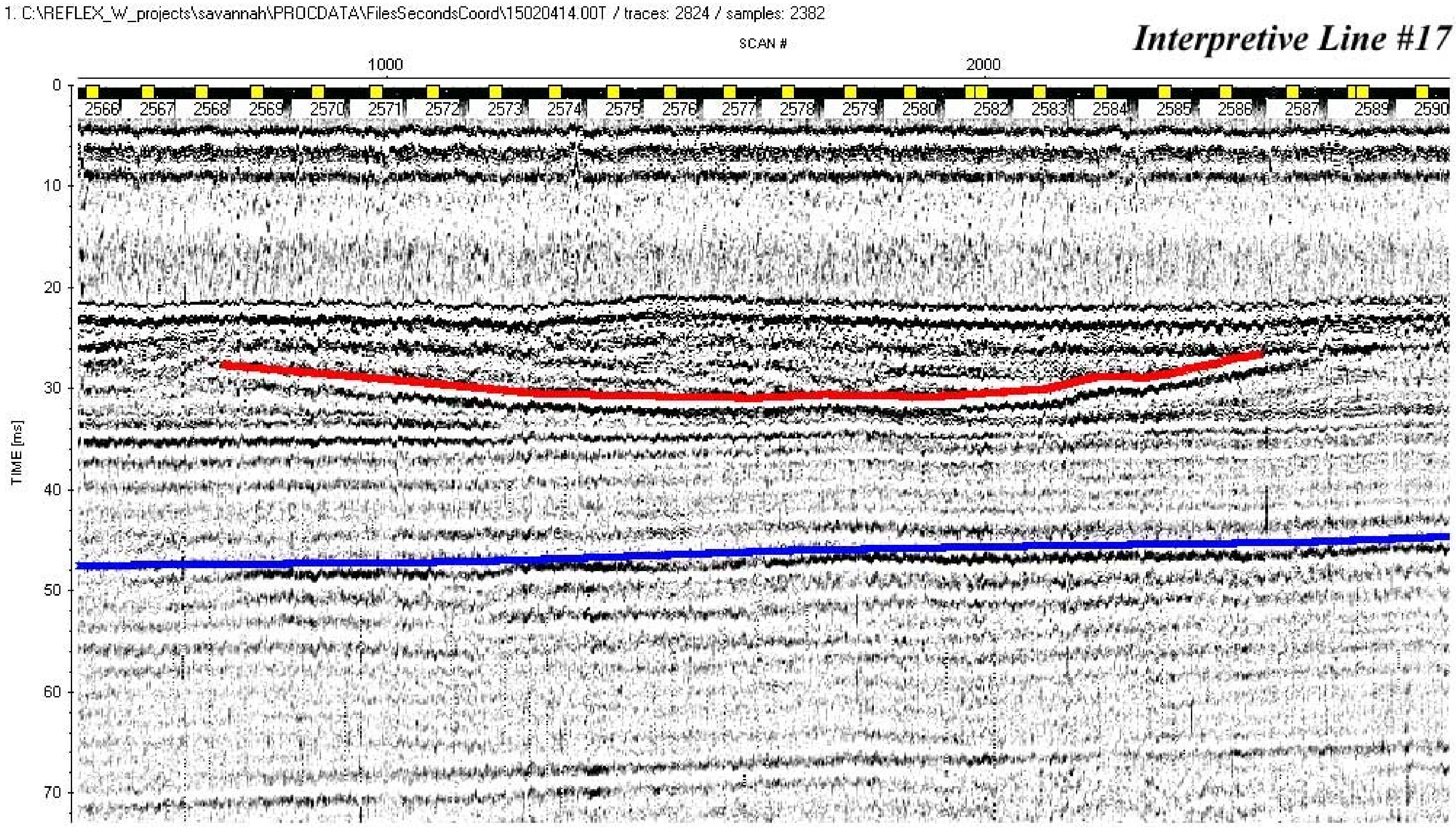



1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\15020411.00T / traces: 2776 / samples: 2382
Interpretive Line#14
SCAN #
1000
2000
TIME [ms]
0
10
20
30
40
50
60
70
2471
2479
2481
2482

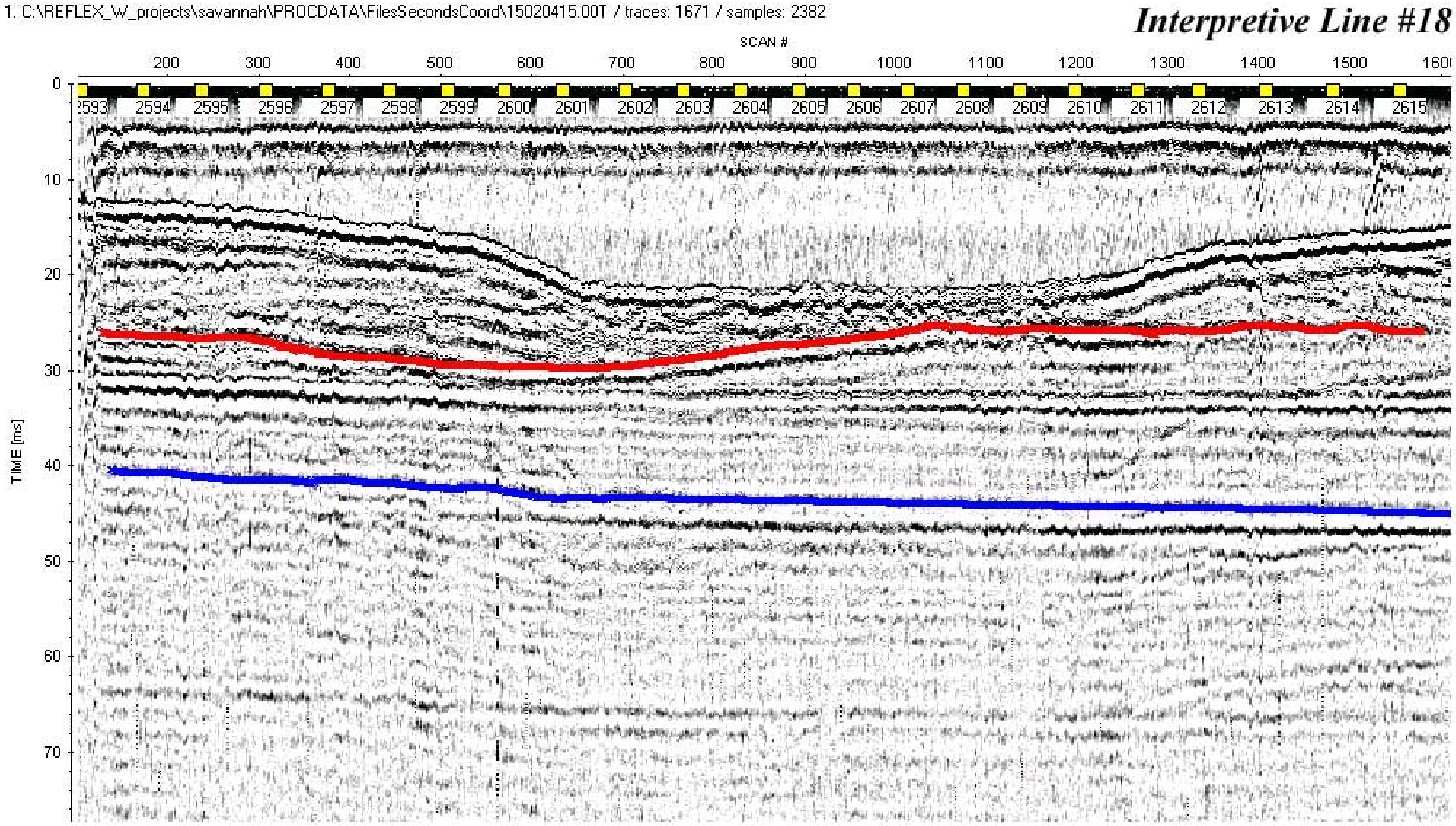


Interpretive Line #15


SHE-4
Interpretive Line #16
1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\15020413.00T / traces: 1764 / samples: 2382
SCAN #
300
400
500
600
700
800
900
1000
1100
1200
2538
2539
2540
2541
2542
2543
2544
2545
2546
2547
2548
2549
2550
2551
2552
0
10
20
30
40
50
60
70
TIME [ms]



Interpretive Line #17


1. C:\REFLEX_W_projects\savannah\PROCDATA\FilesSecondsCoord\15020415.00T / traces: 1671 / samples: 2382
Interpretive Line #18
SCAN #
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
160
593
2594
2595
2596
2597
2598
2599
2600
2601
2602
2603
2604
2605
2606
2607
2608
2609
2610
2611
2612
2613
2614
2615
TIME [ms]
0
10
20
30
40
50
60
70