Sublake Geologic Structure from High-Resolution Seismic-Reflection Data from Four Sinkhole Lakes in the Lake Wales Ridge, Central Florida

By A.B. Tihansky, J.D. Arthur, Florida Geological Survey and D.W. DeWitt, Southwest Florida Water Management District

---

U.S. GEOLOGICAL SURVEY

Open-File Report 96-224

Prepared in cooperation with the

SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

Tallahassee, Florida
1996

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

Use of brand names is for descriptive purposes only, and does not constitute endorsement by the U. S. Geological Survey.

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough Street
Tallahassee, FL 32301

Copies of this report may be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225

CONTENTS

Figures

Figures--Continued

Figures--Continued

Tables

SUBLAKE GEOLOGIC STRUCTURE FROM HIGH-RESOLUTION SEISMIC-REFLECTION DATA FROM FOUR SINKHOLE LAKES IN THE LAKE WALES RIDGE, CENTRAL FLORIDA

by A.B. Tihansky, J.D. Arthur, and D.W. DeWitt

ABSTRACT

Seismic-reflection profiles from Lake Wales, Blue Lake, Lake Letta, and Lake Apthorp located along the Lake Wales Ridge in central Florida provide local detail within the regional hydrogeologic framework as described by litho- and hydrostratigraphic cross sections. Lakes located within the mantled karst region have long been considered to be sinkhole lakes, originating from subsidence activity. High-resolution seismic-reflection data confirm the origin for these four lakes.

The geologic framework of the Lake Wales Ridge has proven to be a suitable geologic setting for continuous high-resolution seismic-reflection profiling in lakes; however, the nature of the lake-bottom sediments largely controls the quality of the seismic data. In lakes with significant organic-rich bottom deposits, interpretable record was limited to areas where organic deposits were minimal. In lakes with clean, sandy bottoms, the seismic-reflection methods were highly successful in obtaining data that can be correlated with sublake subsidence features. These techniques are useful in examining sublake geology and providing a better understanding of how confining units are affected by subsidence in a region where their continuity is of significant importance to local lake hydrology.

Although local geologic control around each lake generally corresponds to the regional geologic framework, local deviations from regional geologic trends occur in

sublake areas affected by subsidence activity. Each of the four lakes examined represents a unique set of geologic controls and provides some degree of structural evidence of subsidence activity. Sublake geologic structures identified include: (1) marginal lake sediments dipping into bathymetric lows, (2) lateral discontinuity of confining units including sags and breaches, (3) the disruption and reworking of overlying unconsolidated siliciclastic sediments as they subside into the underlying irregular limestone surface, and (4) sublake regions where confining units appear to remain intact and unaffected by nearby subsidence activity. Each lake likely is underlain by several piping features rather than one large subsidence feature.

INTRODUCTION

In 1994, the U.S. Geological Survey, in cooperation with the Southwest Florida Water Management District, began a geophysical study to determine the geologic structure beneath selected lakes located within the Lake Wales Ridge area of Florida.

Lakes are a prevalent feature in the Florida landscape. The Lake Wales Ridge of central Florida is the largest of several elongate north-south trending ridges. Numerous closely-spaced depressions and lakes occupy this area of central Polk and Highlands Counties (Brooks, 1981; White, 1958, 1970) (fig. 1).

Many of these water-filled depressions are of sinkhole origin, resulting from the settling and infilling of overlying siliciclastic materials into the underlying karst limestone surface (Bishop, 1956; White, 1958, 1970; Sinclair and others, 1985; Sinclair and Stewart, 1985; Lane, 1986; Ford and Williams, 1989). Most lakes within this region are internally drained (no surface-water inflow or outflow). Studies of lake water-budgets in this type of setting have shown that the effects of rainfall, evaporation, ground-water pumping, surface-water inflow, and ground-water inflow or lake leakage can vary significantly between each lake basin (Stewart, 1966; Barcelo and others, 1990; Lee and others, 1991; Grubbs, 1995; Lee and Swancar, in press).

Lake levels in this region have fluctuated historically in response to changes in hydrologic conditions. During drought periods, some lake water levels decline dramatically, while other lakes may not decline significantly. When rainfall is higher than normal, many lakes overfill and flood adjacent areas. Adjacent lakes that are subject to similar changes in meteorological and hydrologic conditions often do not exhibit similar lake-level fluctuations. It is probable that the geologic framework beneath each lake controls the degree of interconnection between the lake and the ground-water system.

Prior to the use of geophysical data-collection methods, information on geology beneath lakes was limited to extrapolations of geologic logs for wells constructed around each lake. The ability to interpret sublake structure was, therefore, limited and the existence and the morphology of buried sinkhole structures could not be documented with certainty (Clark and others, 1963). Understanding the hydrology of lakes and their

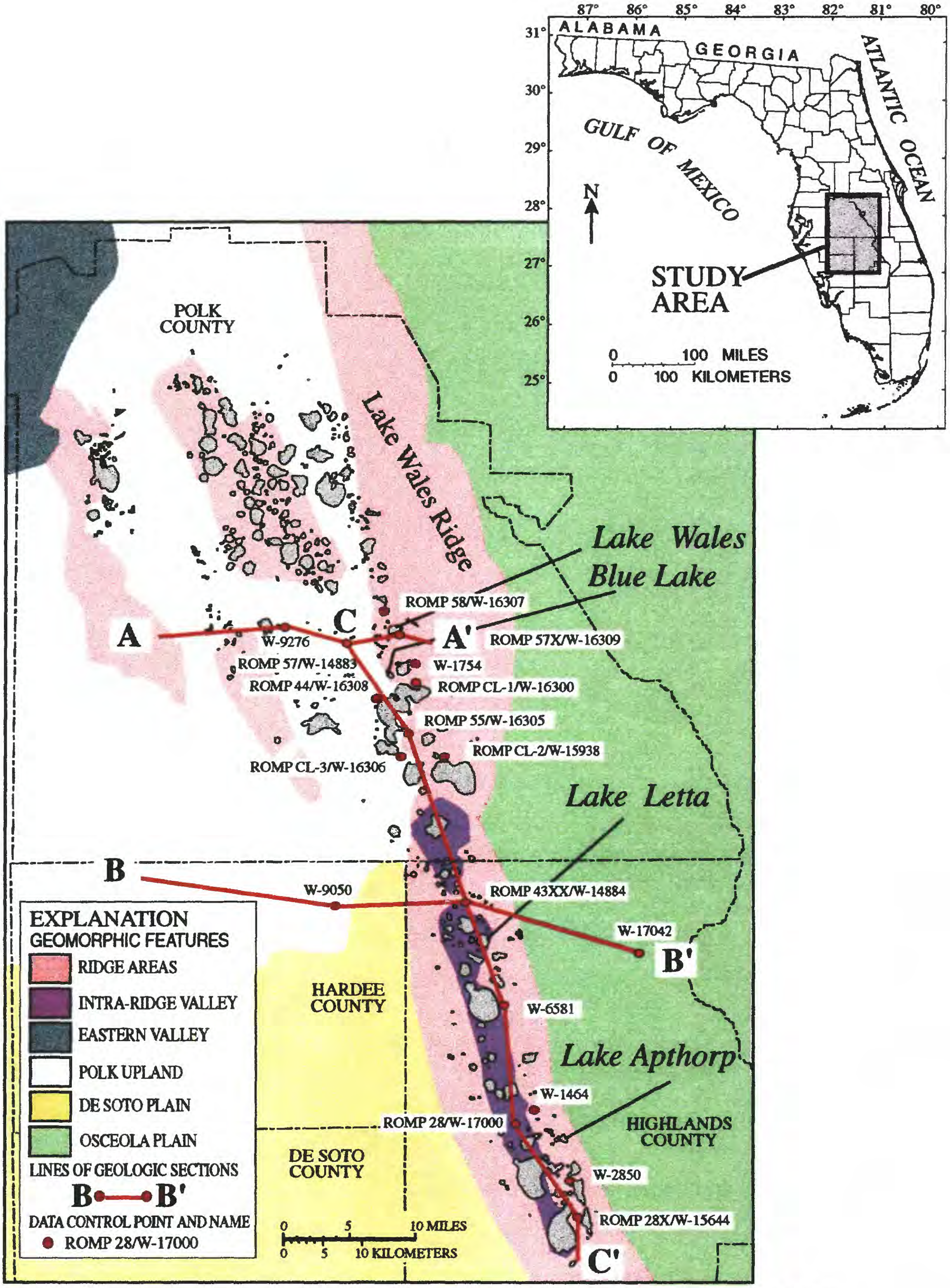


Figure 1. Regional geomorphic features of central Florida (adapted from White, 1970), locations of lakes along the Lake Wales Ridge, geologic sections and regional well control.

relation to the regional hydrostratigraphy is difficult without this information. In a karst region, the geology may vary significantly beneath a lake and the lake-adjacent region due to the highly irregular limestone surface at depth. The vertical variability of the buried limestone surface is commonly 30 to 40 meters (100 ft) over short lateral distances and can exceed 100 meters (300 ft) (Stewart and Parker, 1992). The high variability in thickness, distribution, and lithology of geologic materials adjacent to and infilling a sinkhole structure is difficult to predict but plays a major role in controlling how a lake responds to hydrologic changes.

Previous studies on lakes in various parts of Florida have shown that lake-level changes reflect an intricate set of controlling factors, including variations in the geologic framework and the hydrologic properties of materials within and adjacent to the lake basin (Stewart, 1966; Robertson, 1973; Ryan, 1989; Barcelo and others, 1990; Lee and others, 1991; Motz and others, 1991; Sacks and others, 1992; Belanger and Kirkner, 1994; Grubbs, 1995; Lee and Swancar, in press). Among these controls are variations in the geologic framework and hydrologic properties of materials within and adjacent to the lake basin. Such geologic controls can determine the susceptibility of a lake to ground-water leakage and the rate at which a lake responds to changes in external stresses of climate and ground-water pumping. The previous hydrologic studies indicate the influence of local geology on the interconnection between lakes and their surrounding hydrogeologic system. An accurate description of the sublake geologic framework will provide additional understanding of lake and ground-water interactions.

Purpose and Scope

This report presents sublake geologic interpretations of Lake Wales and Blue Lake, in Polk County, and Lake Letta and Lake Apthorp, in Highlands County, Florida (fig. 1). The purpose of this report is to:

(1) describe the local geologic structure beneath four lakes along the Lake Wales Ridge based upon the interpretation of high-resolution seismic-reflection surveys;

(2) present new regional stratigraphic information for the Lake Wales Ridge that contains detailed lithologic descriptions of the shallow units most relevant to seismic-reflection surveys and lake/ground-water interactions, and;

(3) relate the local sublake geologic features to the regional hydrostratigraphy described by large scale geologic sections. Lake and ground-water interactions vary significantly along the Lake Wales Ridge and reflect both local and larger scale hydrologic controls. Accurate inferences regarding the hydrologic controls of lakes in this area can be made when the relation between local sublake geologic structure and regional stratigraphy are understood.

Previous Investigations

Stewart and Parker (1992) demonstrated that continuous subsurface profiles can greatly enhance the understanding of the subsurface geologic framework. Their study combined a dense network of geologic control points with hydrologic and geophysical techniques that provided a detailed geologic framework of a region of mantled karst in west-central Florida. This dense network of data points described a highly irregular limestone surface at depth with small localized vertical shafts infilled with reworked overburden materials. They concluded that these shafts perforate the confining unit above the Upper Floridan aquifer (UFA) and provide preferential avenues for recharge of surficial waters to the UFA. These small localized features are hydrologically important because they control both the volume and locations of ground-water recharge to the UFA.

Previous studies employing continuous high-resolution seismic-reflection techniques in Florida lakes and other surface-water bodies have had variable success in describing geologic structure at depth. Several studies in Florida have used seismic-reflection techniques specifically in geologic studies of the sublake region (Locker and others, 1988; Snyder and others, 1989; Lee and others, 1991; Sacks and others, 1992; Subsurface Detection Investigations, 1992; Evans and others, 1994; Kindinger and others, 1994). Overall, these studies report that most Florida lakes contain one or more infilled subsidence features. Commonly, these studies recognized small vertical "pipes" or shafts similar to those described by Stewart and Parker (1992). The "pipes" may exhibit great vertical relief, which often corresponds to the more subdued relief shown in the bathymetry of the lake. Sublake subsidence features appear to modify or breach confining units and are probably associated with karst and limestone dissolution at depth. The subsidence features vary in size and usually are infilled with siliciclastic materials from overlying units. The distribution and properties of this infilling material can influence the hydrologic character of the lake.

While site-specific lake studies have documented the occurrence of these features beneath some lakes, these data have not been related back to the regional stratigraphic framework; however, Sinclair and others (1985) suggest that sinkhole type and subsidence activity generally is related to regional hydrogeology trends. The development of detailed sublake geology within the regional geologic framework of the Lake Wales Ridge, provides an opportunity to document how and to what extent local and larger scale geologic features control subsidence and also how local subsidence features affect regional hydrogeology.

The enhanced descriptions of sublake geology obtained using these techniques can be applied to other lake-related studies. These geologic interpretations have improved numerical simulations of lake and ground-water interactions in several studies (Ryan, 1989; Grubbs, 1995; Lee and Swancar, in press).

METHODS

High-resolution seismic-reflection techniques were used to obtain continuous images of geologic units beneath 17 lakes located within the Lake Wales Ridge. Of the 17 lakes surveyed, four were selected for detailed interpretation based on the superior quality of the seismic-reflection data, the availability of geologic control, the location of the lakes in the regional geologic setting, and their distribution within the Lake Wales Ridge. In 1995, the geophysical data set was augmented by results of a cooperative study between the Florida Geological Survey and the Southwest Florida Water Management District describing the local and regional hydrogeologic framework along the Lake Wales Ridge.

Seismic-Reflection Methods

Seismic-reflection data were collected using a Geopulse high-resolution profiling system. This system consisted of an ORE power supply and filter/amplifier unit, an EPC graphic recorder, towed acoustic source or "boomer", and an ITI 10-element hydrophone array. Data also were recorded on digital audio tape for playback capabilities. The seismic profiles were recorded using both 100 and 150 millisecond sweep ranges, with band-pass filters commonly set from 300 to 5,000 hertz (Hz). The power supply was commonly set at 175 Joules. These surveys were conducted from a 17-foot johnboat. The configuration of equipment for data collection is shown in figure 2.

Shoreline landmarks as well as data from a global positioning system (GPS) were used to aid in navigation; transects were plotted onto lake base maps during data collection. Positions were plotted at 5-minute intervals or less depending on the size of the lake. In addition, positions were plotted for all course changes and sublake geologic features observed in the seismic record. Transects were run in a grid pattern and along the perimeter of each lake, especially where mid-lake regions of the lake did not provide interpretable seismic-reflection record.

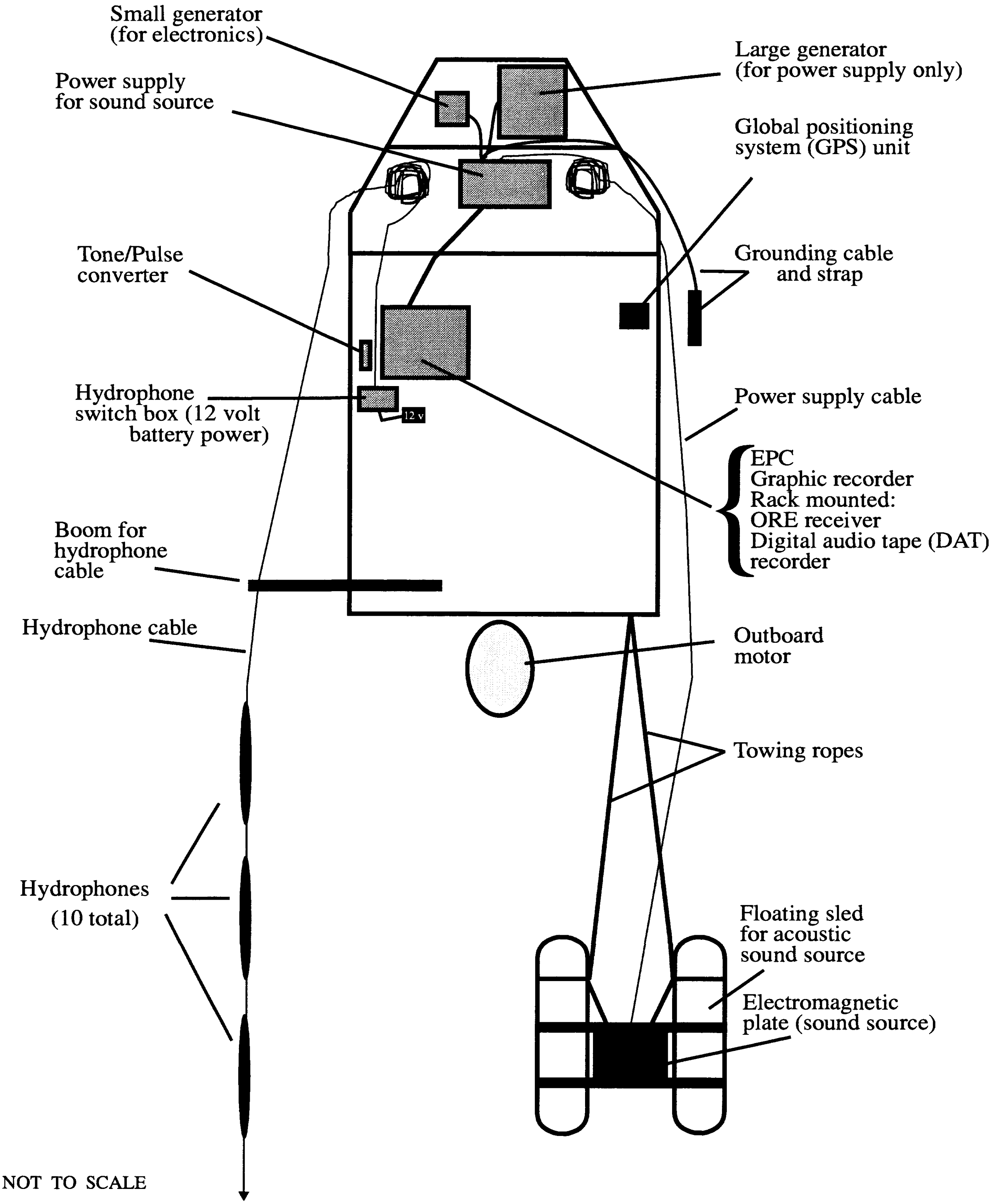


Figure 2. Setup and deployment configuration of seismic-reflection equipment on a 17-foot johnboat.

Geologic correlation to sublake high-resolution seismic data was done on a lake-by-lake basis. Wells used for correlation were selected for geologic control based on proximity to the lake, location within similar physiographic areas, availability of detailed geologic information, and regional hydrogeologic trends. The surficial geology and the stratigraphic column for the study area are shown in figures 3 and 4 respectively.
The seismic depths of identifiable lithostratigraphic boundaries were converted to distance below land and lake surface using an acoustic velocity of 1,800 meters per second (m/s) (McQuillan and Ardus, 1977; Sheriff, 1980; Locker and others, 1988; Lee and others, 1991; Sacks and others, 1992; Kindinger and others, 1994; Evans and others, 1994). All seismic profiles are calibrated with the lake surface as zero-depth

Seismic data interpretation was done using standard interpretation methods of Payton, 1977; Brown and Fisher, 1980; Sheriff, 1980. Prominent subbottom reflections and characteristic reflection "packages" were identified within the seismic-reflection profiles. Where transects crossed, the interpretation was checked for consistency. The depths to identified seismic units were calculated by converting travel times to approximate depths using 1,800 m/s as the average acoustic velocity for unconsolidated materials. The expected range of seismic depths for specific geologic units identified in the control wells was calculated using this same acoustic velocity value.

Seismic reflectors generated by changes in lithologic properties of the geologic units at depth can be correlated to the upper bounding surfaces of distinct lithologic units. Prominent or characteristic reflectors identified in lake seismic-reflection profiles were correlated to both proximal and regional lithologic logs. These correlations were limited to the maximum depth resolution of the seismic equipment; about 100 meters (300 ft) below land surface. In addition to identifying specific reflectors within the seismic reflection record and correlating them to lithologic units, seismic-reflection characteristics were described and related to specific seismic facies (table 1).

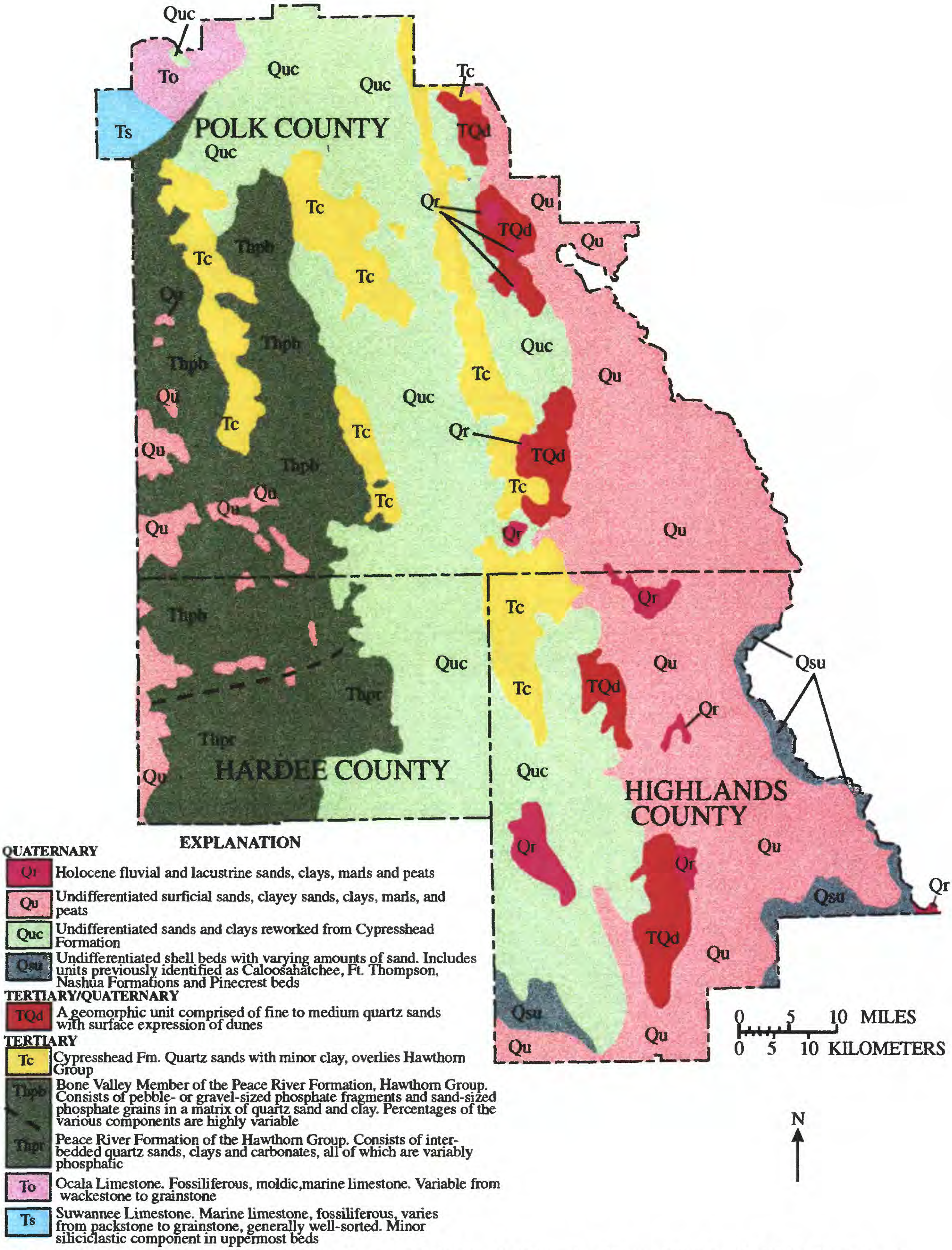


Figure 3. Geologic map of Polk, Hardee, and Highlands Counties (from Campbell, 1992; Scott and Campbell, 1993; and Arthur, 1993; respectively).

System	Series	Lithostratigraphic unit	Hydrostratigraphic unit	Generalized lithology
Quaternary	Pleistocene	Undifferentiated sand, shell, and clay (UDSC)	Surficial Aquifer System (SAS)	Highly variable lithology ranging from unconsolidated sands to clay beds with variable amounts of shell fragments, gravel-sized quartz grains and reworked phosphate
Tertiary	Pliocene	Hawthorn Group: Peace River Formation	Intermediate Aquifer System and/or Intermediate Confining Unit (IAS - ICU)	Interbedded sands, clays and carbonates with siliciclastic component being dominant and variably mixed; moderate to high phosphate sand/gravel content
	Miocene	Hawthorn Group: Arcadia Formation (Tampa Member; Nocatee Member)		Arcadia Formation is a fine-grained carbonate with low to moderate phosphate and quartz sand, variably dolomitic Tampa Member is a sandy, low phosphate wackestone Nocatee Member is a clayey, carbonate, mud-bearing sand with low amounts of phosphate
	Oligocene	Suwannee Limestone	Floridan Aquifer System: Upper Floridan Aquifer (UFA)	Suwannee Limestone is a fine- to medium-grained packstone to grainstone with trace organics and variable dolomite and clay content
	Eocene	Ocala Limestone		Ocala Limestone is a chalky, very fine- to fine-grained wackestone/packstone varying with depth to a biogenic medium- to coarse-grained packstone grainstone; trace amounts of organic material, clay, and variable amounts of dolomite
		Avon Park Formation		Avon Park is a fine-grained packstone with variable amounts of organic-rich laminations near top; limestone with dolostone interbeds typical in upper part, deeper beds are continuous dolostone with sulfate near base

Figure 4. Litho-hydrostratigraphic column for units that occur within the study area (Missimer and others, 1994; Scott and others, 1994; Wingard and others, 1994; Covington, 1993).

Table 1. Descriptions of seismic-facies characteristics, geologic interpretations, and symbols used in interpreted profiles.

SEISMIC FACIES	INTERPRETATION	SYMBOL ON PROFILES
Low amplitude, reflection-free	Uniform lithology, A-Rapid deposition with little to no internal structure, or B-Disrupted units associated with subsidence, downward piping and raveling	**RF**
Continuous, high amplitude, concordant parallel reflectors, may exhibit 'SAG' structure	Possibly clay or other unit capable of deformation in response to loss of support at depth	**HAR, SAG**
Low- to high-amplitude disrupted and intermittent reflectors	Irregular surface, possibly karst surface of limestone	**ISR**
High amplitude ringing multiples	Organic-rich lake-bottom sediments	**RM**
High amplitude, chaotic, reflectors, obscuring data	Gas in lake-bottom sediments	**HAC**
Laminated, concordant, parallel, high to moderate amplitude reflectors	Recent lake-bottom sediments	**RLS**

The seismic facies may indicate the lithologic properties of materials at depth and also may be used in delineating geologic units as part of the seismic data interpretation (Mitchum, Vail, and Thompson, 1977; Mitchum, Vail, and Sangree, 1977; Mitchum, 1977).

One of several problems associated with the seismic record includes the masking of data by strong lake-bottom multiples. The loss of interpretable record can be associated with biogenic gas in the highly organic sediments in low areas of the lake bottom and is a common problem in many lake records (Locker and others, 1988; Snyder and others, 1989; Lee and others, 1991; Sacks and others, 1992; Evans and others, 1994; Kindinger and others, 1994).

Regional Stratigraphic Methods

The regional geologic sections (figs. 5, 6, and 7) were constructed by the Florida Geological Survey (FGS) and the Southwest Florida Water Management District (SWFWMD). The hydrogeologic units were described by the SWFWMD using wells in the Regional Observation Monitoring-well Program (ROMP). Stratigraphic units were identified or confirmed by the FGS for all of the ROMP sites. Additional information from FGS logs was used to supplement the ROMP data. Occasionally, specific formation boundaries were uncertain and their inferred contacts are dashed on the cross sections.

HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework of the study area can be described on a regional as well as local scale. The regional framework consists of the general lithostratigraphy and hydrostratigraphy of the Lake Wakes Ridge area whereas sublake geology describes the local scale features that can be related to the regional framework.

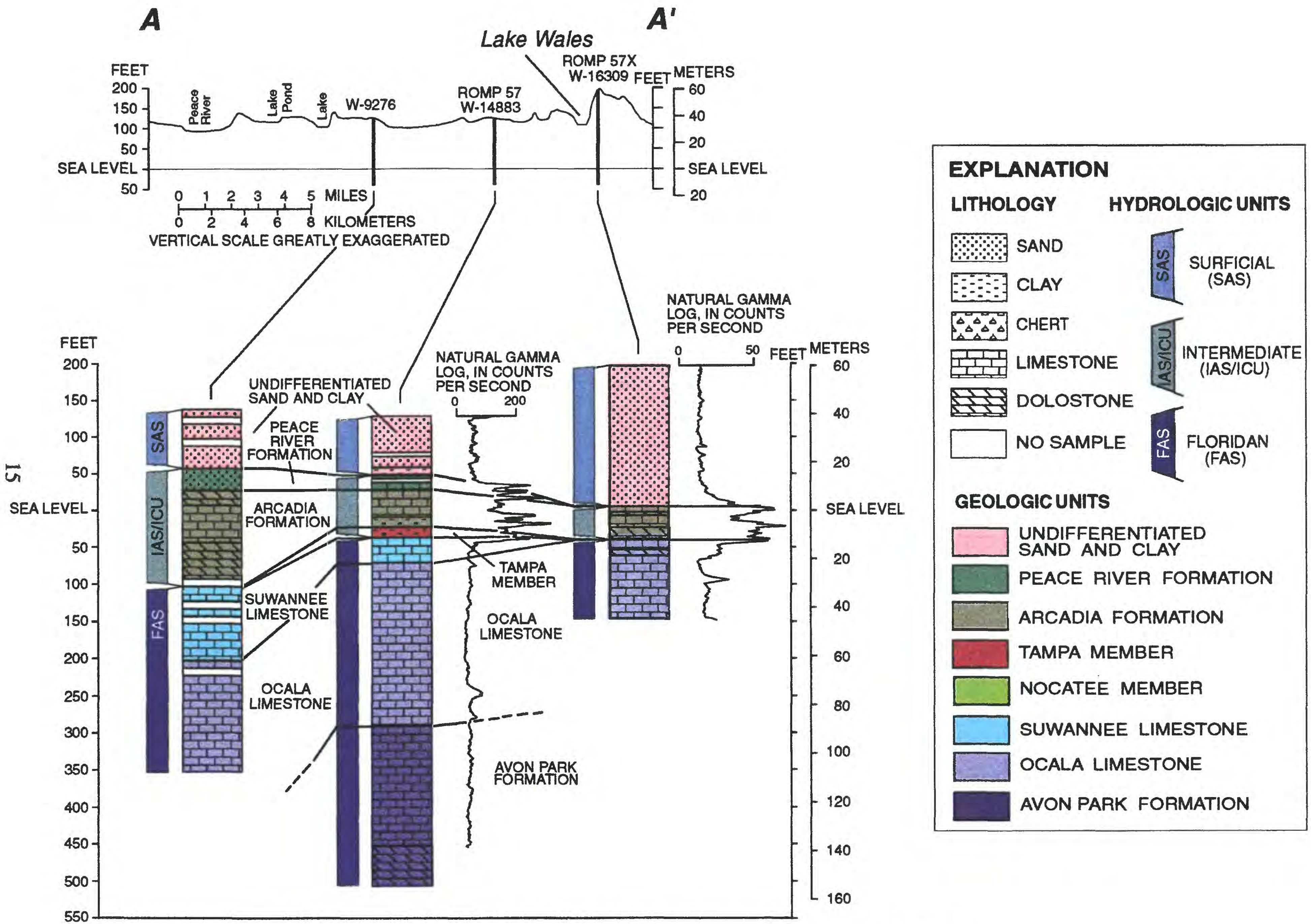


Figure 5. Regional geologic section A-A'. Location shown in figure 1.

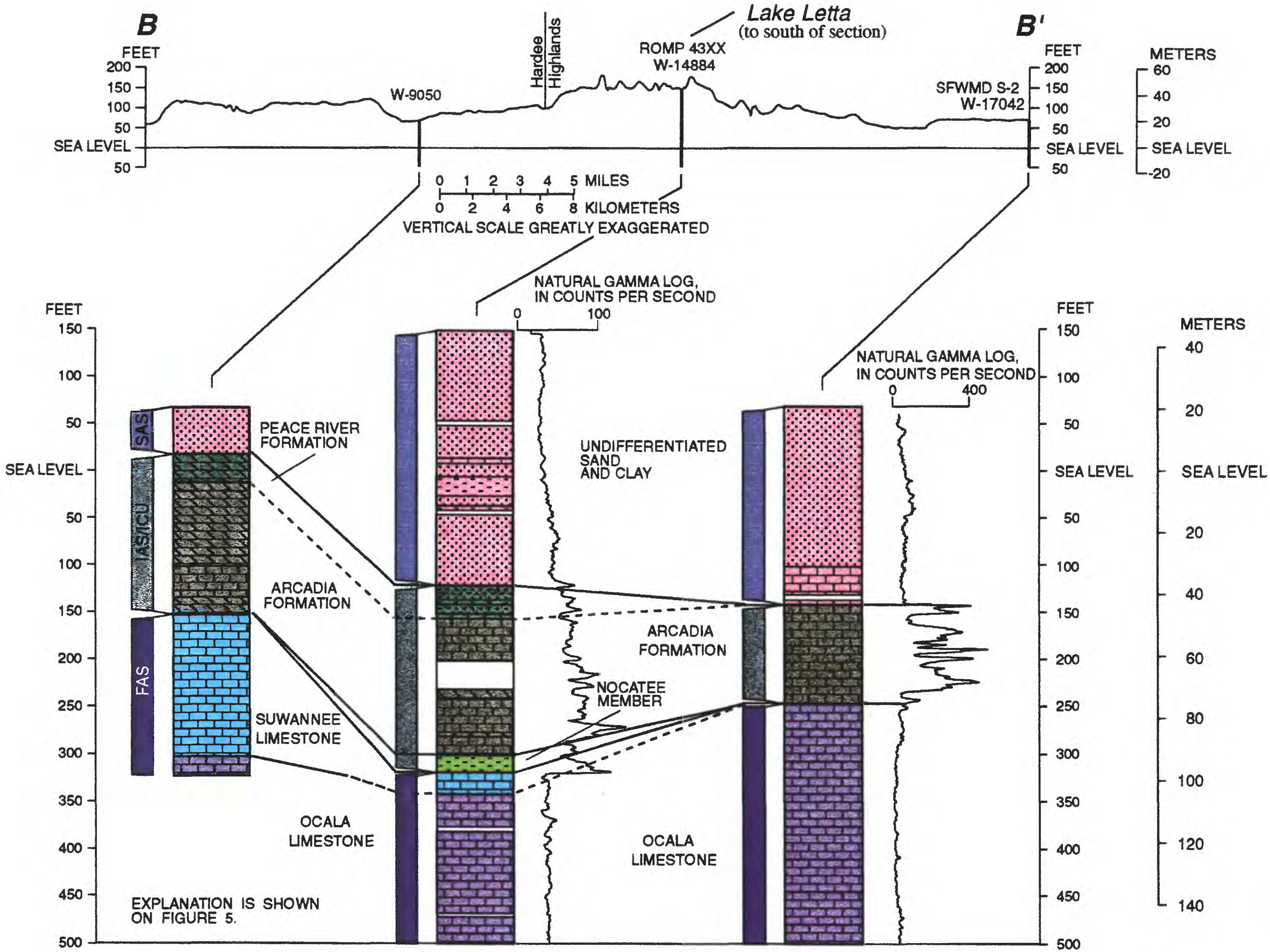


Figure 6. Regional geologic section B-B'. Location shown in figure 1.

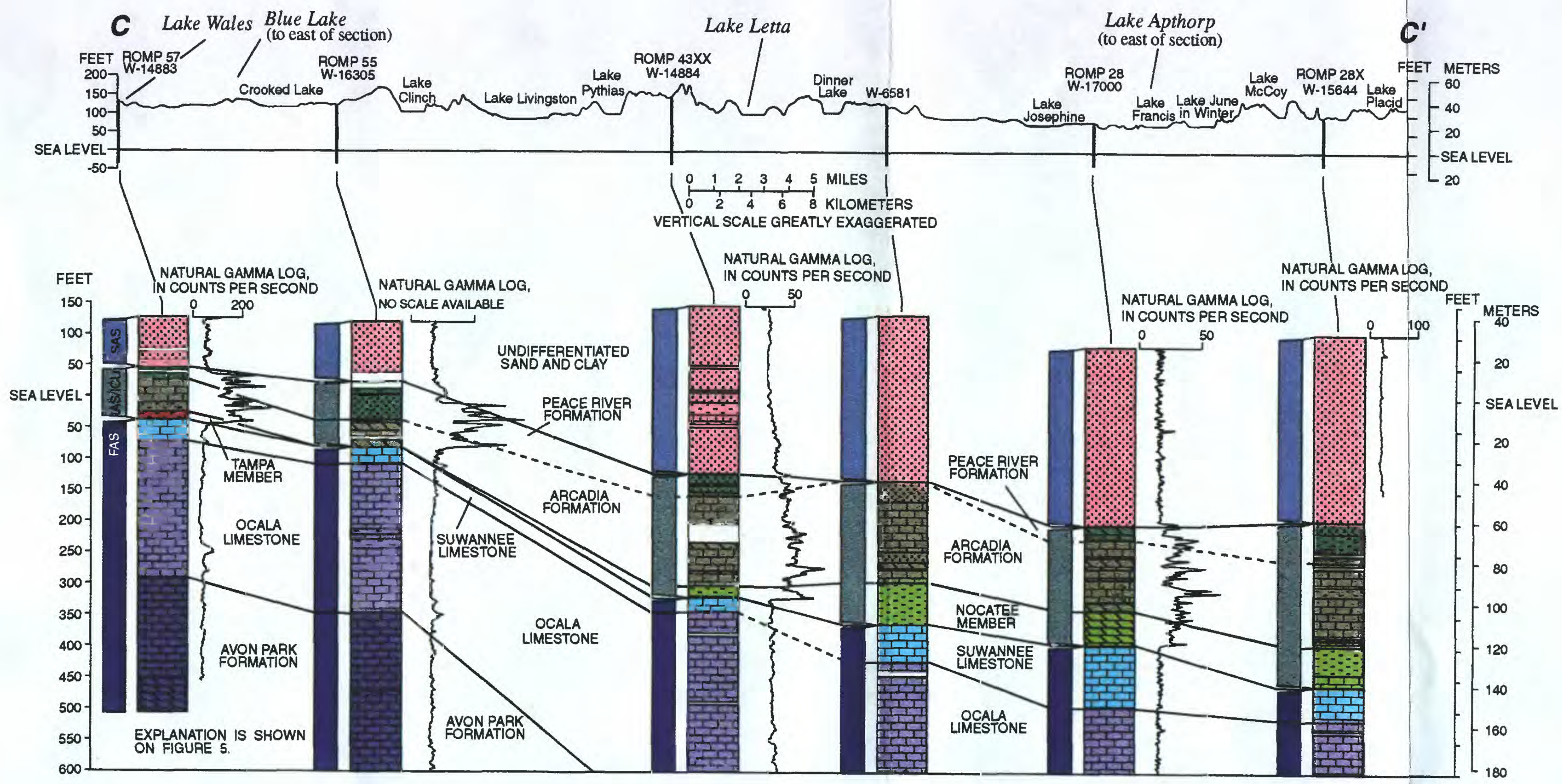


Figure 7. Regional geologic section C-C'. Location shown in figure 1.

Lithostratigraphy

The general geology of the study area can be summarized as a thick sequence of carbonates (both dolomite and limestone) that constitute the majority of materials that make up the Floridan carbonate platform (FCP). In the study area, the uppermost limestone corresponds to carbonates of the Arcadia Formation and the Suwannee Limestone. Most of the uppermost limestone of the Floridan carbonate platform is an irregular, unconformable surface due to extensive dissolution and karstification. Within the study area, the vertical range of this irregularity is on the order of 10 to 20 meters (30 to 70 ft). This carbonate surface is overlain by siliciclastic materials of varying thickness The distribution and thickness of these materials are shown in figure 8.

These siliciclastic materials range from marine authigenic clays to well-sorted, clean sands of a coastal shoreline environment and are extremely variable in both lithologic and hydraulic properties. A geologic map of the surficial geology is shown in figure 3. All geologic units cropping out within the study area are composed of unconsolidated siliciclastic materials. The geologic units described in the litho-hydrostratigraphic column in figure 4 and shown in subsequent geologic sections are discussed below. Altitude of the top of the Avon Park Formation (Miller ,1986), of middle Eocene age, ranges from approximately 90 to 240 meters (300 to 800 ft) below sea level. The Avon Park Formation ranges in thickness from approximately 380 to 450 meters (1,250 to 1,500 ft) in the study area (Miller, 1986). While this formation can play some role within the deeper hydrogeologic framework, it is not expected to exert significant control on the shallower hydrogeologic framework and therefore is not included as part of this study.

The upper Eocene Ocala Limestone (Dall and Harris, 1892) unconformably overlies the Avon Park Formation. Altitude of the top of the Ocala Limestone ranges from approximately 12 to 160 meters (40 to 510 ft) below sea level within the study area. Thickness of this formation is fairly uniform within the study area, averaging about 90 meters (300 ft). The Ocala Limestone ranges from a chalky, very-fine-to fine-grained wackestone to packstone to a biogenic medium- to coarse-grained packstone to grainstone. Porosity is variable within this unit and generally is moldic and intergranular

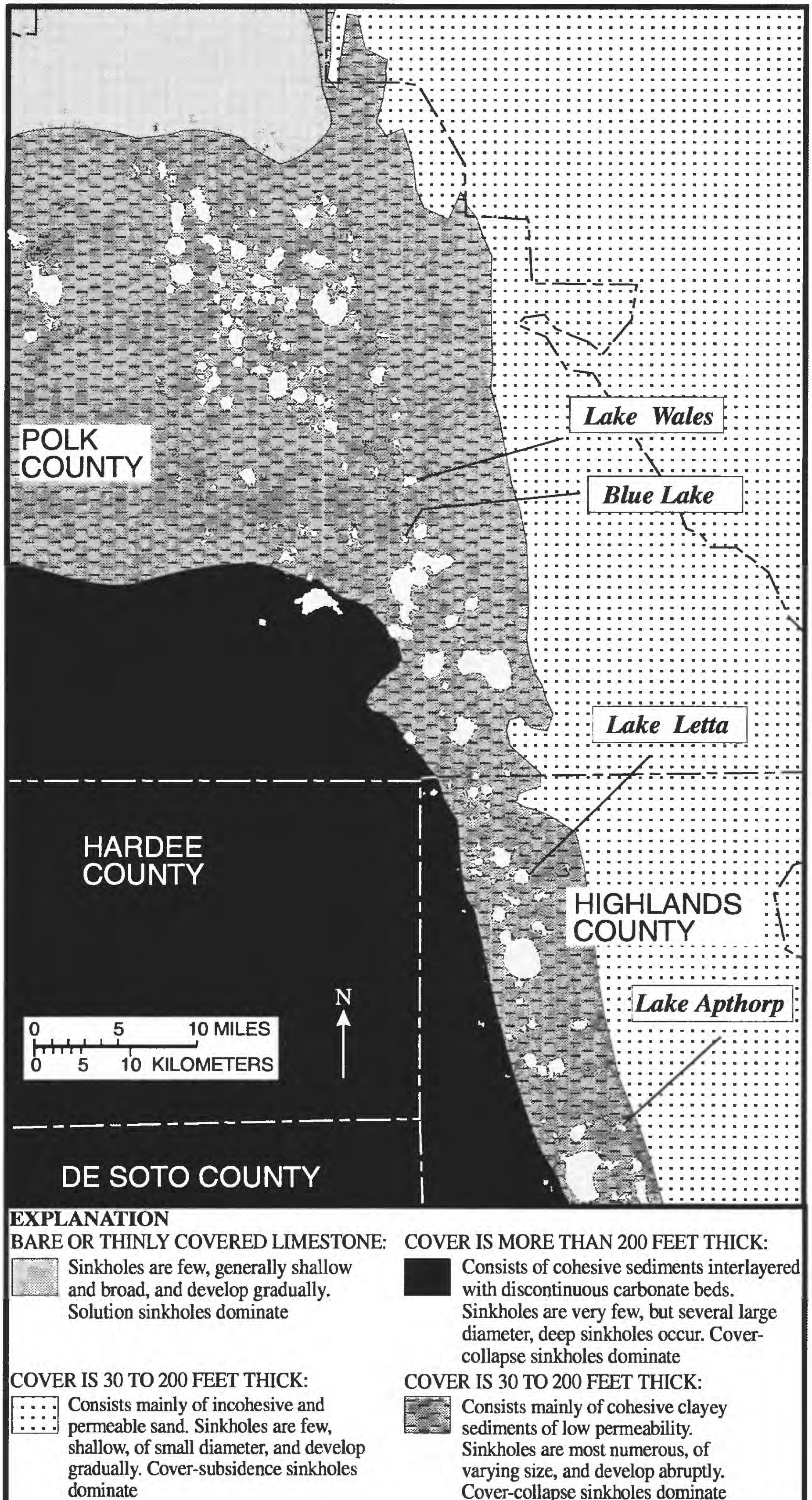


Figure 8. Lithologic characteristics of materials overlying the surface of the Floridan carbonate platform and predominant types of associated sinkhole development within the regional study area (adapted from Sinclair and Stewart, 1985).

with occasional macrofossil molds. To the west of the study area, and in other areas of Florida, the Ocala Limestone is well known for its high degree of karstification and dramatic karst features. Within the study area, the presence of these features is uncertain. Although this unit may control subsidence features observed near the surface, the Ocala Limestone occurs beyond the depth resolution of this investigation, 90 meters (300 ft) below land surface, and was not detected in any seismic profiles.

Formations overlying the unconformably-bound Ocala Limestone include the lower Oligocene Suwannee Limestone (Cooke and Mansfield, 1936), along the Lake Wales Ridge, or the Hawthorn Group along the eastern flank of the ridge. Where present, the Suwannee Limestone lies on top of the Ocala Limestone. The top of the Suwannee limestone ranges between 12 and 130 meters (40 and 430 ft) below sea level; the Suwannee Limestone averages approximately 15 meters (50 ft) in thickness along the ridge, thinning to the east. The lithology of the Suwannee Limestone ranges from medium-grained packstone to grainstone. This unit includes trace amounts of sand and clay within the upper sections. Porosity is variably moldic and intergranular. Similar to the Ocala Limestone, dissolution within the Suwannee Limestone also can control the development of subsidence features within the Lake Wales Ridge; however, this unit occurs below the maximum depth resolution of seismic profiles. The upper surface of the Suwannee Limestone is an unconformity that is overlain by Hawthorn Group sediments.

Hawthorn Group sediments are late Oligocene to early Pliocene in age and generally consist of phosphatic siliciclastics and carbonates (fig. 4) (Scott, 1988; Wingard and others, 1994; Covington, 1993). The identification, nature of continuity and thickness of these units is the primary focus of this study because these units control the hydrologic interaction between the surficial aquifer system and the Upper Floridan aquifer, and also because the physical properties and depths to these units are appropriate for the seismic-reflection techniques. The Hawthorn Group generally is composed of sandy, phosphatic clay and dolostone that ranges in thickness from 25 to 75 meters (75 to 250 ft) across the study area. In the study area, the Hawthorn Group consists of the Arcadia Formation, which includes the Tampa and Nocatee Members, and the Peace River Formation which includes the Bone Valley Member.

The Arcadia Formation is the lower unit of the Hawthorn Group. The top of the Arcadia Formation ranges from 8 meters (25 ft) above to 115 meters (375 ft) below sea level; the formation ranges in thickness from 20 to 80 meters (70 to 270 ft). The formation is a sequence of yellowish-gray to light-olive-gray clays and clayey carbonate with highly variable amounts of quartz sand and sand- to gravel-size phosphate grains. Porosity of this unit generally is intergranular and moldic. The carbonate-rich Tampa Member is limited to the northern part of the study area (fig. 4). The Nocatee Member is characteristically an olive-gray to yellow-gray clay to fine sand with dolomite, trace phosphate grains and organic materials. The Nocatee Member forms the base of the Arcadia Formation within the Hawthorn Group in the central and southern part of the study area. The unit pinches out towards the north, against the topographically higher carbonates of the Suwannee Limestone.

The Peace River Formation usually overlies the Arcadia Formation. The Peace River Formation has been described by Scott (1988) as a yellow-gray to olive-gray, interbedded sand, clay, and carbonate with the siliciclastics being dominant. Variable amounts of phosphate sand and gravel, as well as occasional carbonate beds, are interspersed throughout the unit. Delineation of the boundary between the Peace River Formation and the underlying Arcadia Formation becomes increasingly difficult toward the southern part of the Ridge. Slight lithofacies changes in the Peace River Formation, overall declines in phosphatic content, increased siliciclastics in the upper Arcadia Formation and a possible conformable contact between the Peace River and the Arcadia Formations contribute to the difficulty in identifying a boundary between the two formations in this area (figs. 5, 6, and 7). Locally, the Peace River Formation can be more than 18 meters (60 ft) thick.

Post-Hawthorn Group sediments occur throughout the study area and range in thickness from approximately 24 to 90 meters (80 to 300 ft). These sediments are primarily sand, shell and clay in varying proportions. Lithostratigraphic units in this sequence include reworked Peace River Formation sediments, the Cypresshead Formation (Citronelle equivalent) and the undifferentiated sand and clay unit (UDSC) with variable organic and shell content. Surficial Quaternary eolian deposits occur locally along the flanks of the Lake Wales Ridge. Lithologic variations within the UDSC units reflecting changes in confining conditions at depth, are of interest in this study. The occurrence of discontinuous units, steeply dipping beds or infilling sequences, can indicate subsidence events or the presence of dissolutional features at depth.

Hydrostratigraphy

The hydrostratigraphy of the Lake Wales Ridge consists of a three-layer system with two significant aquifers; the unconfined surficial aquifer system (SAS), and the artesian Floridan aquifer system (FAS), separated by sediments generally assigned to the intermediate aquifer system/intermediate confining unit (IAS/ICU). Aquifer delineation is controlled mainly by lithostratigraphy, with aquifer system boundaries falling at or near major lithologic contacts (fig. 4).

The SAS is contained within the UDSC and the Cypresshead Formation, and is present throughout the Lake Wales Ridge. The SAS ranges in thickness from 15 meters (50 ft) in the northwestern regions of the Lake Wales Ridge, to more than 107 meters (350 ft) below topographic highs in the southern regions of the study area. Hydraulic properties of the SAS vary with composition and thickness. Reported hydraulic conductivity values range from 0.3 to 17 meters per day (m/d) (1 to 55 ft/d) (Hutchinson, 1978; Lee and others, 1991). Clay content typically increases and hydraulic conductivity decreases near the base of the surficial sediments, which directly overlie phosphatic clay and carbonate of the Hawthorn Group.

The intermediate aquifer system/intermediate confining unit (IAS/ICU), which separates the SAS from the underlying Floridan aquifer system, is composed of the Hawthorn Group sediments. Within the Lake Wales Ridge, the IAS/ICU generally is confined or under artesian conditions (Duerr and others, 1988; Barcelo and others, 1990). Hydrologic characteristics of the IAS/ICU are not well-defined, and the complex nature of the Hawthorn lithology (see previous section) produces highly variable hydraulic properties. Permeable zones, where dissolution has enhanced porosity, occur in the Arcadia Formation (Evans and others, 1994; Barcelo and others, 1990); however, little data are available to document the lateral continuity of these permeable zones and quantify this porosity enhancement.

Collectively, the Hawthorn Group sediments act as a regional confining unit overlying the Floridan aquifer system. Confining properties of the Hawthorn Group sediments have been quantified using test sites on the Lake Wales Ridge. Hydraulic conductivities of 0.2 m/d (0.5 ft/d) were determined for the IAS/ICU from aquifer tests. Based on laboratory testing of core samples from the Arcadia Formation, vertical hydraulic conductivities ranged from 3.0×10^{-7} m/d to 3.0×10^{-4} (10^{-7} to 10^{-4} ft/d). Leakance coefficients of the upper confining unit can be highly variable, ranging from 1.0×10^{-5} to 3.0×10^{-4} (Yobbi, 1996). Localized confining properties of the IAS/ICU vary with formational thickness, lithologic composition, and the occurrence of breaches or discontinuity of confining units due to sinkhole collapse features.

The FAS, made up of the Upper Floridan aquifer (UFA) and the Lower Floridan aquifer is the principal artesian aquifer underlying the Lake Wales Ridge study area. The Upper and Lower Floridan aquifers are separated by a confining unit, which is composed of low permeability evaporite units. Generally, the FAS is identified as a vertically continuous sequence of carbonate rocks, composed of the Suwannee and Ocala Limestones, and all or part of the Avon Park Formation. The top of the FAS ranges from 10 meters (30 ft) below sea level in the northern Ridge area to about 140 meters (430 ft) below sea level at the southern end of the Lake Wales Ridge (figs. 5, 6, and 7).

Sublake Geology

An important set of interdependent factors control subsidence and sinkhole formation within the Lake Wales Ridge. These factors are: (1) the distribution, thickness, and lateral continuity of the regional confining units that mantle the soluble carbonate units at depth; (2) the acidity and flow direction of ground water within the lake and adjacent lake and ground-water environment; (3) paleohydrologic conditions that might have altered the competence of subsurface strata, and (4) current hydrologic conditions that can trigger new subsidence events (Sinclair and Stewart, 1985).

Effects of paleohydrologic conditions on the karstification of the carbonate surface, the composition, deposition, and distribution of confining materials over this limestone surface, and the ultimate reworking of these siliciclastics into the buried karst surface has resulted in a complex geologic history. The change in sedimentation from carbonate to siliciclastic materials during the Tertiary period reflects changes in climate, sea level, and paleoceanographic processes resulting in the complex interfingering of carbonate and siliciclastic stratal units within the Floridan carbonate platform. Relative sea level fluctuations ranged from more than 100 m above present-day sea level during the Miocene age to more than 100 m below present-day sea level during Pleistocene age (Haq and others, 1988). The associated climatic changes caused extensive changes on land, such as changes in the amount of subaerially exposed land mass, vegetative cover, weathering and fluvial processes and, of particular interest to this study, changes in hydrologic conditions. During sea level highstands, the limestone surface was flooded and marine depositional processes smoothed over this irregular surface by filling in voids and effectively sealing off the exposed carbonate surface.

Over time, and repeated sea level fluctuations, extensive unconformities developed along the exposed surfaces of these units. The development of surface- and ground-water systems alternating with periods dominated by marine, near-shore marine, coastal, lacustrine, and fluvial processes reworked these units into complex geometries. The depositional and erosional histories have left a partially preserved, partially reworked, geologic record of these events.

Sea level changes also caused major fluctuations in ground-water levels that affect sinkhole formation. Decreases in ground-water levels, responding to a drop in sea-level, affected the entire hydrogeologic system (Watts and Hansen, 1988; Grimm and Jacobson, 1992). Significant declines in ground-water head elevations, especially where cavities and voids have formed in underlying geologic units, cause a loss of buoyant support for the overlying sediments, inducing sinkhole formation (Sinclair and others, 1985; Chen and Beck, 1989; Ford and Williams, 1989). This is a well-documented cause for modern sinkhole development. Thus, it is probable that historical declines in ground-water levels were accompanied by significant subsidence throughout the ridge area. As overlying sediments settled into the underlying supporting framework, the sediments and ground-water system reached equilibrium. If the sinkholes become "plugged" and precipitation is sufficient, the surficial aquifer can become perched. These depressions become swamps, ponds or lakes as water levels increase. Recent observations of sinkholes forming in this region indicate that this type of subsidence activity continues under present hydrologic conditions.

The presence and lithologic character of the insoluble siliciclastic deposits control ground-water recharge routes. In areas where clays are thin, discontinuous, or locally breached, effective internal drainage is developed, and downward ground-water recharge occurs. Effective downward leakage is prevented where clays are thicker and continuous and surface-water drainage systems develop. Because clays control downward movement of water, their presence within the intermediate confining unit supports surficial water tables and can alter ground-water chemistry through ion-exchange processes (Berndt and Katz, 1992; Katz and others, 1995A, Katz and others, 1995B).

Once ground water moves through the confining units, it becomes part of the Upper Floridan carbonate aquifer. Ground-water flow in carbonate rocks occurs predominantly along preferential avenues enlarged during the formation of secondary porosity. These ground-water flow zones tend to develop along joints, fractures, bedding planes, lithologic boundaries, and unconformable surfaces. Although the underlying carbonates continue to be susceptible to dissolution processes, a thick layer of dense clay can have sufficient structural strength to bridge a large solution cavity in the underlying carbonate material. Over time, however, aggressive recharge water moving along an established preferential flow path can further enlarge pre-existing cavities and voids, ultimately leading to collapse or subsidence. Sinkholes that eventually breach the confining unit are commonly infilled with material from overlying unconsolidated surficial sediments.

The ideal subsidence depression develops slowly as the land surface and underlying beds gradually sag into the enlarging cavity. Depending on whether the sinkhole is a subsidence or a collapse depression, the infilling can consist of disrupted, reworked unconsolidated materials, or sagging, relatively intact stratal units. If the overlying units are unconsolidated and subsidence occurs gradually, overlying materials are piped or slowly ravel into subsidence features. If the overlying units are clay-rich and can be easily deformed, folding or sagging commonly occurs (Ford and Williams, 1989). However, collapse depressions are the result of an abrupt rupture of the materials bridging an underlying cavity. The abrupt nature of the collapse usually causes significant disruption of the original depositional characteristics. The infilling sediments are left with little, if any, internal depositional structure. In both types of sinkholes, hydrologic properties are altered. The infilling sediments can have significantly higher hydraulic conductivity than the original confining unit and thereby provide a preferential avenue for ground-water recharge to occur below a lake of sinkhole origin (Grubbs, 1995; Lee and Swancar, in press).

Sinkhole development is accelerated when the water moving through the limestone is acidic. Surficial ground water, especially in an internally drained lake basin, can be slightly acidic because the major recharge component, rainfall, has a naturally low pH (Katz and others, 1995A, 1995B; Pollman and others, 1991). The natural acidity can be further enhanced if recharge water is exposed to significant carbon dioxide from bacterial decomposition of organic matter in the soil zone, such as lake-adjacent swampy lowlands or organic-rich lake-bottom sediments (Stumm and Morgan, 1981).

The contributing basins of the lakes in the Lake Wales Ridge include both well-drained sand hills and swampy, adjacent wetlands. Some of the lakes have accumulated significant organic-rich deposits. These deposits may be tens of meters thick (Grimm and others, 1993; Binford and Brenner, 1986) depending upon the age of the lake and the rate of organic sedimentation. Although the low-hydraulic conductivity of these organic deposits can contribute to lake bottom confinement, these sediments also can alter the chemical properties of ground water in the sublake region (Ford and Williams, 1989; Katz and others, 1995A, 1995B; Lee and Swancar, in press).

Downward leakage is variable throughout the Lake Wales Ridge. Present hydrologic conditions within the Lake Wales Ridge indicate a high potential for ground-water recharge; particularly downward leakage from the surficial aquifer system to the underlying confined aquifer in ridge and upland areas (Yobbi, 1996). Generally, water-table elevations in this region are higher than the potentiometric surfaces of the ground water below, providing an ideal setting for preferential downward ground-water flow within the sublake region. The hydraulic connectivity between a lake (surficial aquifer system) and the Upper Floridan aquifer is determined by the distribution and thickness of the confining unit materials. Breaches due to subsidence and sinkhole formation provide the most direct hydrologic connection between these aquifers by increasing downward leakage in the sublake region. The Lake Wales Ridge has been described as one of the most sinkhole-prone regions in Florida (Sinclair and Stewart, 1985). This region is characterized by many, predominantly cover-collapse type sinkholes, the size and shape of which are controlled partly by the thickness and composition of the unconsolidated material that covers the limestone. Dissolution features also are common within the buried carbonate units (Sinclair and Stewart, 1985).

Present-day hydrogeologic characteristics within the ridge, such as the high occurrence of, and potential for, sinkhole development, high recharge potential, the presence of naturally acidic recharge water within the lake and ground-water environment, create conditions conducive to the continued development of subsidence features. Subsidence activity modifies the siliciclastic overburden creating breaches in confining units. Studies of the geologic structure beneath the many, internally-drained lakes located within the Lake Wales Ridge provide an opportunity to document the existence, morphology, and evolution of sinkhole-lakes and their relation to the underlying hydrogeologic framework.

SEISMIC-REFLECTION INTERPRETATION

The regional geologic framework for the Lake Wales Ridge is described by three geologic sections: A-A′, B-B′, C-C′ constructed using 10 wells along and across the Lake Wales Ridge (figs. 5, 6, 7). Eight additional wells were used to improve resolution of specific geologic trends and to supplement lithologic data (fig. 1). Generally, all geologic units thicken and dip to the south. The Hawthorn Group thickens to the southwest, whereas the sandy units of the UDSC thicken along the Lake Wales Ridge and eastward.

Seismic Reflection Characteristics

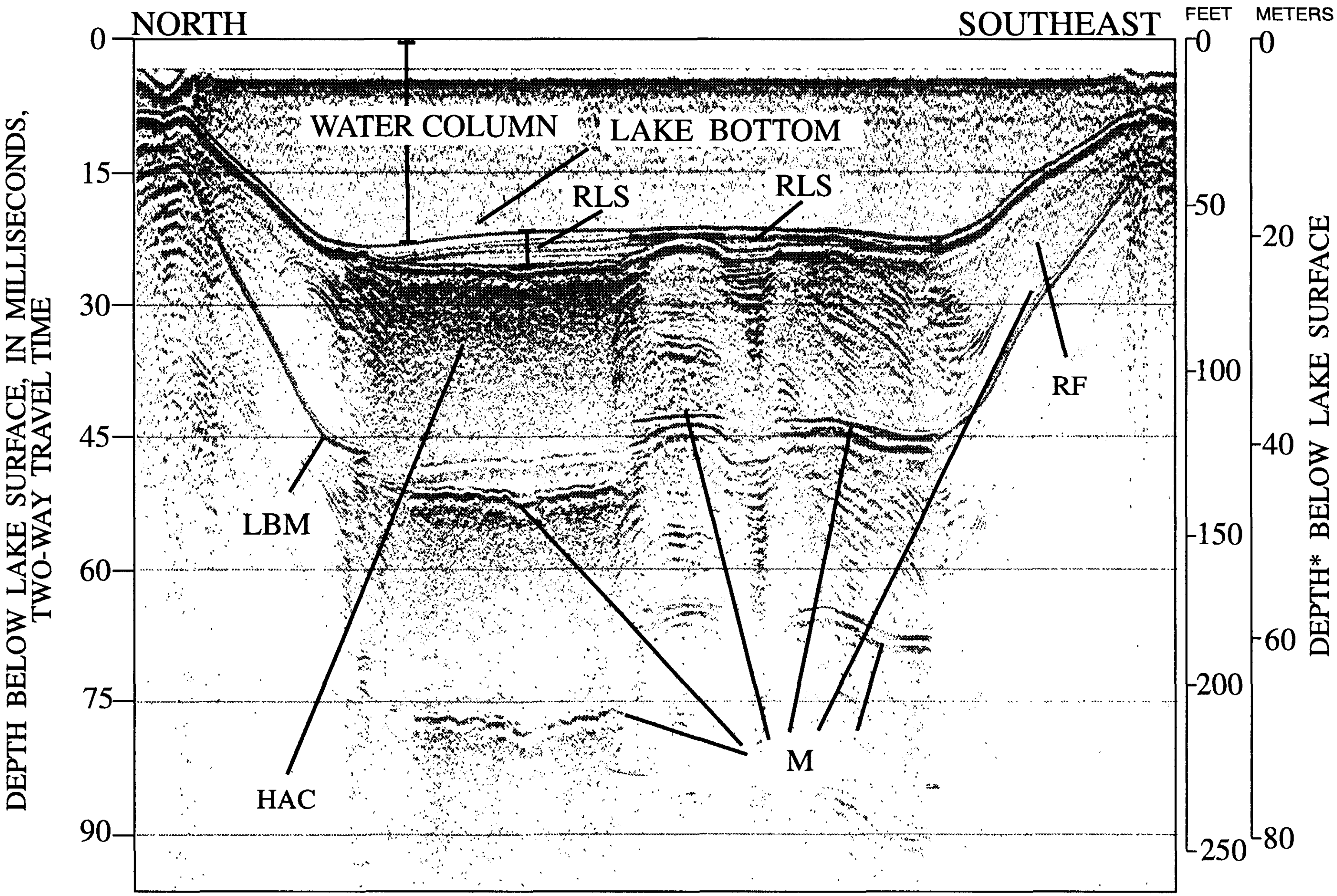
Distinct seismic facies were identified during this study (figs. 9 a-e) (table 1). Seismic facies have a distinct appearance in the graphical record and generally represent a specific change in the lithologic character of the geologic materials. The interpretation of the seismic facies identified in this study are summarized in table 1 with abbreviations used to identify these facies in the interpreted seismic profiles. The lack of cores obtained in the sublake region prevents direct correlation between the seismic record and local sublake geology; therefore, these interpretations have not been verified and will ultimately require direct correlation to sublake geology.

In all four lakes there were zones where the seismic signal was completely obscured or generated numerous lake-bottom multiples that often masked other reflective surfaces (figs. 9a, 9b, 9d, 9e). These multiples are present probably because of biogenic gas in the organic matter in the lake-bottom sediments. Seismic transects containing obscured data returns also contained 'windows' of good data (fig. 9b). Accumulations of recent lake-bottom sediments are clearly observed (fig. 9a).

A reflection-free seismic unit was often observed in upper lithologic sequences associated with subsidence features. This seismic characteristic indicates either a very uniform lithology, or a sedimentary unit with disrupted or no internal structure. Examples of this seismic unit are shown in figures 9a, 9c, and 9d.

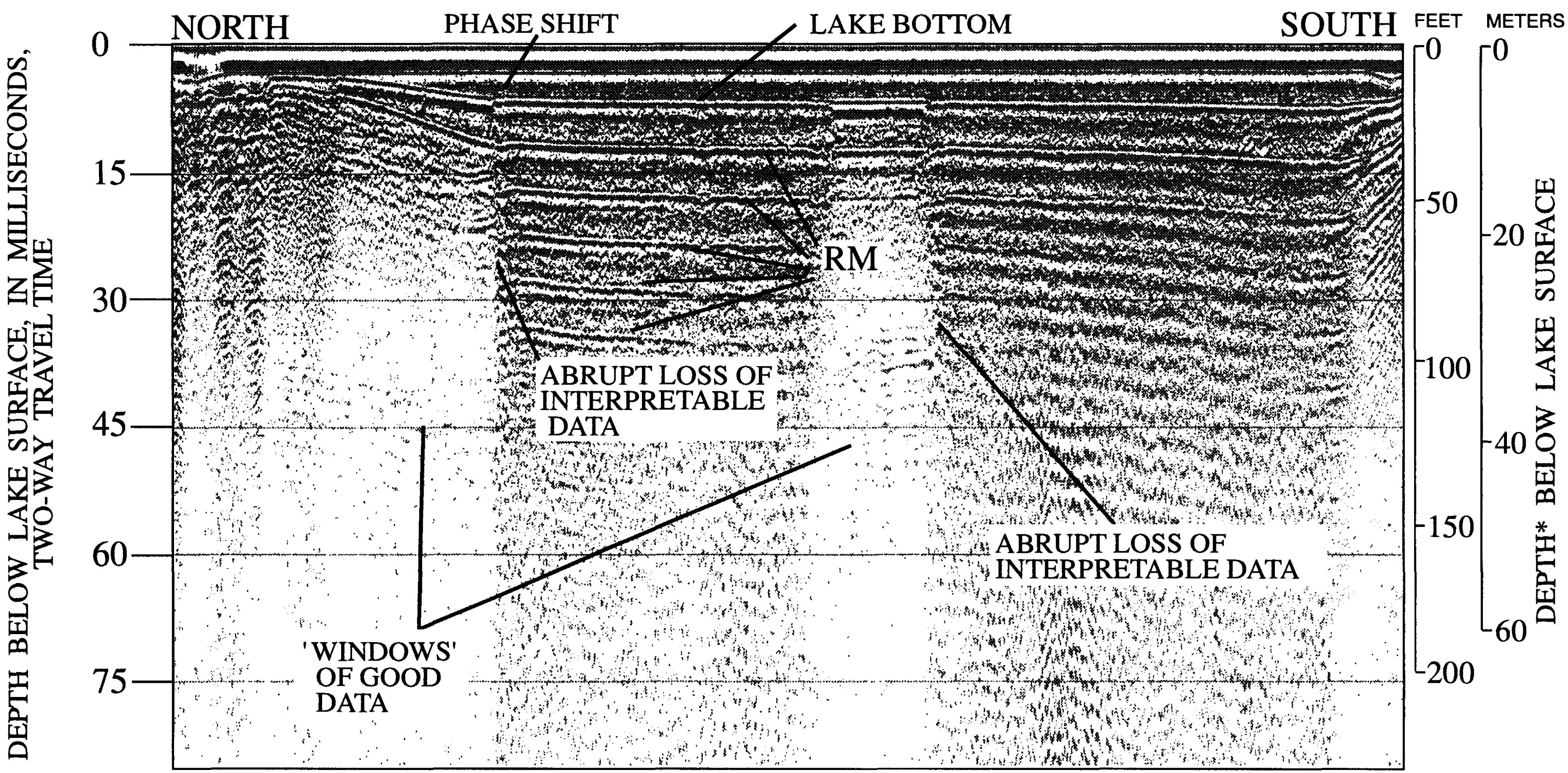
Another distinct seismic facies observed during this study is characterized by continuous, concordant reflectors. This unit commonly exhibits sagging structures inferring the loss of support at depth. This seismic unit possibly corresponds to a clayey unit that is capable of deformation. Examples are shown in figures 9d and 9e.

An intermittent, less-concordant unit also was observed in several profiles. This unit occurred intermittently and possibly corresponds to the karst surface of a carbonate



* Based on acoustic velocity of 1,800 meters per second.

Figure 9a. Examples of lake-bottom multiples (LBM), sub-bottom multiples (M), reflection-free zone (RF), high-amplitude chaotic zone (HAC), and well-laminated recent lake-bottom sediments (RLS) from Blue Lake transect number 6.



* Based on acoustic velocity of 1,800 meters per second.

Figure 9b. Examples of ringing lake-bottom multiples (RM), abrupt loss of interpretable data, and 'windows' of good data (associated with phase shift), from Lake Wales, transect number 13.

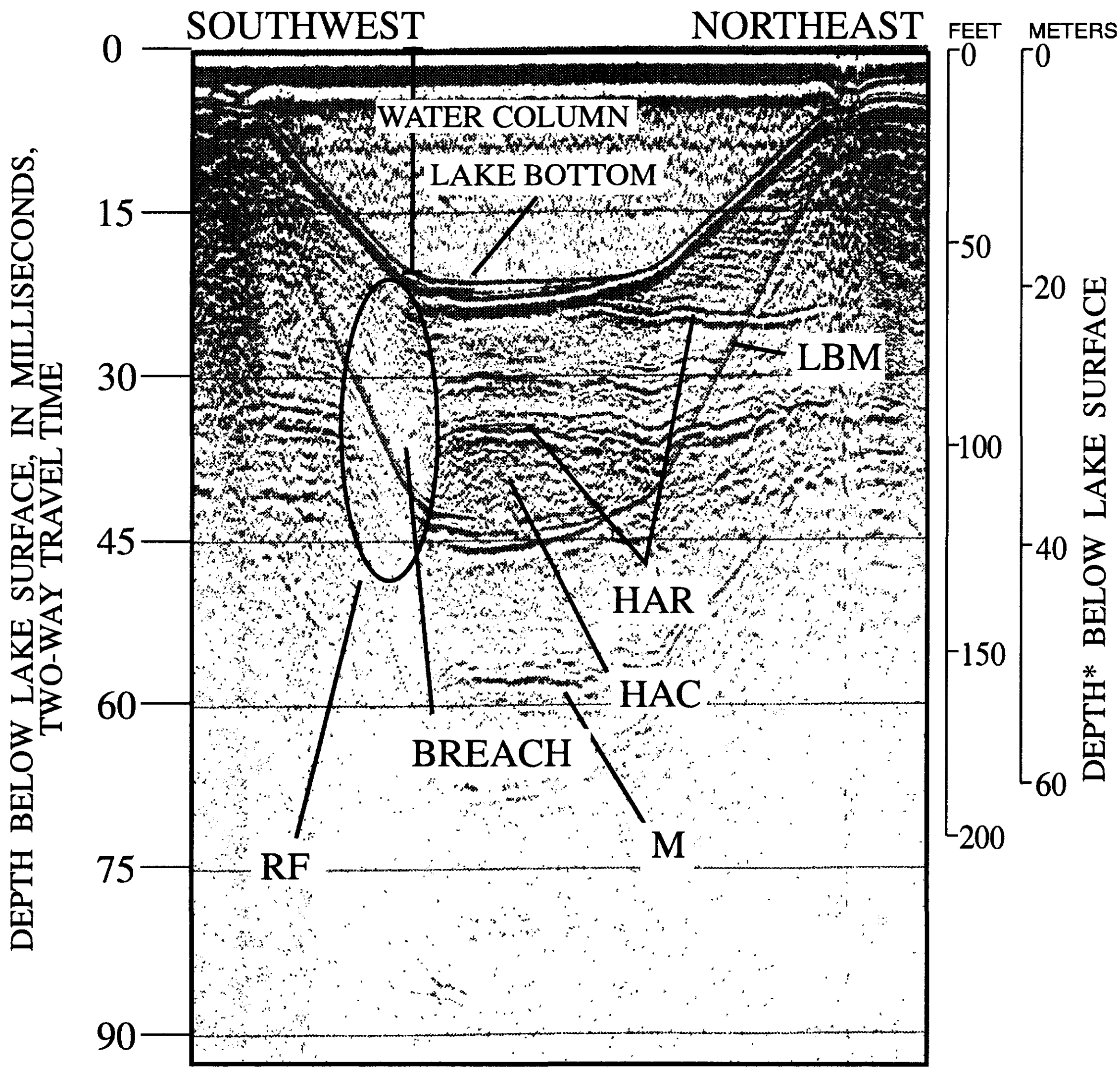
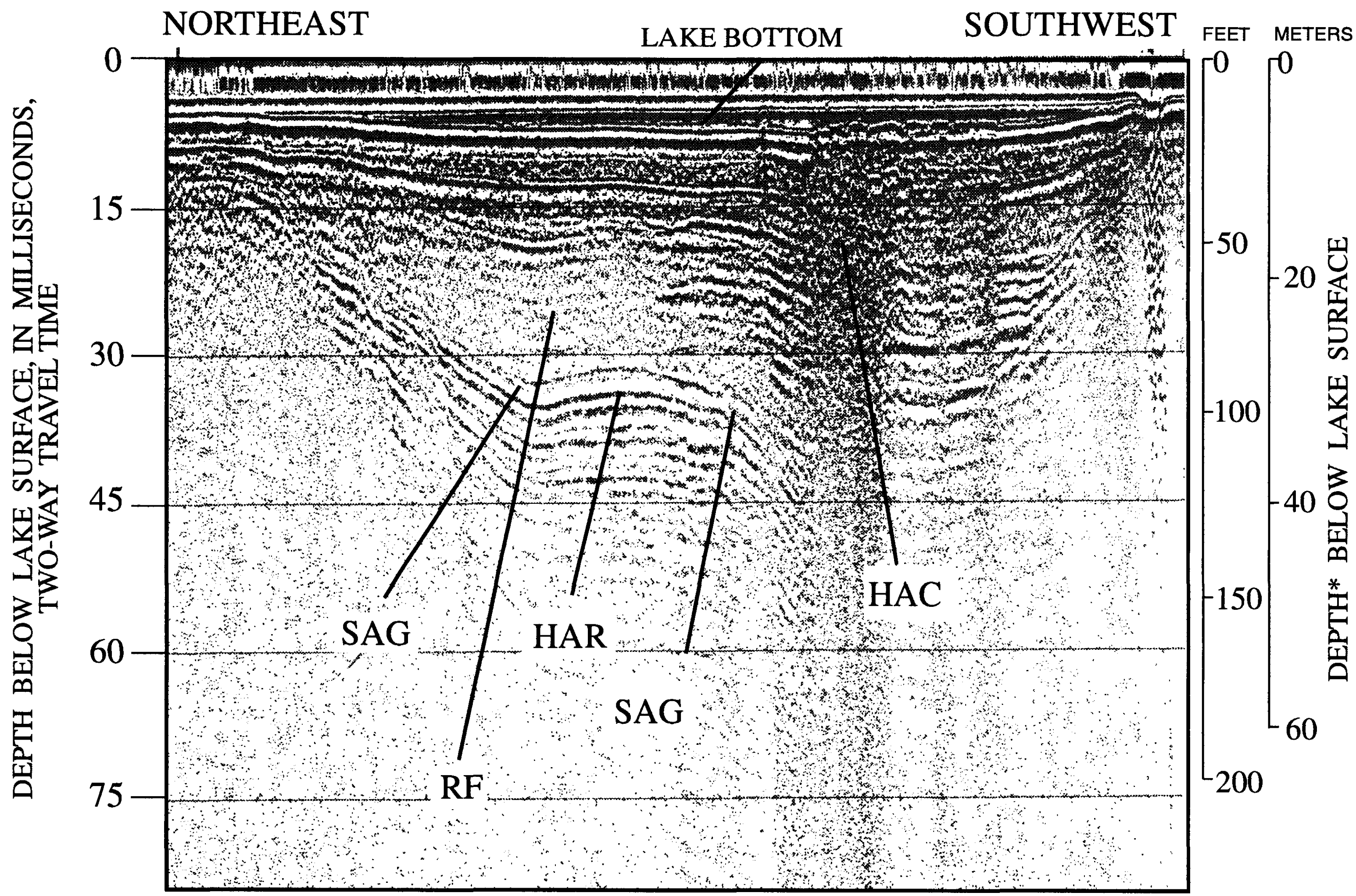
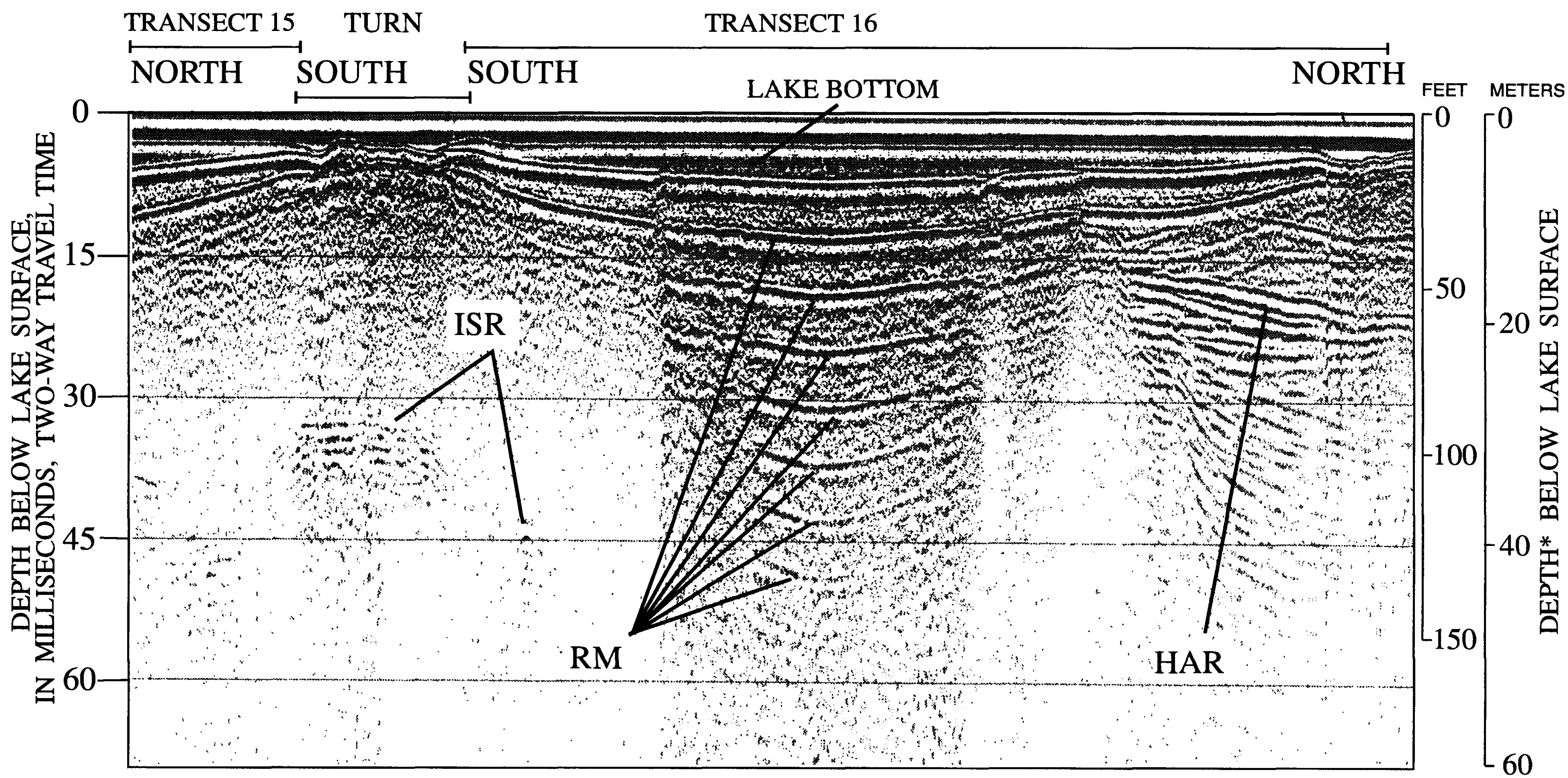


Figure 9c. Examples of high-amplitude concordant reflector (HAR), breach in continuous unit with reflection-free (RF) seismic facies infilling the breach, high-amplitude chaotic (HAC) zone, and lake and subbottom multiples (LBM) and (M). Data are from Blue Lake transect number 12.



* Based on acoustic velocity of 1,800 meters per second.

Figure 9d. Examples of high-amplitude, concordant reflector package (HAR), with sagging structures (SAG), high-amplitude chaotic zone (HAC), and reflection-free zone (RF). Data are from Lake Letta transect number 4.



* Based on acoustic velocity of 1,800 meters per second.

Figure 9e. Examples of the variability of seismic-reflection characteristics observed in Lake Wales. Data shown here illustrate a low- to high-amplitude intermittent reflector (ISR), high-amplitude concordant reflector (HAR), and areas of poor-quality data with ringing lake-bottom multiples (RM) obscuring sublake data. Data are from Lake Wales transect numbers 15 and 16.

unit. Examples of this unit are shown in figure 9e. Examples of seismic characteristics shown in figures 9a-9e, the observance of structural features within the sublake records and their relation to local and regional stratigraphy is discussed below in the context of each individual lake.

Sublake Seismic-Reflection Interpretation

The interpretation of the seismic-reflection data collected at each lake is presented separately below. Several illustrations are used to present the data for each lake. These include: a base map of the lake including bathymetric data when available, locations of the seismic transects, several representative seismic-reflection profiles that best illustrate the sublake geologic features identified at each lake during this study, and a final interpretation of sublake geology and possible confining conditions.

Lake Wales

Regional trends described by geologic sections A-A', B-B', and C-C' (figs. 5, 6, and 7), indicate the Peace River Formation, the Tampa Member of the Arcadia Formation, and the Suwannee Limestone pinch out in the Lake Wales region. At ROMP 57X, located directly south of Lake Wales, the Arcadia Formation is approximately 15 meters (50 ft) thick bounded above by the UDSC and below by the Ocala Limestone. The absence of these units within close proximity of the lake implies this region has been affected by dissolution and subsidence activity that has significantly removed, reworked, and altered the original distribution of the geologic units. As a result, the geologic framework beneath Lake Wales is highly variable.

The seismic depths to the upper surfaces of the Peace River and the Arcadia Formations were calculated using proximal well control. Locations of the seismic transects collected at Lake Wales are shown in figure 10. The top of the Peace River Formation, if present, is expected to be between 21 and 25 milliseconds (ms) and the seismic depth to the top of the Arcadia Formation is expected to be between 25 and 40 ms. Expected ranges of seismic depth for these two units are shown on seismic profiles (figs. 11 and 12).

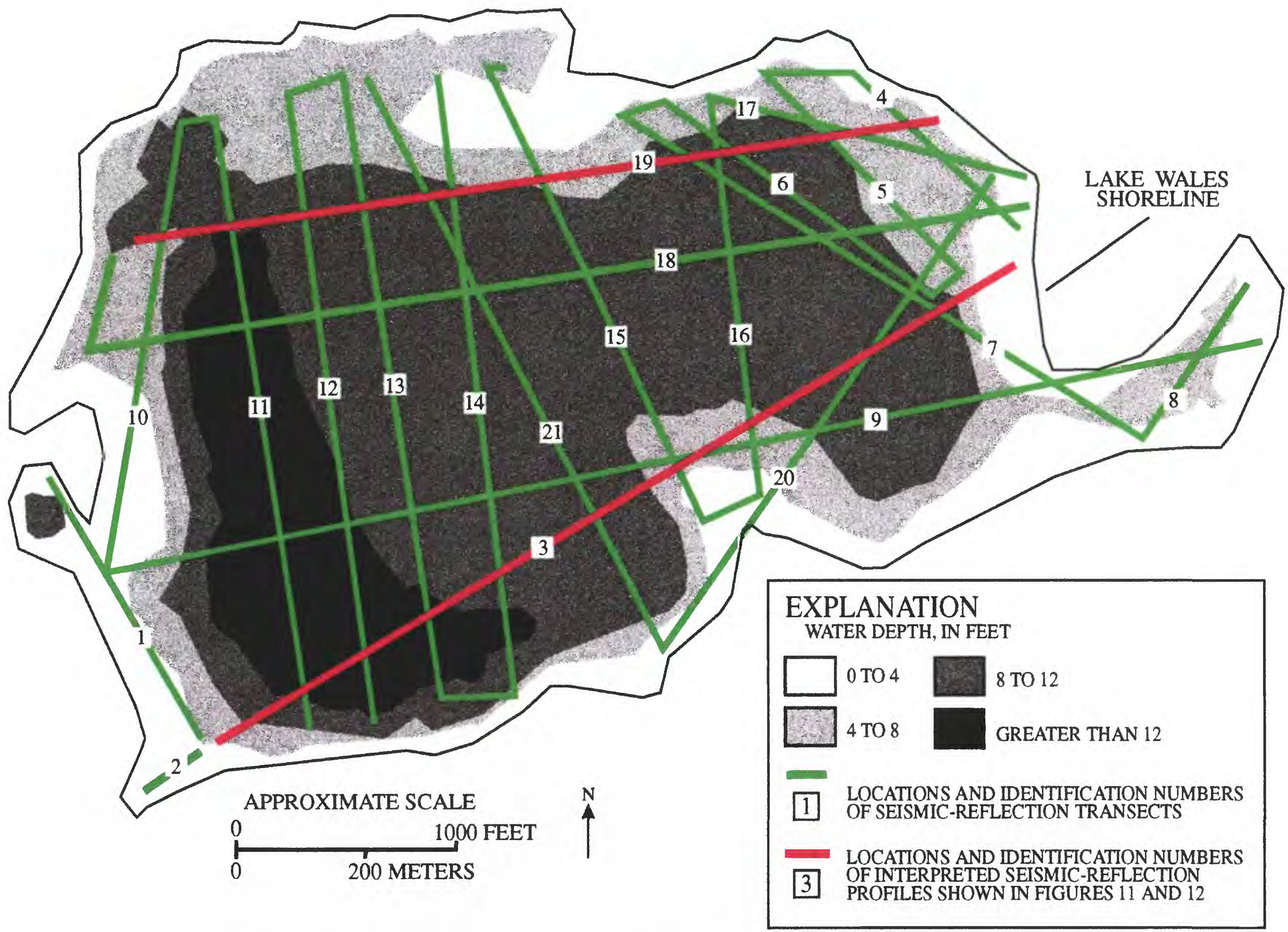


Figure 10. Lake Wales bathymetry and locations of seismic-reflection profile transects.

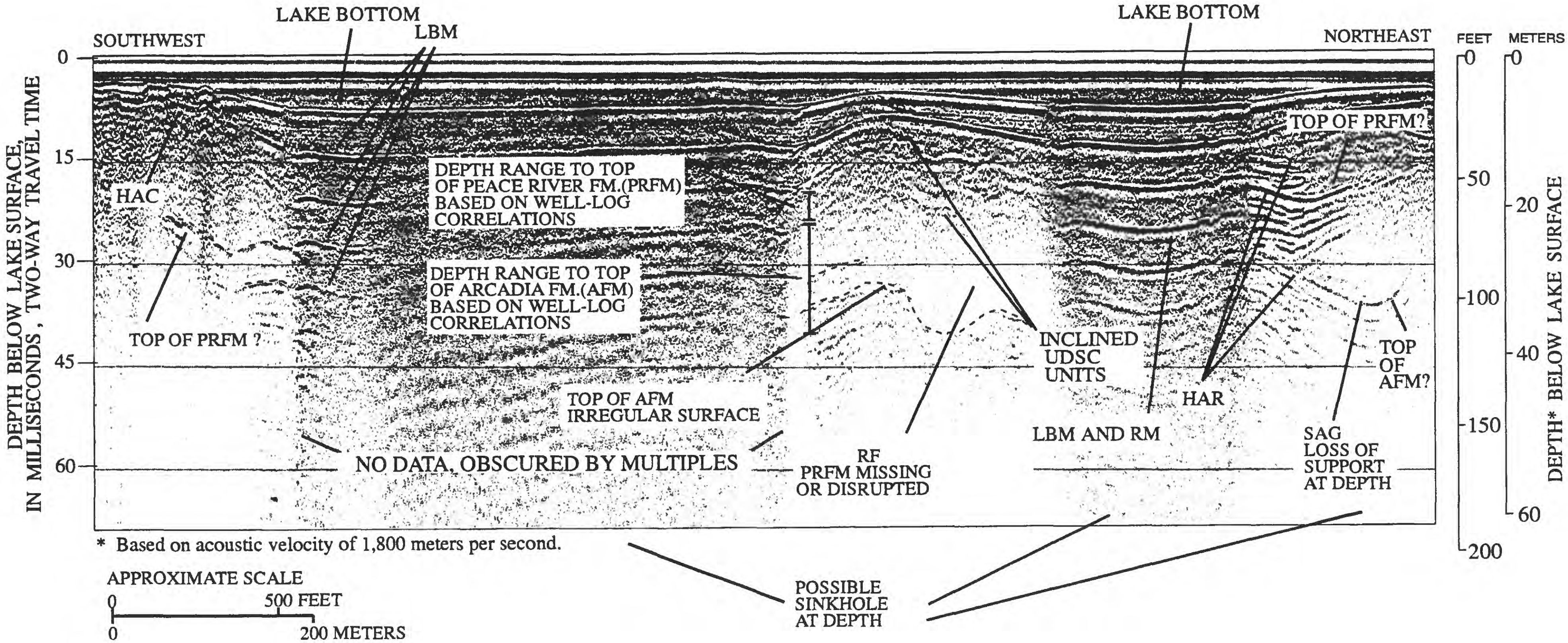


Figure 11. Seismic-reflection profile and interpretation for Lake Wales transect number 3. See figure 10 for location.

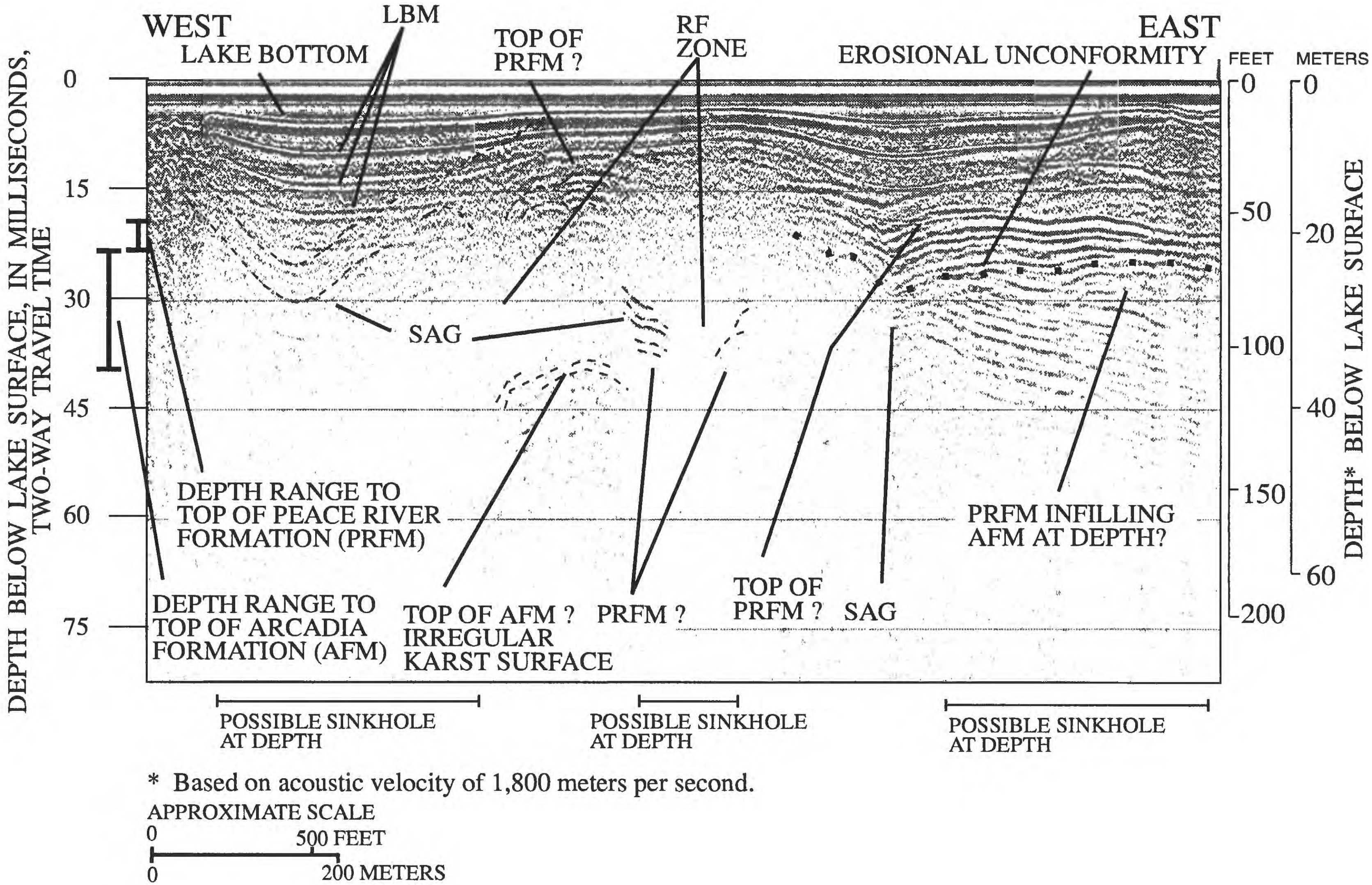


Figure 12. Seismic-reflection profile and interpretation for Lake Wales transect number 19. See figure 10 for location.

The irregular surface observed between 30 and 45 ms seismic depth was correlated to the Arcadia Formation (figs. 11 and 12). The highly variable nature of the top of the Arcadia, based on borehole data, is supported by the seismic record. The top of the Arcadia Formation is a karstified carbonate surface. In certain areas below Lake Wales, a high amplitude concordant reflective unit was observed above the irregular surface of the Arcadia Formation. The seismic depth to the top of this unit averages 20 ms. This depth corresponds to the expected depth of the top of the Peace River Formation. This geologic formation is not noted at ROMP 57X to the south of Lake Wales but is noted in wells to the north and the west. Because the Peace River Formation occurs intermittently in the Lake Wales region, it is probable that erosional remnants of this clayey unit are intact, especially in basins. Evidence of erosional remnants is shown in the seismic records in figures 11 and 12.

The absence of continual Arcadia and Peace River reflector packages along transect 19 indicates that much of the material has been disrupted. Where the Peace River Formation is intact, it seems to control bathymetry, corresponding to shallower areas of the lake (fig. 10). Deepest parts of the lake correspond to areas where the Arcadia Formation is overlain by seismic units that are reflection-free, shallow undifferentiated units or areas where the seismic signal is obscured. Because the Peace River Formation is a clayey, low permeability unit, it is possible that where the formation is intact, there probably is better lake-bottom confinement (fig. 13). However, in areas where the Arcadia is not overlain by these confining units, or where both of these units appear to have been disrupted, it is probable that poor confining conditions exist at depth (fig. 13). Sags observed within the remnant Peace River Formation indicate that lack of support at depth may be contributing to the deformation of this unit as it subsides into the underlying surface.

These records indicate that Lake Wales is underlain by a system of subsidence features with variable degrees of disturbance and breaching within the overlying Hawthorn Group sediments (fig. 13). Because of this relation, sublake hydrogeologic conditions probably range from confined to unconfined.

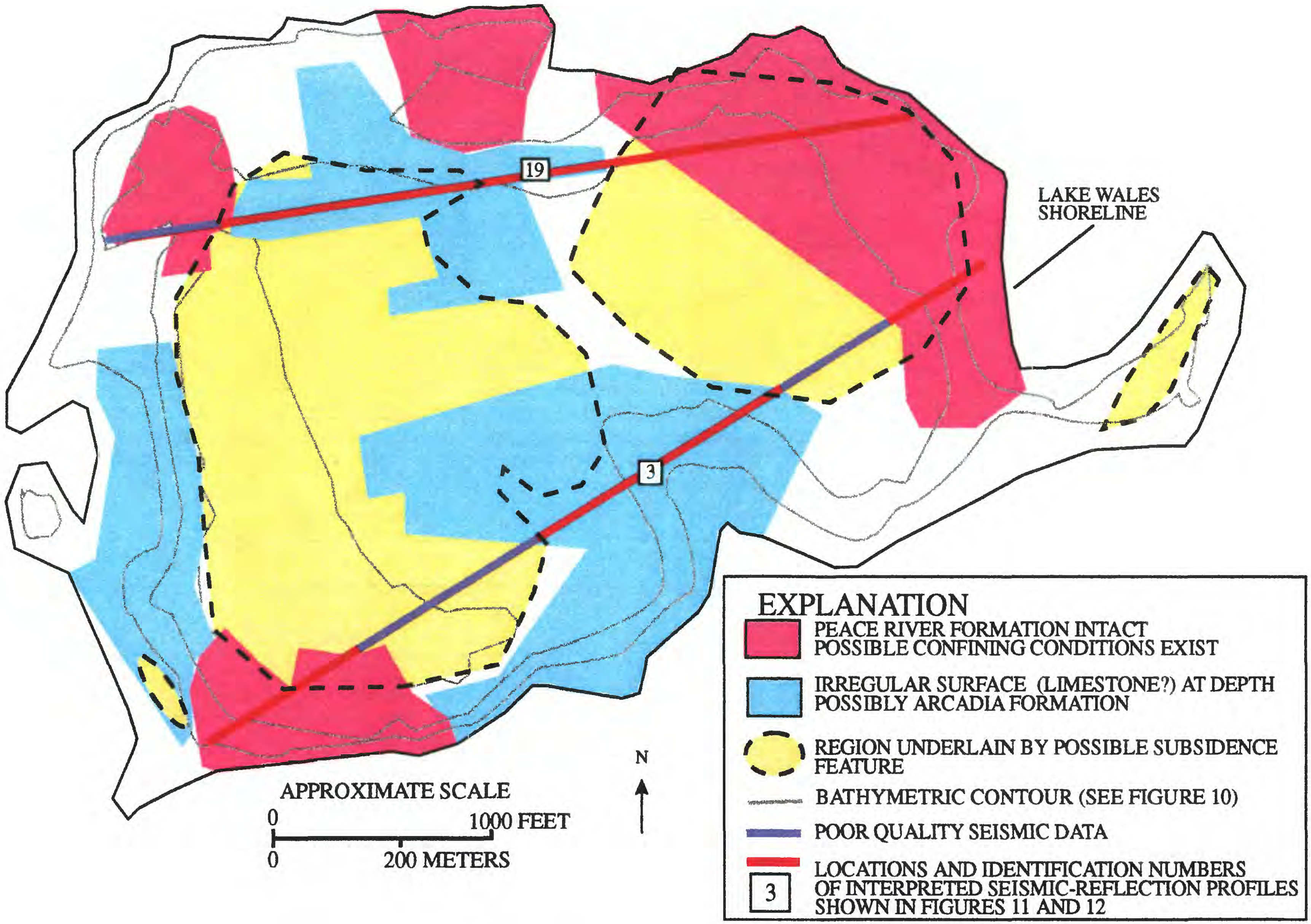


Figure 13. Sublake geology of Lake Wales based on interpretation of seismic-reflection data.

Blue Lake

Regional hydrogeologic trends observed in the geologic sections A-A', B-B', and C-C' (figs. 5, 6, and 7), indicate that both the Peace River and Arcadia Formations are present in the Blue Lake region and the undifferentiated sand and clay unit (UDSC) thickens to the south and east. The geologic map of the study area shows that surface or near surface geologic units in the Blue Lake area contain beds of the Cypresshead Formation (fig. 3). The Tampa Member of the Arcadia Formation is thin or absent in the Blue Lake area. Correlations of seismic data to the regional geology were made based on wells ROMP 57 to the northwest, ROMP 57X to the north, FGS W-1754 to the northeast, ROMP CL-1 to the southeast, ROMP CL-3 and ROMP 55 to the south-southeast, and ROMP 44 to the southwest. Wells CL-3 and ROMP 55, like Blue Lake, are located along the western margin of the Lake Wales Ridge and probably represent geologic conditions most similar to those occurring beneath Blue Lake; therefore, these wells were given greater consideration in making geologic correlations to the seismic-reflection data. The thickening of the UDSC units indicates that these units may be significant sublake geologic units. Seismic depths to the tops of the geologic units were calculated using appropriate proximal control wells. Locations of the seismic transects collected at Blue Lake are shown in figure 14. Geologic data show that the Peace River Formation exhibits a significant degree of vertical variability. The Peace River Formation is not observed to the north of Blue Lake in ROMP 57X, and the seismic depth ranges from 23 ms to the northwest to 50 ms to the northeast. The average seismic depth to the top of the Peace River Formation in this area was determined to be 37 ms. The Arcadia Formation also exhibits vertical variability, with the top of this formation ranging in seismic depth from 38 to 60 ms with an average depth of 54 ms in this area. Seismic depth to the top of the Suwannee Limestone in this area ranges from 40 to 75 ms. The expected seismic ranges and average seismic depths to the tops of these units are shown on the seismic profiles (figs. 15, 16, 17, and 18).

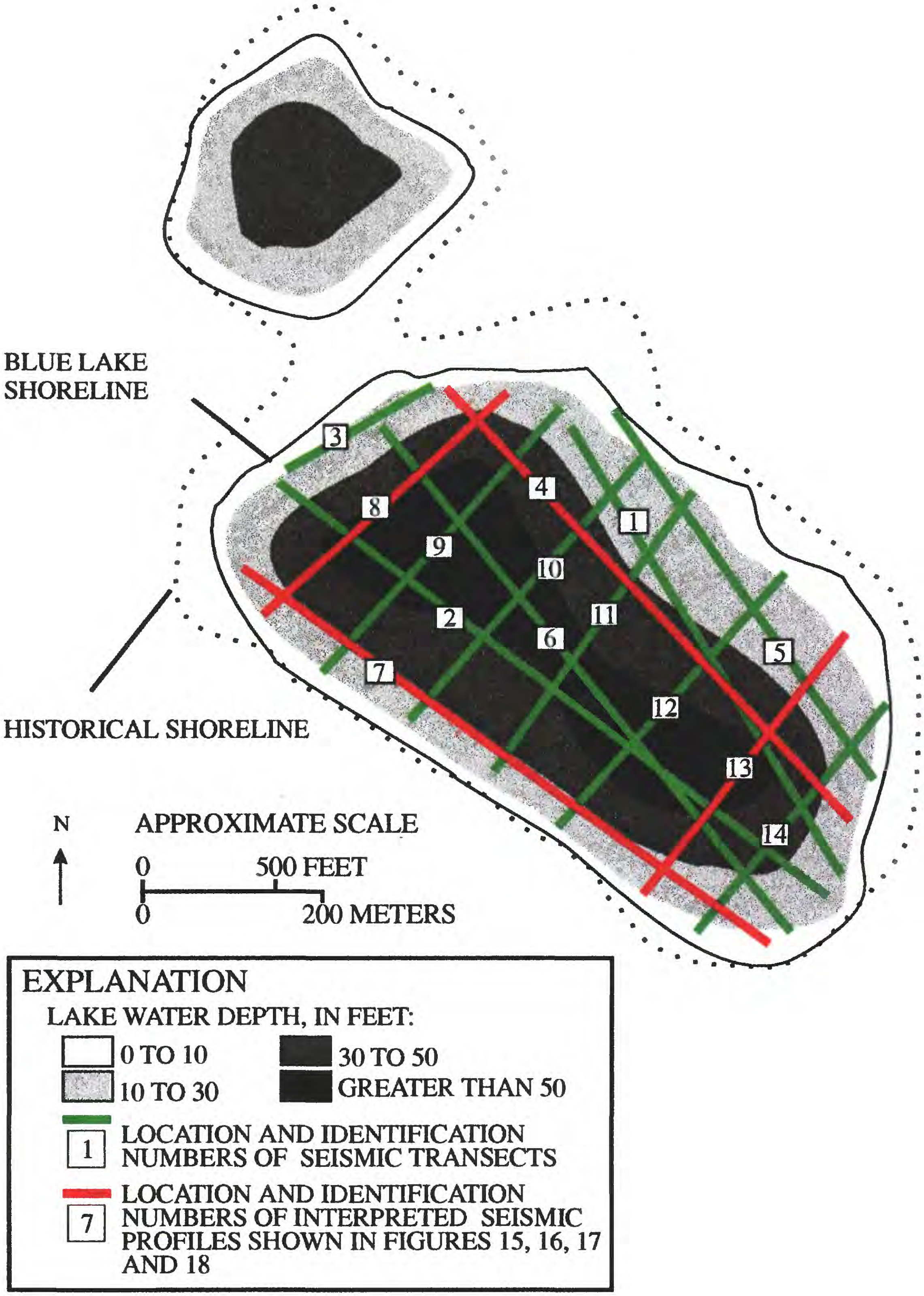
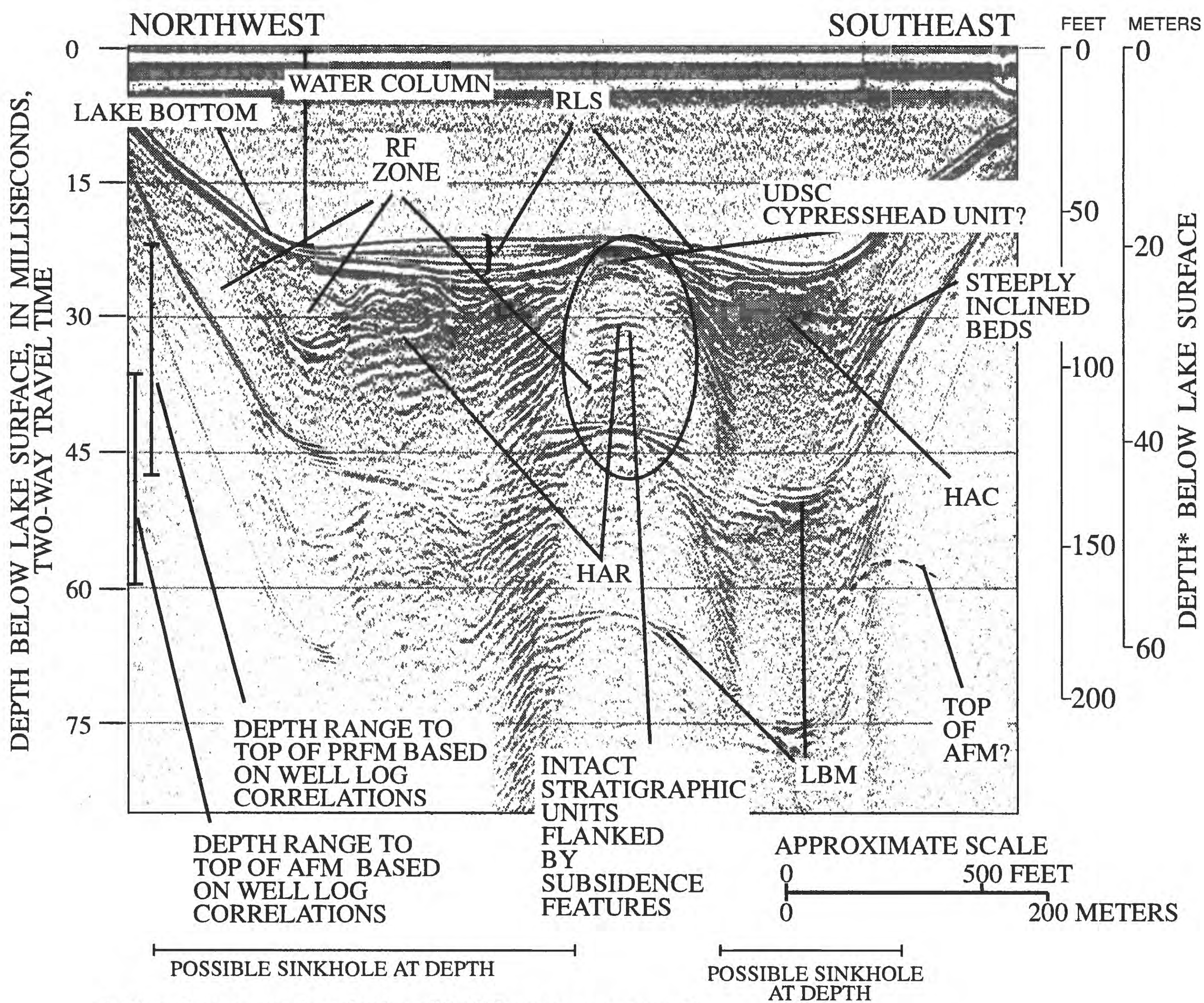
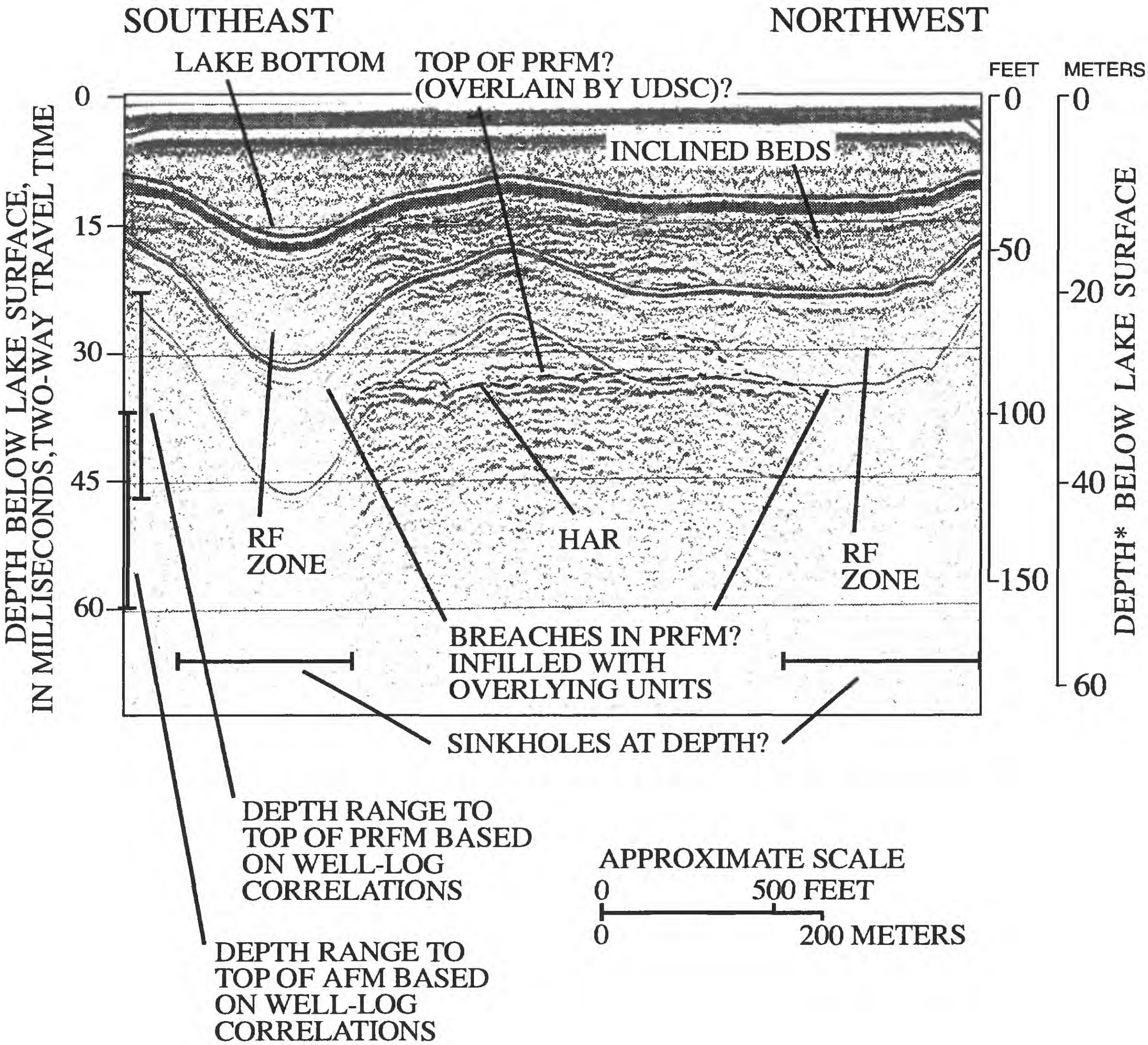


Figure 14. Blue Lake bathymetry and locations of seismic-reflection profile transects.



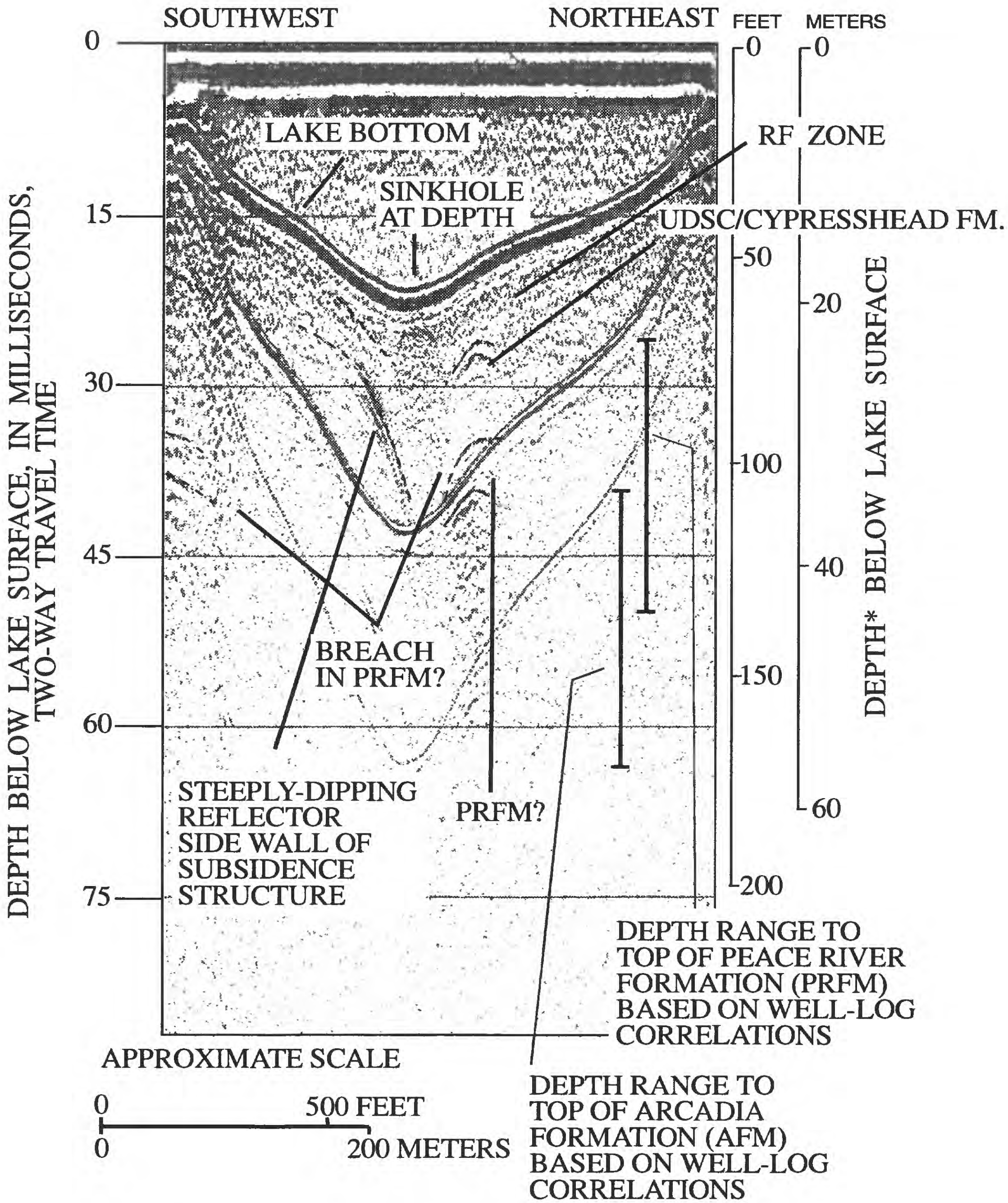
* Based on acoustic velocity of 1,800 meters per second.

Figure 15. Seismic-reflection profile and interpretation for Blue Lake transect number 4. See figure 14 for location.



* Based on acoustic velocity of 1,800 meters per second.

Figure 16. Seismic-reflection profile and interpretation for Blue Lake transect number 7. See figure 14 for location.



* Based on acoustic velocity of 1,800 meters per second.

Figure 17. Seismic-reflection profile and interpretation for Blue Lake transect number 8. See figure 14 for location.

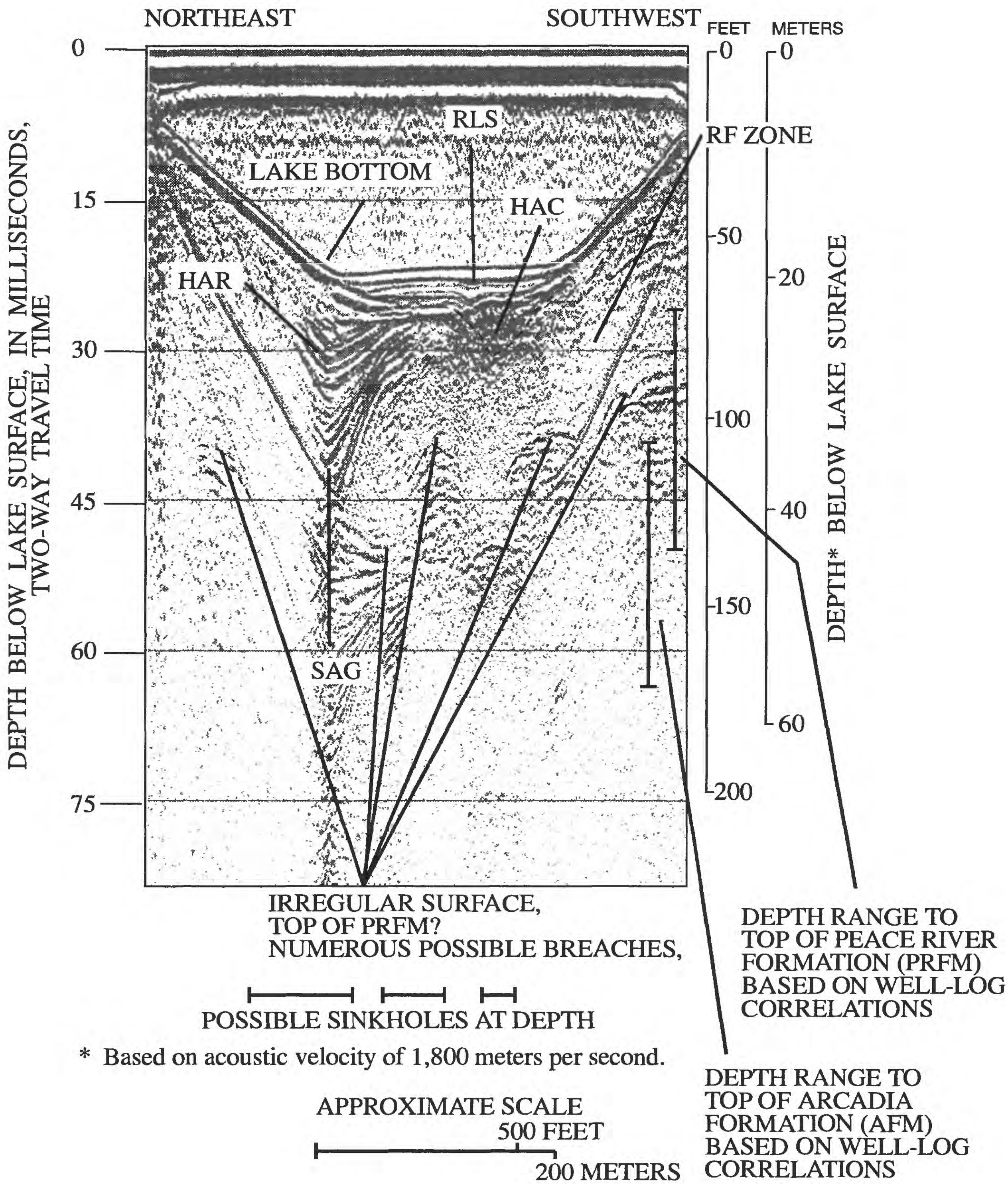


Figure 18. Seismic-reflection profile and interpretation for Blue Lake transect number 13. See figure 14 for location.

Although the Cypresshead Formation occurs along the ridge, it was not delineated in the well logs used for correlations (fig. 3). For this reason, seismic depths of this undifferentiated unit were not calculated.

The seismic-reflection record obtained at Blue Lake clearly illustrates the occurrence of subsidence features in the sublake region. Representative examples of breaches, subsidence, infilling and sags are shown in the seismic record collected along transects 4, 7, 8, and 13, (figs. 15, 16, 17, and 18, respectively). Transect 4 shows the remnant of the Peace River Formation that controls the bathymetry at Blue Lake (figs. 14 and 15). Infilling sediments, probably Cypresshead Formation and other UDSC units, have subsided into the two breaches that flank this remnant Peace River Formation pinnacle. These overlying units occur both as sagging, concordant reflectors that have been deformed during subsidence events, and much steeper, disrupted units characterized by chaotic infilling with less internal seismic structure. Along the lake margin at approximately 55 ms, the presence of a hyperbolic reflector, corresponding to the Arcadia Formation, implies that this unit can be present although it was not detected in much of this record (fig. 15). The Arcadia reflectors may not have been detected because they were masked by strong lake-bottom multiples or the seismic signal was attenuated by the overlying units such that the deeper Arcadia Formation reflectors were too faint to be recognized; however, as suggested by the variability exhibited in well logs, the upper surface of this unit may be highly irregular. This unit might have been removed within the sublake region in conjunction with cover-collapse sinkhole formation, which would also account for the intermittent appearance of the Arcadia reflector in the sublake region.

The flat-lying continuous reflector that has been effectively breached in localized areas has been correlated to the Peace River Formation. A distinct breach in the sublake region within the Peace River and younger sediments is clearly shown in the seismic profile collected along transect 7 (fig. 16). This was probably caused by a loss of support at depth, further indicating the presence of cavities and voids within the carbonate units at depth. Loss of support at depth exceeded the strength of the Peace River Formation to support the overlying materials and cover-collapse occurred. The overlying UDSC units exhibit more dipping and response to the breach, implying they were less cohesive and probably contributed additional infilling materials. Seismic profiles collected along transects 8 and 13 (figs. 17 and 18) show where the Peace River presumably has been more disturbed by subsidence activity and consequently is less continuous. Along transect 8, steeply dipping beds overlying a small localized sinkhole at depth directly correlate with lake bathymetry (figs. 14 and 17).

Downward leakage from Blue Lake can be controlled by these features. Where the Peace River Formation occurs below Blue Lake, probable confinement conditions exist (fig. 19). The limited occurrence of the Arcadia Formation in the seismic-reflection profiles indicates that cavities could exist within this formation in the sublake region. The presence of cavities and the reworking of infilling materials would result in less-effective confinement.

Subsidence events recorded in the sublake sediments are now covered by overlying deposits indicating equilibrium conditions between the overlying materials and the existing underlying framework. However, recent sinkhole occurrence in the Crooked Lake Basin (Evans and others, 1994) and to the southeast near ROMP CL-3 indicates that overlying sediments in this area are continuing to adjust and settle into the underlying framework. During the formation of a sinkhole near ROMP CL-3 in July 1991, the interconnection between the surficial aquifer and the Upper Floridan aquifer was directly observed. Hydrographs (figure 20) from continuous water-level data recorders on the SAS and UFA wells at ROMP CL-3 show the Upper Floridan and surficial aquifers were effectively connected during this subsidence event. The drop in the SAS water level coincides with a sudden rise in the water level of the UFA. These data indicate that localized sinkhole events effectively breach the IAS/ICU in this area. Because Blue Lake is located in a similar geologic setting, it is probable that the lake also can have an enhanced hydraulic connection with the Upper Floridan aquifer by localized breaches in confinement in the sublake region. The influence of subsidence activity on near-surface sediments observed in the seismic-reflection record strongly implies that Blue Lake was formed as a result of sinkhole subsidence and is underlain by geologic structures that can significantly influence hydrologic interactions between the lake and ground-water system.

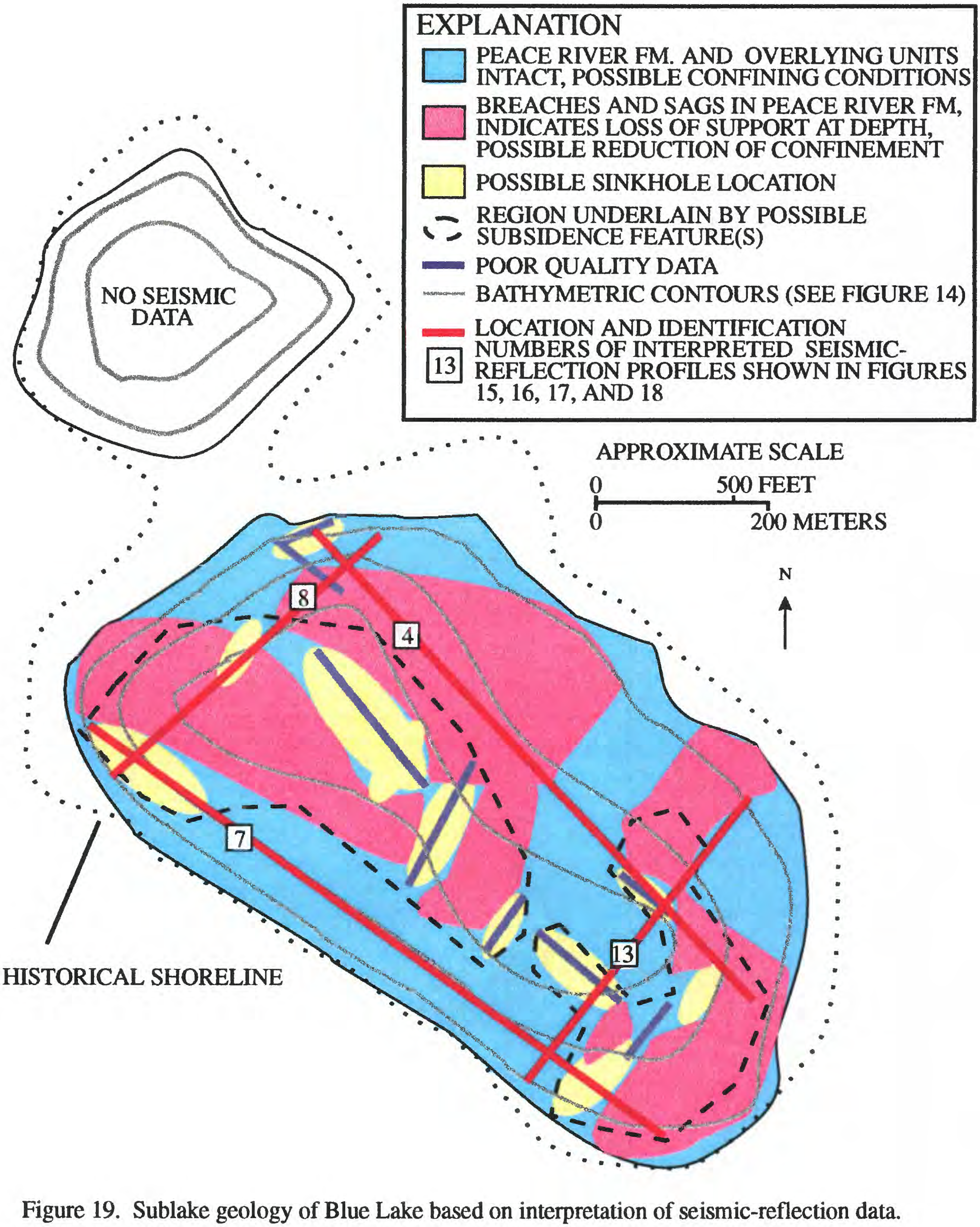


Figure 19. Sublake geology of Blue Lake based on interpretation of seismic-reflection data.

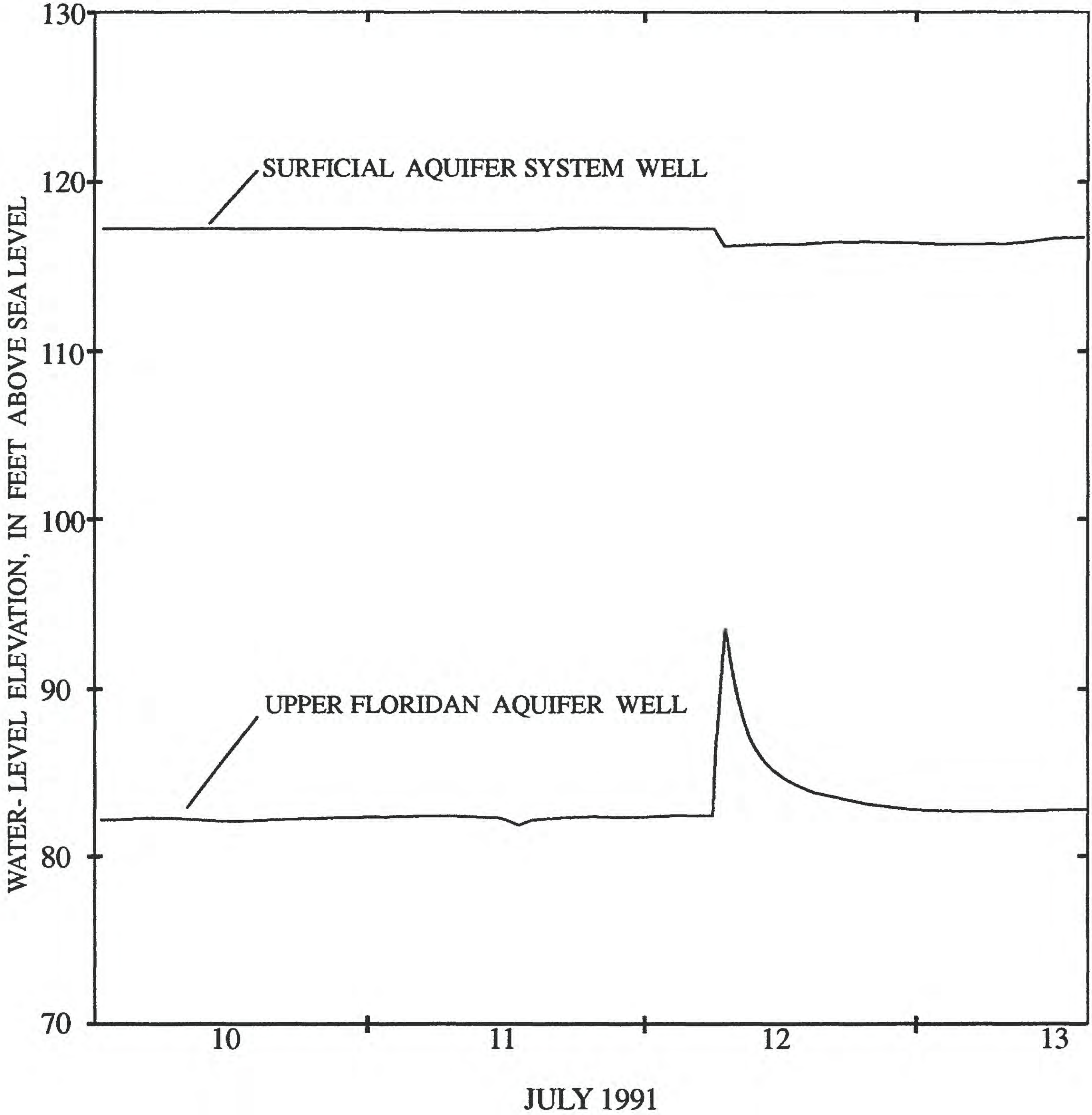


Figure 20. Hydrographs from ROMP CL-3 surficial and Upper Floridan aquifer monitoring wells from July 10 through July 13, 1991. The hydrographs show the response of the surficial and Upper Floridan aquifers during the formation of a sinkhole on the morning of July 12, 1991, approximately one-half mile away from monitoring site.

Lake Letta

Regional geologic trends, described by the geologic sections A-A', B-B', and C-C' (figs. 5, 6, and 7), show a thickening of sand and clay units both within the Arcadia Formation and the overlying UDSC within the Lake Letta region. Stratigraphic control was limited to two wells: ROMP 43XX to the north and FGS W-6581 to the south (fig. 1). Geologic trends between wells ROMP 43XX and FGS W-6581 indicate an increase in carbonate content to the south and the appearance of significant, possibly continuous, clayey units within the UDSC at altitudes similar to the Peace River Formation updip to the north. Although Lake Letta is located within the Intra-Ridge Valley, neither control well is located within this physiographic province (fig. 1). For this reason, ROMP 28, located much farther south, is used as a reference for possible related physiographic trends.

Locations of the seismic transects collected at Lake Letta are shown in figure 21. Seismic depths to the top of the Arcadia Formation and significant clay beds within the UDSC unit were calculated using the control wells. The seismic depth to the top of the Arcadia Formation ranges from 73 ms to the north to 78 ms to the south. The top of the clay beds observed within the UDSC in the geologic logs were calculated to have a seismic depth of 50 ms.

A faint reflector observed in seismic transects at an average seismic depth of 80 ms correlates with the top of the Arcadia Formation (figs. 22 and 23). The reflective unit occurring at 50 ms may correspond to the clay units identified within the UDSC (fig. 22). In figures 22 and 23, high amplitude concordant seismic units occur at seismic depths ranging from 15 to 30 ms, shallower than significant geologic units identified in the control wells. These localized features exhibit distinct lateral seismic facies changes from a high-amplitude continuous reflector to a reflection-free seismic facies (figs. 22 and 23). These units are observed throughout the Lake Letta basin (fig. 24). Locally they seem to sag into the underlying units.

Sublake geologic interpretation of these localized features in the UDSC is that they represent smaller infilled paleobasins now occupied by Lake Letta (fig. 24).

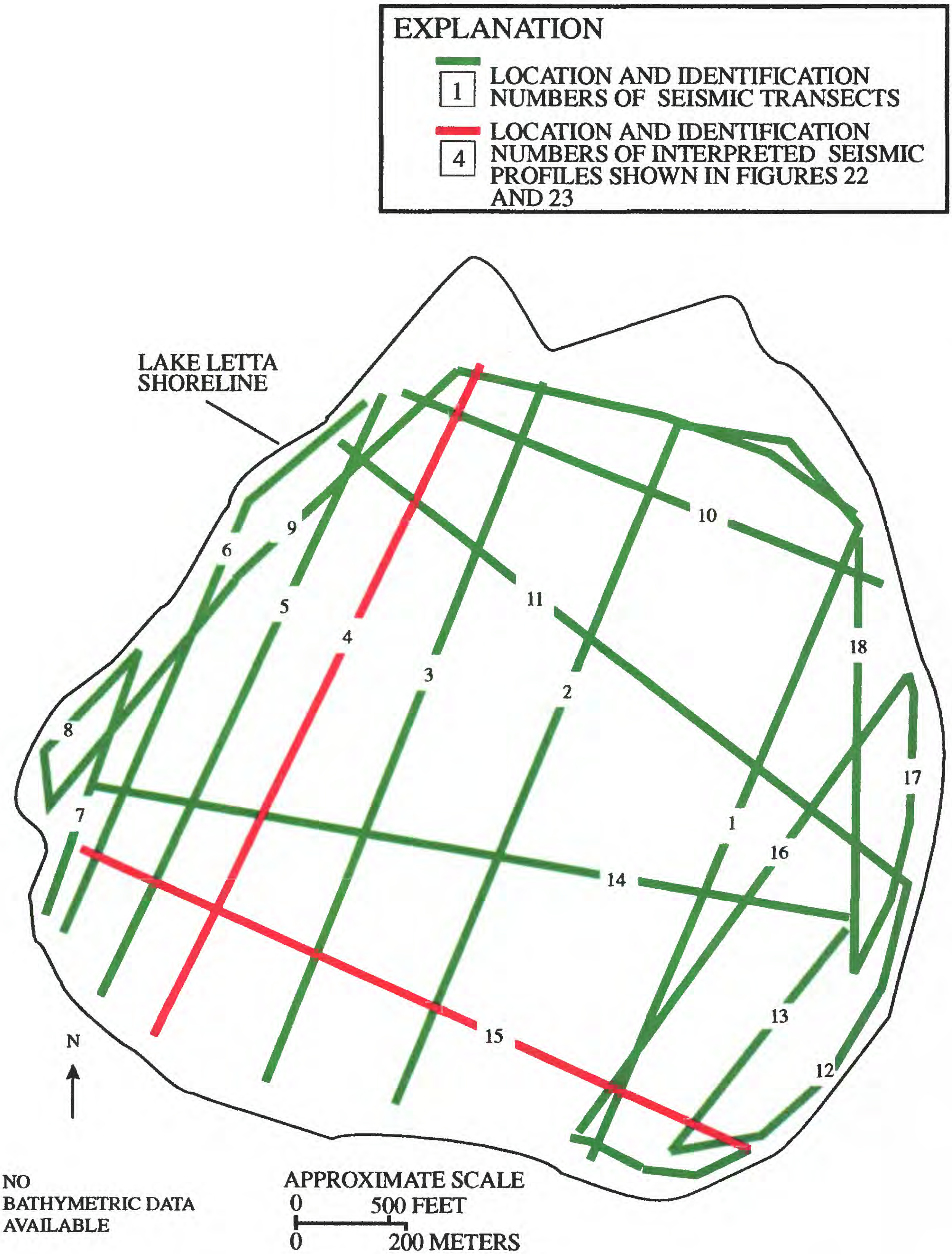
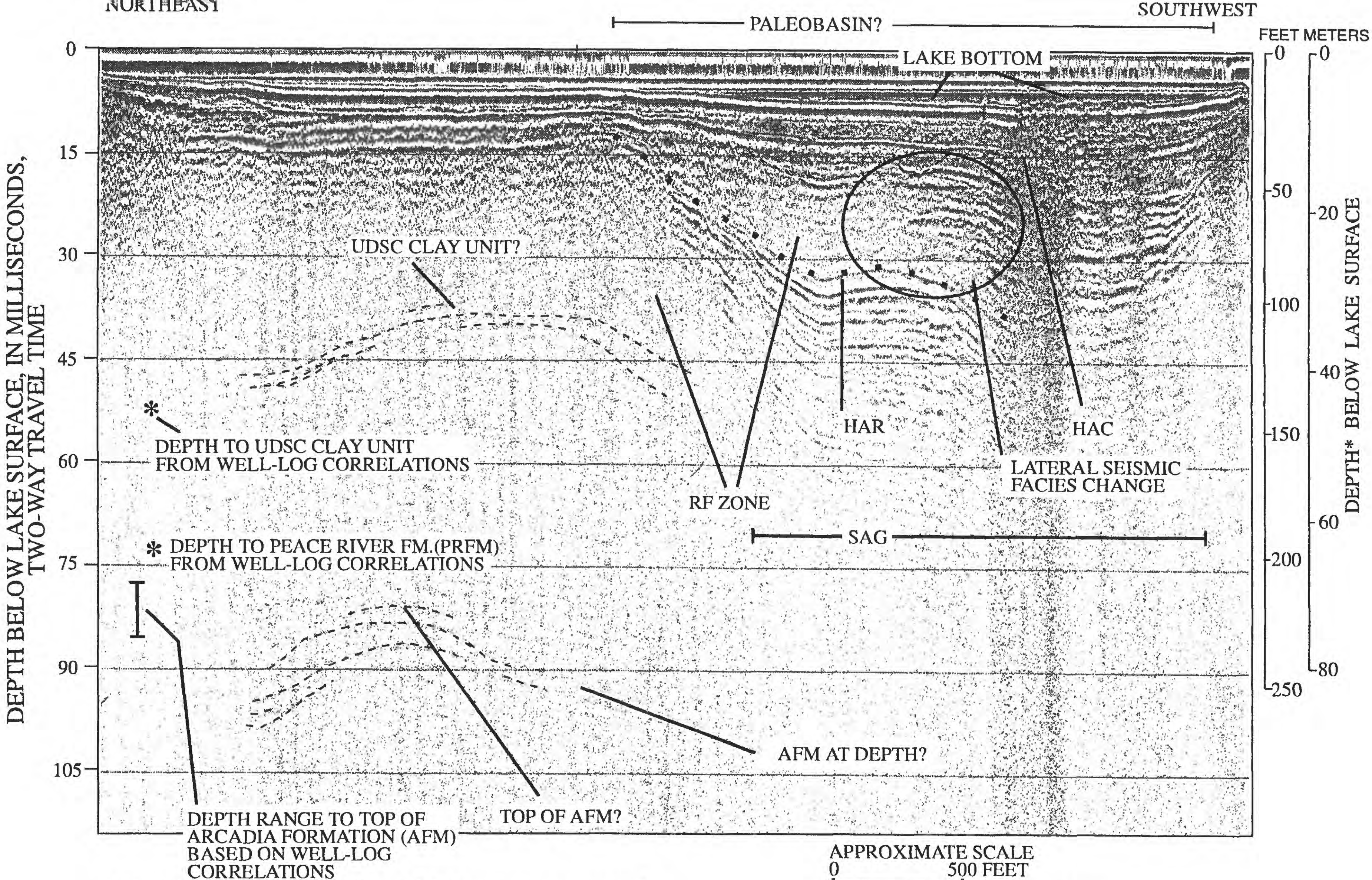
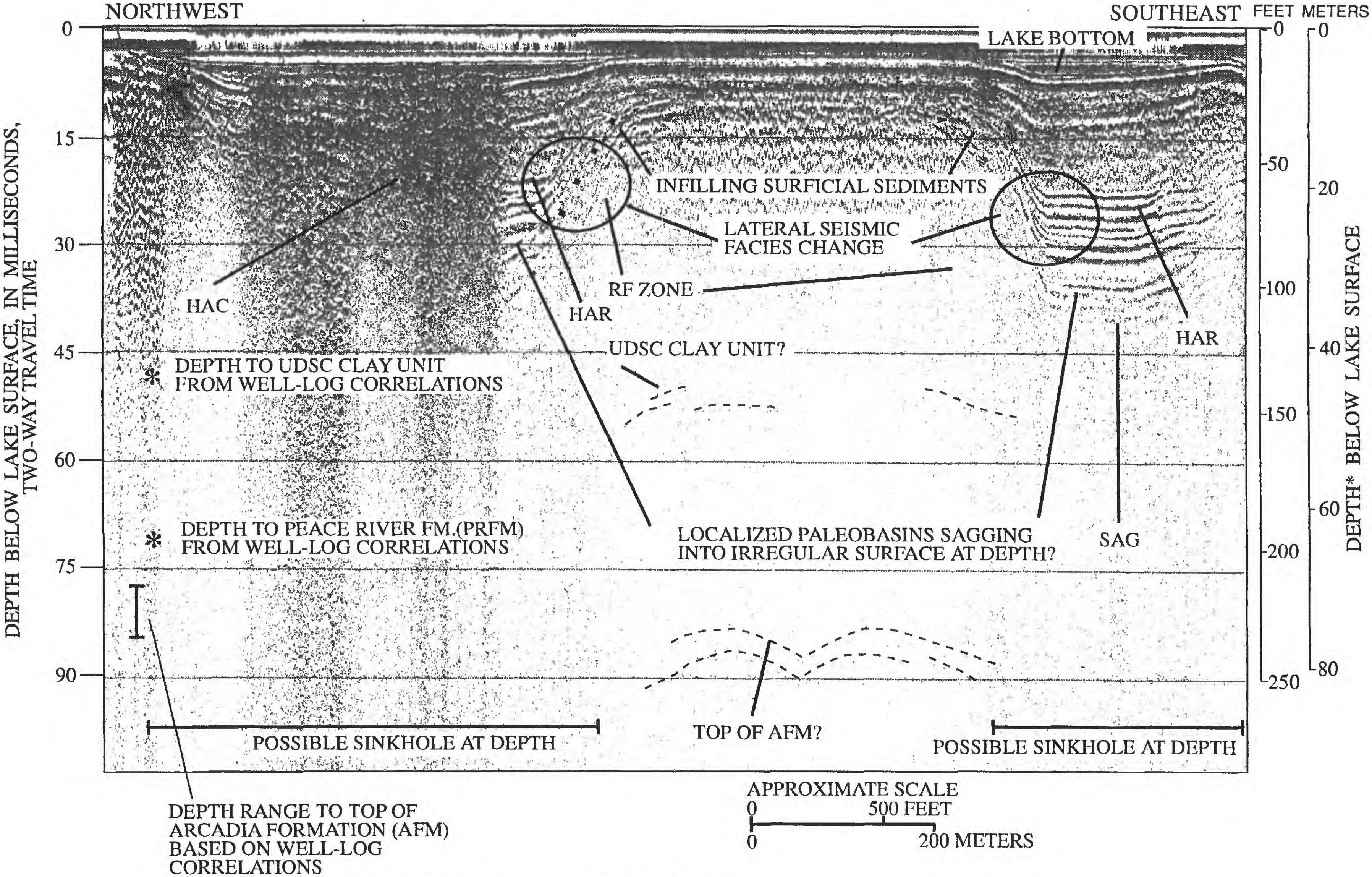


Figure 21. Locations of seismic-reflection profile transects for Lake Letta.



* Based on acoustic velocity of 1,800 meters per second.

Figure 22. Seismic-reflection profile and interpretation for Lake Letta transect number 4. See figure 21 for location.



* Based on acoustic velocity of 1,800 meters per second.

Figure 23. Seismic-reflection profile and interpretation for Lake Letta transect number 15. See figure 21 for location.

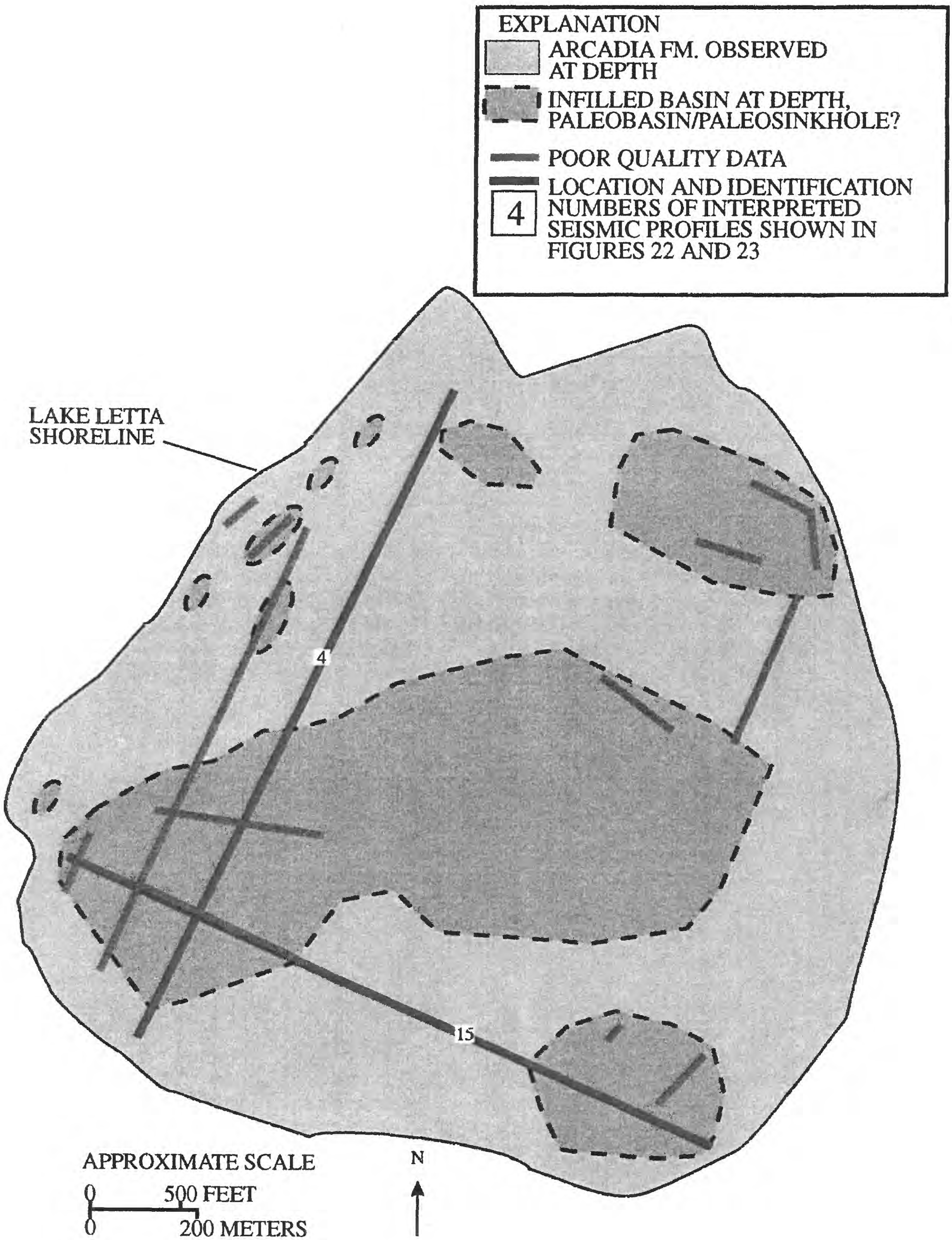


Figure 24. Sublake geology of Lake Letta based on interpretation of seismic-reflection data.

Where the clayey unit of the UDSC at 50 ms seems to be continuous and free of disruption, there is no paleobasin (figs. 22 and 23). Below these paleobasins, the reflectors correlating to both the UDSC clay unit and the Arcadia Formation are not observed. The loss of the reflectors beneath these basins can be due to attenuation of the seismic signal but downward dipping trends along the margins of these basins are observed in nearly all seismic profiles. These deeper units (the clay unit identified within the UDSC and Arcadia Formation) are probably breached or modified and the overlying younger aged materials infilling these basins are slowly subsiding, with minor stratigraphic disruption (sagging) into these breaches.

The origin of these paleobasins is unclear; however, the presence of lateral seismic facies changes suggests a distinct lithologic change. Distinct changes in sedimentation might accompany changes in lake level. The lack of sublake lithologic control prevents a direct correlation of these units to a known lithologic unit. The high amplitude reflectors associated with the paleobasin could be peat or organic-rich deposits that are remnants of a more extensive deposit that covered a regionally extensive wetland area such as the Intra-Ridge Valley or their deposition might have been limited to local basins and paleosinkholes. Originally, if the unit were regionally extensive, it might have been reworked or removed from higher elevations and preserved only within the low paleobasinal areas. Although this has not been confirmed with core data directly beneath the lake, organic materials are present in the upper 30 meters (100 ft) at ROMP 28, south of Lake Letta, also located within the Intra-Ridge Valley.

The paleobasins observed beneath Lake Letta were probably created by cover-collapse paleosinkholes. Under hydrologic conditions during low sea level stands, subsidence activity might have breached the confining units of the Arcadia Formation and the UDSC. At higher sea level stands, these sinkholes might have been flooded either as lakes, wetlands or extensive swamp areas. Local basins would have been subsequently infilled with fine-grained lacustrine materials. At lower sea level stands, and lower water-table elevations, these deposits would have settled into the underlying framework, easily deforming and draping into the irregular surface at depth. Changes in sedimentation associated with the lower sea level stands (more sand and less clay) would have infilled these basins and leveled off the region with units of more regional extent and composition such as the thick, sandy deposits of the upper UDSC within the Lake Wales Ridge.

The seismic record obtained in Lake Letta appears to show the occurrence of these geologic mechanisms. Figure 22 provides evidence of this concordant unit sagging in response to subsidence activity at depth. There is evidence of infilling and leveling shown in the lateral seismic facies changes and the burial of the local paleobasins beneath present Lake Letta. The relation between the paleobasins and the Intra-Ridge Valley is unclear, but it is interesting to note that seismic data from other lakes located within the Intra-Ridge Valley are also underlain by similar paleobasin features at similar seismic depths.

Sublake core data are not available to confirm the sediment types speculated to occur in the sublake region; however, from a hydrologic standpoint, the paleobasins seem to be well separated, and where present, can actually provide better sublake confinement if infilled with fine-grained sediments having low hydraulic conductivity.

Lake Apthorp

Geologic trends described by the geologic sections A-A', B-B' and C-C' (figs. 5, 6, and 7) and well data from ROMP 28 to the northwest, FGS W-1464 to the north, and FGS W-2850 and ROMP 28X to the south of Lake Apthorp show an increase in the overlying UDSC to a thickness of more than 100 meters (300 ft). The gamma log for ROMP 28X shows a relatively uniform lithologic composition until the top of the Arcadia Formation (fig. 7). The Peace River Formation is present to the northwest of Lake Apthorp in ROMP 28, and to the south at ROMP 28X, but it has not been differentiated from the rest of the Hawthorn Group sediments to the north of Lake Apthorp in FGS W-1464. Significant clays were observed within the UDSC at ROMP 28X and FGS W-2850. At ROMP 28X these clays include mica which indicates that these units are of the Cypresshead Formation (Pliocene age) and are not part of the Peace River Formation.

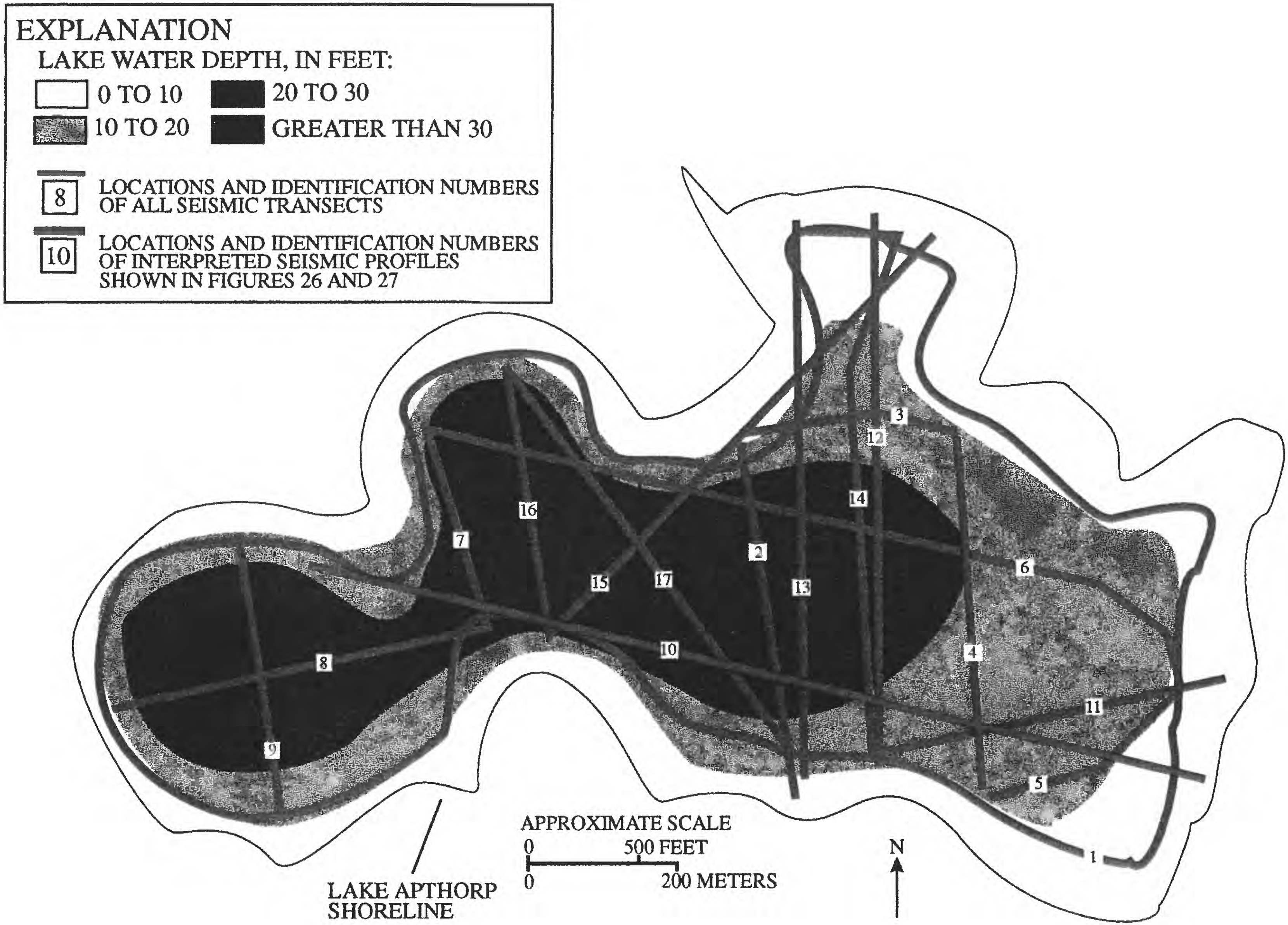
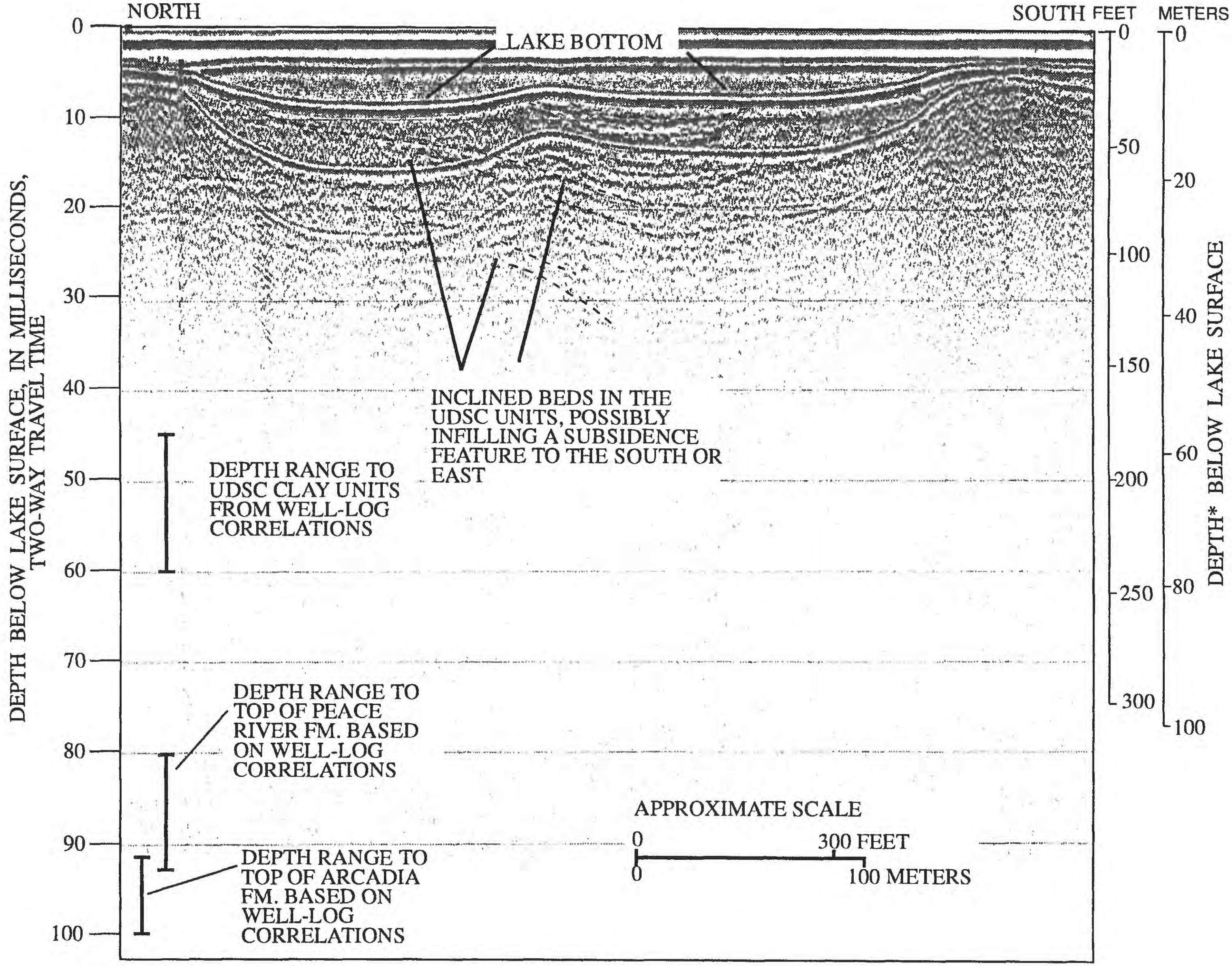


Figure 25. Lake Apthorp bathymetry and locations of seismic-reflection profile transects.

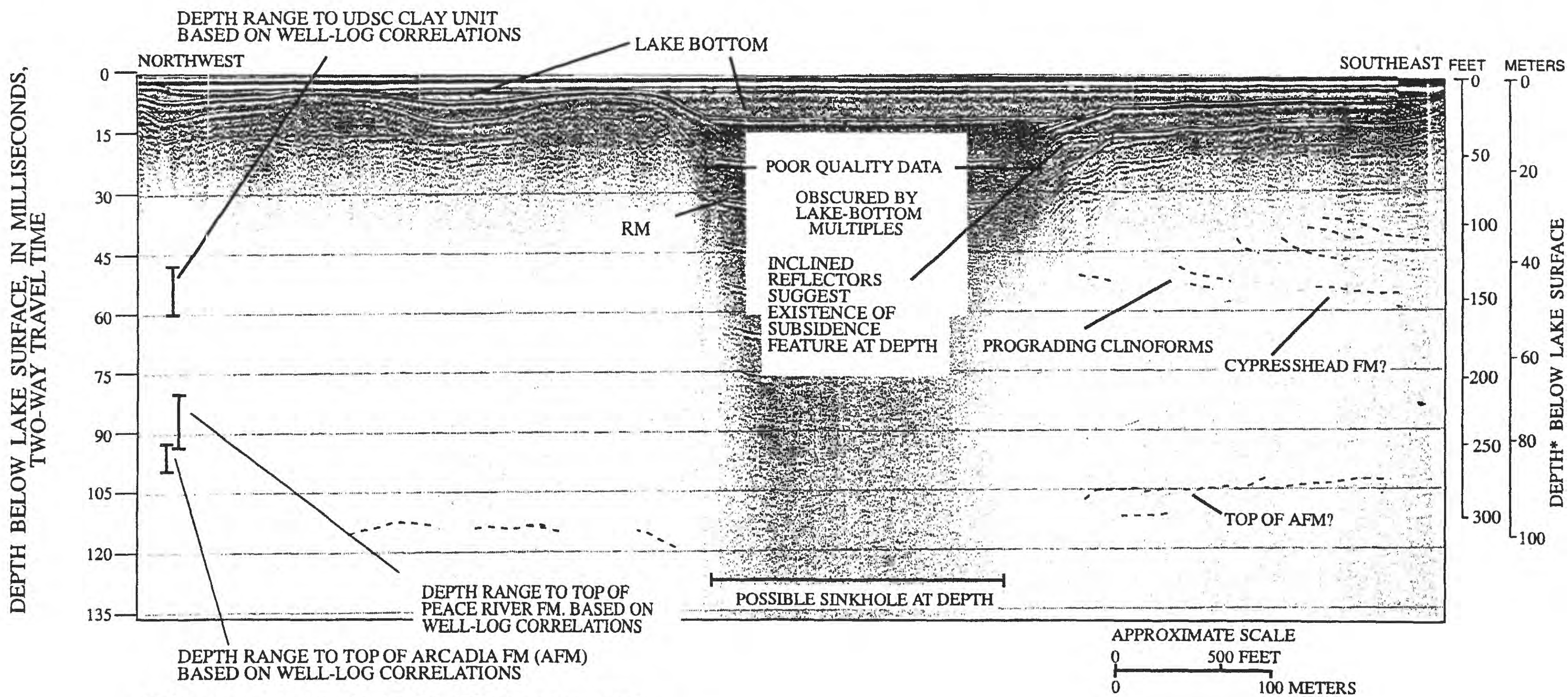
Locations of the seismic-reflection profile transects collected at Lake Apthorp are shown in figure 25. Seismic depths to the top of the geologic units were determined from the control wells. The top of the UDSC clay unit identified in ROMP 28X and FGS W-2850 is expected to occur at a seismic depth between 45 and 60 ms. The top of the Peace River occurs at an average seismic depth of 93 ms to the northwest of the lake. The seismic depth to the top of the Arcadia Formation ranges from 100 ms to the north and northwest to 89 ms to the south of Lake Apthorp. Because the depth to the geologic units of primary interest to this study are the greatest at Lake Apthorp, the seismic-reflection data were collected using two different sweep settings. Transects 1-9 were collected using a 100-ms sweep in order to resolve shallow seismic units in more detail and to better define the presence of shallow units along the lake margins (fig. 26). Transects 10-17, collected using a 150-ms sweep, could not be used to resolve the shallower UDSC units but could be used to define deeper units in the sublake region (fig. 27).

Most of the seismic record at Lake Apthorp is obscured by lake-bottom sediments. However, limited areas have been useful in providing information about the geologic structure beneath Lake Apthorp. Most of the interpretation is based on trends observed in the seismic data and on interpretations done on the other lakes included in this study. The faint reflector identified in figure 27 between 105 and 120 ms generally corresponds to the expected seismic depth of the top of the Arcadia Formation. Reflectors that correspond to the Peace River Formation within this area were not observed during this study. Above the Arcadia Formation, prograding clinoforms were observed between 30 and 60 ms. These units probably correspond to the clayey units observed within the UDSC and may be the Cypresshead Formation (fig. 27). The occurrence of prograding clinoforms in the sublake region implies that the underlying units must have been fairly continuous during the deposition of these prograding units. Some of the shallower reflectors observed along the lake margin are inclined and seem to dip or infill towards the south (fig. 26). Although no basin or subsidence feature was observed toward the south, the true dip of these units may be toward the south or southeast towards a possible subsidence feature identified on the eastern margin of the lake (fig. 28).



* Based on acoustic velocity of 1,800 meters per second.

Figure 26. Seismic-reflection profile and interpretation for Lake Apthorp transect number 4. See figure 25 for location.



* Based on acoustic velocity of 1,800 meters per second.

Figure 27. Seismic-reflection profile and interpretation for Lake Apthorp transect number 10. See figure 25 for location.

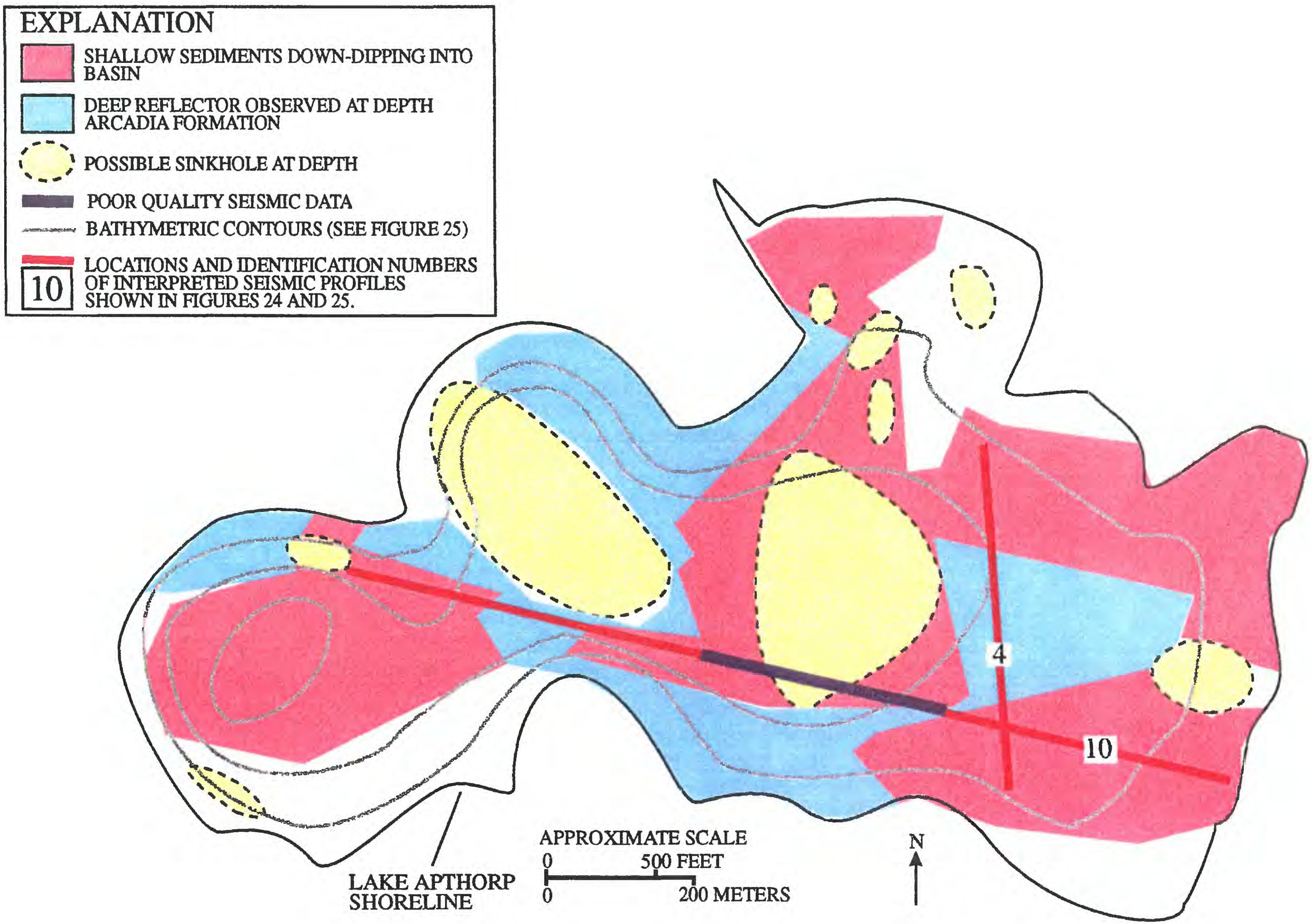


Figure 28. Sublake geology of Lake Apthorp based on interpretation of seismic-reflection data.

Inclined reflectors observed in the shallower sediments along the margins of the deeper parts of the lake imply subsidence activity within this lake basin has occurred. Although breaches or collapse features could not be clearly identified at depth, trends observed in surficial sediments along the margins of the deeper parts of the lake infer subsidence activity has taken place. The absence of reflectors associated with the Peace River Formation and the discontinuity of the Arcadia Formation also implies that disruption and /or modification of these formations might have been the result of subsidence activity. These characteristics suggest that breaches may exist at depth below areas of the lake currently occupied by organic-rich sediments. The surficial aquifer system and the UDSC are much thicker here than the rest of the study area. Lake bottom confinement likely varies depending on the lithology of these units.

RELATION OF SUBSIDENCE TYPE AND SUBLAKE CHARACTERISTICS TO REGIONAL STRATIGRAPHIC FRAMEWORK

In a regional context, these lakes provide information useful for understanding the stratigraphy of the deposits overlying the Florida carbonate platform. The lakes also provide localized continuous geologic information describing the complex stratigraphic relation between the buried karstified limestone and the overlying siliciclastic units. However, because the relation between the carbonate units and the siliciclastic units also controls the hydrologic system, the presence or absence of the Hawthorn Group can have a profound effect on subsidence activity, the disruption of confining units, the occurrence of lakes, ponds and wetlands, and the interconnection between lakes and the underlying ground-water system.

The distribution, thickness, and lithology of these siliciclastic materials determine both local and regional hydrogeologic characteristics along the Lake Wales Ridge. The regional stratigraphy along the Lake Wales Ridge follows general lithologic and structural trends described at that scale; however, on the local scale, lithologic and hydrologic properties and average thickness or depth to a specific geologic unit can vary significantly from the regional trends.

Hydrologic trends probably follow the same relation as the stratigraphy. While large-scale regional trends adequately describe the regional hydrologic framework, the presence of these localized geologic features likely alters the local hydrologic system. Departures from the regional hydrologic trends observed in local hydrologic data would provide further evidence of the importance of these small local disruptions within the regional geologic framework.

Sublake geology interpreted from seismic-reflection data indicates that subsidence features are highly localized. Although the high-resolution seismic data have not been correlated to sublake core data, the seismic data provide strong evidence of subsidence activity beneath lakes along the Lake Wales Ridge. Lakes occupy topographic lows that intersect the surficial aquifer system. In each lake, the geology in the major areas within the sublake region is not affected by these subsidence features. The sublake region does not represent a complete geologic anomaly with respect to the regional geologic trends; instead, these lakes often are underlain by several locally distinct subsidence features. Overall, sublake geologic trends fit reasonably well into the regional geologic framework based on correlations to the regional lithostratigraphic sections. These small, localized subsidence features are seldom considered in a regional context nor are they incorporated into regional descriptions. Internally drained basins and topographic lows are a characteristic feature of the Lake Wales Ridge and their prevalence may be representative on a regional scale.

All four lakes, Lake Wales, Blue Lake, Lake Letta, and Lake Apthorp, likely were formed by subsidence activity. Although subsidence within the Lake Wales Ridge area has been characterized predominantly as cover-collapse sinkhole type, the seismic-reflection records demonstrate that subsidence activity beneath these four lakes can be a combination of cover-subsidence and cover-collapse mechanisms depending on the historical hydrogeologic setting.

Toward the north of the study area within the Lake Wales Ridge, the limestone is closer to the surface and the clay units are thinner and less continuous. Where clay units are thin or absent, cover-subsidence can occur. Lake Wales, which is underlain by the thinnest section of Hawthorn Group sediments of the four lakes studied, exhibits extreme geologic variability as the Hawthorn Group sediments pinch out or are reworked by subsidence and dissolution activity. The seismic record from Lake Wales shows evidence of cover-subsidence, as well as various stages of cover-collapse activity including sags and draping of the clayey confining units that have not been breached. Farther south, at Blue Lake, the Hawthorn Group and overlying units are thicker and cover-collapse sinkholes are likely to form. Specific areas of Blue Lake show cover-collapse sinkhole morphology, but other areas are underlain by regions where piping and raveling have occurred. Subsidence beneath Blue Lake represents a combination of cover-collapse and cover-subsidence activity resulting in an irregular distribution of confinement. Evidence of sagging, disruption, and complete removal of the confining units beneath the lake indicates that confinement ranges from well confined to poorly confined.

Within the Intra-Ridge Valley physiographic feature, seismic-reflection data from Lake Letta indicate that a complex sequence of subsidence and infilling episodes occurred in geologic units of Pliocene and younger age. Preserved paleobasins within the Lake Letta basin have been identified but cannot be resolved without further study. These may be paleosinkholes or erosional remnants of a more regionally extensive geologic unit. The physiographic relation between Lake Letta, the buried paleobasins, and the Intra-Ridge Valley is unclear. Confining conditions are difficult to assess due to the complex nature of the infilling units and the lack of lithologic control.

At the southern end of the Lake Wales Ridge, Hawthorn Group sediments are more deeply buried and UDSC units are thickest. At these depths, the resolution of subsidence features within the Hawthorn Group and deeper formations is poor. However, based on the data for Lake Wales, Blue Lake, Lake Letta, and other seismic studies of lakes in the Lake Wales Ridge, comparisons can be made between these interpretations and the Lake Apthorp data. Inferred breaches identified within the seismic-reflection record provide evidence that subsidence has occurred in the Lake Apthorp basin and controls present-day bathymetry.

Subsidence activity, accelerated by water-level fluctuations in both the SAS and the FAS, can result from both short and long term changes in hydrologic conditions. Short-term changes in hydrologic conditions reflect seasonal factors. Long-term changes in hydrologic conditions include the response of hydrologic systems to climatic and sea level fluctuations, which have historically exceeded 100 meters (330 ft) both above and below present sea level. The subsidence history of these lakes probably reflects the interaction of the regional geologic framework, the historical climatic and sea level fluctuations, and the paleohydrology; however this history is beyond the scope of this study. The seismic-reflection data clearly demonstrate that over time, these interactions have played a major role in the development of geomorphologic features within the Florida carbonate platform. The formation of numerous sinkhole lakes is a result of the interaction of the hydrologic system with the geologic framework.

CONCLUSIONS

Collectively, lake seismic-reflection data indicate that significant subsidence has occurred along the Lake Wales Ridge, creating depressions and numerous lakes. The seismic-reflection data contribute to a better understanding of the subsidence mechanisms that formed these lakes, how the subsidence has altered the original depositional structure, and the relation of these subsidence features to the hydrogeologic framework.

On a local scale, each lake represents a unique set of hydrogeologic controls. The lake data presented in this report illustrate how local geologic variability fits into the regional setting of the Lake Wales Ridge. This study demonstrates that sublake geophysical studies provide a viable method for assessing the degree of sublake confinement when related to proximal geologic control points. Lake seismic-reflection techniques provide an opportunity to more accurately describe sublake geologic structure, which further enhances the understanding of lake- and ground-water interactions.

REFERENCES

Arthur, J.D., 1993, Geologic map of Highlands County: Florida Geological Survey Open-File Map Series, No. 52, 1 sheet.

Barcelo, M.D., Slonena, D.L., Camp, S.C., and Watson, J.D., 1990, RIDGE II A Hydrologic Investigation of the Lake Wales Ridge: Southwest Florida Water Management District Technical Report. 130 p.

Belanger, Thomas V. and Kirkner, Robert A., 1994, Groundwater/surface water interaction in a Florida augmentation lake: Lake and Reservoir Management v. 8, no. 2, p.165-174.

Berndt, Marian. P., and Katz, Brian. G., 1992, Hydrochemistry of the surficial and intermediate aquifer systems in Florida: U.S. Geological Survey Water-Resources Investigation Report 91-4186. 24 p.

Binford, Michael W., and Brenner, Mark, 1986, Dilution of ^{210}Pb by organic sedimentation in lakes of different trophic states and application to studies of sediment-water interactions: Limnology and Oceanography, v. 31, no. 3, p. 584-595.

Bishop, E.W., 1956, Geology and ground-water resources of Highlands County, Florida: Florida Geological Survey RI-15, 115 p.

Brooks, H. K., 1981, Guide to the physiographic provinces of Florida: Gainesville, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, 11 p.

Brown, L.F., and Fisher, W. L.,1980, Seismic stratigraphic interpretation and petroleum exploration: AAPG Continuing Education Course Note Series No. 16, p. 25-88.

Campbell, K.M., 1992, Geologic Map of Polk County: Florida Geological Survey Open-File Map Series, no. 46. 1 sheet.

Chen, Jian and Beck, Barry F., 1989, Qualitative modeling of the cover-collapse process, in, Proceedings of the third multidisciplinary conference on sinkholes: St. Petersburg Florida, Oct. 1989, A.A. Balkema Press, NY, p. 89-95.

Clark, William E., Musgrove, Rufus H., Menke, Clarence G., and Cagle, Joseph Jr., 1963, Hydrology of Brooklyn Lake near Keystone Heights, Florida: Florida Geological Survey Report of Investigation no. 33. 43 p.

Coleman, James M., 1989, Recent increased aridity in peninsular Florida: Quaternary Research, v. 13, no. 1, p. 75-79.

Cooke, C. W. and Mansfield, W.C., 1936, Suwannee limestone of Florida [abs]: Geological Society of America, 1935, p. 71-72.

Covington, J.M., 1993, Neogene nannofossils of Florida *in*: Zullo, V.A. and others, (eds.), The Neogene of Florida and adjacent regions: Florida Geological Survey Special Publication 37, 112 p.

Dall, W.H., and Harris, G.D., 1892, Correlation papers-Neocene: U.S. Geological Survey Bulletin 84, 349 p.

Duerr, A.D. , Hunn, J.D., Lewelling, B.R., and Trommer, J.T., 1988, Geohydrology and 1985 water withdrawals of the aquifer systems in southwest Florida, with emphasis on the intermediate aquifer system: U. S. Geological Survey Water-Resources Investigations Report 87-4259, 115 p.

Evans, Mark W., Snyder, Stephen W., Hine, Albert C., 1994, High-resolution seismic expression of karst evolution within the Upper Florida aquifer system, Crooked Lake, Polk County, Florida: Journal of Sedimentary Research, v. B-64, No 2.

Ford, D.C. and Williams, P.W., 1989, Karst geomorphology and hydrology: Unwin Hyman Publishers, London, 601 p.

Grimm, Eric C., and George, L. Jacobson Jr., 1992, Fossil-pollen evidence for abrupt climate changes during the past 18000 years in eastern North America: Climate Dynamics, v. 6, p. 179-184.

Grimm, Eric C., Jacobson, George L. Jr., Watts, William A., Hansen, Barbara C.S., Maasch, Kirk A., 1993, A 50,000-year record of climatic oscillations from Florida and its temporal correlation with the Heinrich events: Science, v. 261, July 9, 1993, p. 198-200.

Grubbs, J.W., 1995, Evaluation of ground-water flow and hydrologic budget for Lake Five-O, a seepage lake in northwestern Florida: U.S. Geological Survey Water Resources Investigation Report 94-4145, 42 p.

Haq, B. U., Hardenbol, Jan, and Vail, Peter M., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, in Sea-level changes--An integrated approach: SEPM Special Publication 42, p. 71-108.

Hutchinson, C. B., 1978, Appraisal of shallow ground-water resources and management alternatives in the upper Peace and eastern Alafia River basins, Florida: U.S. Geological Survey Water-Resources Investigations 77-124, 57 p.

Katz, B.G., Lee, T.M., Plummer, L.N., and Busenberg, E., 1995A, Chemical evolution of groundwater near a sinkhole lake, northern Florida: Part 1, Flow patterns, age of groundwater, and influence of lake water leakage: Water Resources Research, v. 31, no. 6, p. 1549-1564.

Katz, B.G., Plummer, L.N., Busenberg, E., Revesz, K.M., Jones, B.S., Lee, T.M., 1995B, Chemical evolution of groundwater near a sinkhole lake, northern Florida: Part 2, Chemical patterns, mass transfer modeling, and rates of mass transfer reactions: Water Resources Research, v. 31., no. 6, p. 1565-1584.

Kenner, W.E., 1964, Maps showing depths of selected lakes in Florida, Florida Geological Survey IC-40, 82 p.

Kindinger, Jack L., Davis, Jeffrey B., and Flocks, James G., 1994, High-resolution single-channel seismic-reflection surveys of Orange Lake and other selected sites of north-central Florida: U.S. Geological Survey Open File Report 94-616, 48 p.

Lane, Ed, 1986, Karst in Florida: Florida Geological Survey SP-29, 100 p.

Lee, T.M., Adams, D.B., Tihansky, A.B., and Swancar, Amy, 1991, Methods, instrumentation, and preliminary evaluation of data for the hydrologic budget assessment of Lake Lucerne, Polk County, Florida: U.S. Geological Survey Water Resources Investigation 90-4111, 42 p.

Lee, T.M., and Swancar, Amy, in press, Influence of evaporation, ground water, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida: U.S. Geological Survey Water Supply Paper 2439, 64 p.

Locker, Stanley D., Brooks, Gregg R., and Doyle, Larry J., 1988, Results of a seismic-reflection investigation and hydrogeologic implications for Lake Apopka, Florida: Center for Nearshore Marine Science, Final report to the St. John's Water Management District., 39 p.

McQuillan, R., and Ardus, D.A., 1977, Exploring the geology of shelf seas: Houston, Texas, Gulf Publishing Co., 234 p.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan Aquifer System in Florida and in Parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.

Missimer, T.M., McNeill, D.F., Ginsberg, R.N., Muller, P.A., Covington, J.M., and Scott, T. M., 1994, Cenozoic record of global sea-level events in the Hawthorn group and the Tamiami Formation of the Florida Platform [abs]: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A-151.

Mitchum, R. M. Jr., 1977, Glossary of terms used in seismic stratigraphy, in, Payton, Charles E., 1977, Seismic Stratigraphy--Applications to hydrocarbon exploration: Tulsa, OK, AAPG Memoir 26, AAPG publishers p. 205-212.

Mitchum, R.M. Jr., Vail, P.R., Sangree, J. B., 1977, Stratigraphic interpretation of seismic reflection patterns in depositional sequences, in, Payton, Charles E., 1977, Seismic Stratigraphy--Applications to hydrocarbon exploration: Tulsa, OK, AAPG Memoir 26, AAPG publishers p.117-133.

Mitchum, R. M. Jr., Vail, P. R.; and Thompson, S. III, 1977, The depositional sequence as a basic unit for stratigraphic analysis, in, Payton, Charles E., 1977, Seismic Stratigraphy--Applications to hydrocarbon exploration: Tulsa, OK, AAPG Memoir 26, AAPG publishers p. 53-62.

Motz, L.H., Heaney, J.P., Leiter, G., and Deaton, W.K., 1991, Groundwater seepage from karst lakes in Florida, USA, in, Maksimovic, C., ed, New Technologies in urban drainage UDT 1991, Elsevier Applied Science Publishers, London, N.Y. p. 171-176.

Payton, Charles E., ed, 1977, Seismic stratigraphy--Applications to hydrocarbon exploration: Tulsa, OK, American Association of Petroleum Geologists Memoir 26, AAPG publishers, 516 p.

Pollman, C. D., Lee, T.M., Andrews, W.J., Sacks, L.A., Gherini, S. A., and Munson, R.K., 1991, Preliminary analysis of the hydrologic and geochemical controls on acid-neutralizing capacity of two seepage lakes in Florida: Water Resources Research, v. 27, no. 9, p. 2321-2335.

Robertson, Alton F., 1973, Hydrologic conditions in the Lakeland Ridge area of Polk County, Florida: Florida Geological Survey RI-64, 53 p.

Ryan, K. W., 1989, Two-dimensional numerical simulation of the relationship between sinkhole lakes and ground water along the Central Florida Ridge, in: The third multidisciplinary conference on sinkholes: St. Petersburg, Florida Oct. 2-4, 1989, A.A. Balkema Press, NY, p. 33-38.

Sacks, L.A., Lee, T.M., and Tihansky, A.B., 1992, Hydrogeologic setting and preliminary data analysis for the hydrologic-budget assessment of Lake Barco, an acidic seepage lake in Putnam county, Florida: U. S. Geological Survey Water Resources Investigation 91-4180, 28 p.

Scott, T.M., 1988, The lithostratigraphy of the Hawthorn Group (Miocene) of Florida: Florida Geological Survey Bulletin 59, 148 p.

Scott, T.M. and Campbell, K.M., 1993, Geologic Map of Hardee County: Florida Geological Survey Open-File Map Series No. 51.

Scott, T.M., Wingard, G.L., Weedman, S.D., and Edwards, L.E., 1994, Reinterpretation of the peninsular Florida Oligocene A multidisciplinary view [abs]: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A-151.

Sheriff, R.E., 1980, Seismic stratigraphy: Boston, Mass., International Human Resource Development Corporation Publishers, 227 p.

Sinclair, William C., and Stewart, J.W., 1985, Sinkhole type, development, and distribution in Florida: Florida Geological Survey MS-110, 1 p.

Sinclair, William C., Stewart, J.W., Knutilla, R.L., Gilboy, A.E., and Miller, R.L., 1985, Types, features, and occurrence of sinkholes in the karst of west-central Florida: U.S. Geological Survey Water Resources Investigation 85-4126, 81p.

Snyder, Stephen W., Evans, Mark W., Hine, Albert C., and Compton, John S., 1989, Seismic expression of solution collapse features from the Floridan Platform, in: The third multidisciplinary conference on sinkholes, St. Petersburg, Florida Oct. 2-4 1989, A.A. Balkema Press, NY, p. 281-298.

Stewart, Mark and Parker, John, 1992, Localization and seasonal variation of recharge in a covered karst aquifer system, Florida, USA: International Contributions to Hydrogeology, v.13, Springer-Verlag, p. 443-460.

Stewart, Herbert G. Jr, 1966, Ground-water resources of Polk County: Florida Geological Survey RI-44, 170 p.

Stumm, Werner and Morgan, James J., 1981, Aquatic Chemistry: New York, John Wiley and Sons, 780 p.

Subsurface Detection Investigations Inc., 1992, High-resolution seismic reflection profiling in selected lakes in the St. Johns River Water Management District, SDI final report to the St. Johns River Water Management District: SP:SJ 92-SP-13, 81 p.

Watts, W. A. and Hansen, B.C.S., 1988, Environments of Florida in the Late Wisconsin and Holocene, in: Purdy, Barbara A. ed, 1988, Wet Site Archeology: Caldwell, N.J., Telford Press, p. 307-323.

White, William A., 1958, Some geomorphic features of Central Peninsular Florida: Florida Geological Survey Bulletin 41, 92 p.

White, William A., 1970, The geomorphology of the Florida peninsula: Florida Geological Survey Bulletin 51, 164 p.

Wingard, G.L., Weedman, S.D., Scott, T.M., Edwards, L.E., and Green, R.C., 1994, Preliminary analysis of integrated stratigraphic data from the South Venice Corehole, Sarasota County, Florida: U.S.Geological Survey Open-File Report 95-3, 129 p.

Yobbi, D.K., 1996, Analysis and simulation of ground-water flow in Lake Wales Ridge and adjacent areas of central Florida: U.S. Geological Survey Water-Resources Investigation Report 94-4254, 90 p.