

STATE OF FLORIDA
DEPARTMENT OF ENVIRONMENTAL PROTECTION
David Struhs, *Secretary*

DIVISION OF RESOURCE ASSESSMENT AND MANAGEMENT
Edwin J. Conklin, *Director*

FLORIDA GEOLOGICAL SURVEY
Walter Schmidt, *State Geologist and Chief*

Bulletin No. 65

**LATE OLIGOCENE TO PLIOCENE EVOLUTION
OF THE CENTRAL PORTION OF THE
SOUTH FLORIDA PLATFORM:
MIXING OF SILICICLASTIC AND CARBONATE SEDIMENTS**

By

Thomas M. Missimer

Published for the

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Tallahassee, Florida
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METRIC CONVERSION FACTORS

To eliminate duplication of parenthetical conversion of units in the text of reports, the Florida Geological Survey has adopted the practice of inserting a tabular listing of conversion factors. For readers who prefer U.S. units to the metric units used in this report, the following conversion factors are provided.

MULTIPLY	BY	TO OBTAIN
meters (m)	3.281	feet
kilometers (km)	0.6214	miles

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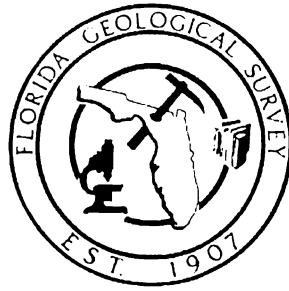
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PREFACE



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The Florida Geological Survey, Division of Resource Assessment and Management, Department of Environmental Protection, is publishing as its Bulletin 65, *Late Oligocene to Pliocene Evolution of the Central Portion of the South Florida Platform: Mixing of Siliciclastic and Carbonate Sediments*, by Thomas M. Missimer. This report summarizes the results of a multi-year investigation of the lithostratigraphy, paleoenvironments, and chronostratigraphy of the upper Paleogene and Neogene sediments underlying the central part of southern Florida. The data presented will be useful to scientists, planners, and citizens in understanding the stratigraphy and geologic history of the strata containing Florida's groundwater aquifers.

Walter Schmidt, Ph.D.
State Geologist and Chief
Florida Geological Survey

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LATE OLIGOCENE TO PLIOCENE EVOLUTION OF THE CENTRAL PORTION OF THE SOUTH FLORIDA PLATFORM: MIXING OF SILICICLASTIC AND CARBONATE SEDIMENTS

By

Thomas M. Missimer, P.G. No. 144

ABSTRACT

Synchronous deposition of carbonate and siliciclastic sediments occurred on the South Florida Platform during the late Oligocene to early Pliocene, producing a large number of complex mixed carbonate/siliciclastic lithologies, some perhaps unique to the region. All 14 defined subfacies contain a mix of carbonate and siliciclastic sediments along with phosphorite grains. Only a small percentage of the stratigraphic section contains sediments with a solely carbonate or solely siliciclastic composition. Transitions between subfacies are both transitional and abrupt. The hypothesis that carbonate and siliciclastic mixed sediment sequences show mostly abrupt boundaries (Mount, 1984) is not supported.

Based on the interpretations of the depositional environments for the 14 subfacies found in the Hawthorn Group, the entire stratigraphic section was deposited on a ramp with a high percentage of the sediments containing a carbonate mud component. Homoclinal ramp deposits are characterized by low, rather uniform slopes from shallow water into the basin with continuous grading of sediment types from nearshore sands to deep water sands and muds. Many described ramp deposits contain little or no mud in the open inner or outer ramp subfacies, such as the eastern Florida ramp, the current west Florida ramp, and other wave-dominated ramps, such as southern Australia, (James and Von der Borch, 1991); (James et al., 1994; Boreen and James, 1993). Modern ramp deposits bordering restricted water bodies, such as the Arabian Gulf, do contain a belt

of muddy open-water inner and outer ramp deposits. Ancient epeiric sea ramp deposits also produced wackestone and mudstone deposits in the open shelf area. Therefore, the southern Florida ramp deposited during the late Oligocene to early Pliocene was more similar to a restricted-sea ramp than a wave-dominated ramp.

A new chronostratigraphy was developed for the upper Paleogene and Neogene sediments on the central part of the South Florida Platform. The ages of the sediments were determined by the combined use of calcareous nannofossils, planktonic foraminifera, diatoms, strontium-isotope stratigraphy, magnetostratigraphy, and carbon and oxygen isotope variations. Based on these integrated dating techniques, the following age constraints using the Berggren et al. (1995b) time scale were placed on the formations in this region: the Suwannee Limestone is constrained between 33.7(?) to 28.5 Ma, the Arcadia Formation of the Hawthorn Group is constrained from between 26.5 to 12.4 Ma, the Peace River Formation of the Hawthorn Group is constrained between 11(?) to 4.3 Ma, the Tamiami Formation is constrained between 4.29 to 2.15 Ma, and the Caloosahatchee Formation is constrained from 2.14 to 0.6 Ma.

Eleven third-order sea-level events were recognized in the stratigraphic record between the late Oligocene and early Pliocene. With the exception of the early Miocene sea-level events, the remaining seven events corresponded closely in time with the global sea-level curve of Haq et al. (1988). However, the depth of flooding on the Florida Platform differed from the relative depths predicted by the Haq curve.

During the late Aquitanian and Burdigalian, Haq observed three third-order sea-level events, but four events were recorded in the cores studied. It is hypothesized that two of the events correlate to event 2.1 of Haq et al. (1988), which is a revision of the global curve.

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Perhaps the most fundamental information provided was the continuous cores collected at South Seas Plantation, Koreschan, and Marco Island. This information was provided by the Florida Geological Survey. I thank Dr. Walter Schmidt, State Geologist, Dr. Thomas Scott, Assistant State Geologist, and their

fine staff for all of the help I received. All of the strontium isotope analyses were performed at the geochronology laboratory, University of Florida under the direction of Dr. Paul Mueller. Many samples were collected from the cores for identification and analysis of calcareous nannoplankton. This work effort was conducted by Mr. J. Mitchner Covington of Tallahassee, formerly with the Florida Geological Survey.

Approximately 125 km of continuous seismic reflection profiles were obtained using the Rice University Research vessel, the R/V Lonestar. I thank Dr. John Anderson of Rice University for his assistance in obtaining the data and his review of the interpretation. Another approximately 500 km of seismic reflection profile data were obtained from the files of the U.S. Geological Survey, Water Resources Division in Fort Myers, Florida. I thank Mr. Henry LaRose for his assistance in obtaining these data.

Considerable assistance was provided by many faculty members at the University of Miami, Rosenstiel School of Marine and Atmospheric Science. Dr. Larry Peterson provided the use of his laboratory for analysis of total carbonate and provided much advice on global oceanographic data during the Miocene. Dr. Leslie Melim provided help using the X-ray diffraction equipment and advice on data analysis. Dr. Robert Warzeski provided critical reviews of many concepts involving the interpretation of the seismic reflection data and geophysical logs. Dr. Andreas Pisera of the University of Warsaw, Poland assisted in the identification of various bryozoa and red algae in thin sections. Dr. Donald Moore provided considerable assistance in the interpreting water depth data for mollusks and information on depositional environments of bryozoans.

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INTRODUCTION

STATEMENT OF PROBLEMS

There is considerable interest in the evolution of carbonate platforms to mixed carbonate-siliciclastic environments (Byers and Dott, 1981; Doyle and Roberts, 1988; Budd and Harris, 1990; Harris and Lomando, 1991). Since mixed carbonate-siliciclastic sediments tend to develop in shoaling-upward sequences, they can provide insights into both sea-level events and sequence stratigraphy (Sarg, 1988). Because of its relative tectonic stability, the Florida Platform is an exceptionally good geographic area to study both the changes in sediment composition with time and the sea-level events which caused the changes. The principal questions posed for research in this report relate to the evolution in sediment deposition with time on the central part of the South Florida Platform (Figure 1) during Oligocene to Pliocene time. Throughout this publication the term "South Florida Platform" will be used to describe the area of Florida lying south of an east-west line running approximately through Lake Okeechobee as commonly used in geographic references on Florida (see Figure 1).

A series of fundamental questions to be answered include: where in the stratigraphic record does the occurrence of siliciclastic sediment begin, what rock types were deposited and in what patterns, and how do the mixed carbonate/siliciclastic rock types relate to water depth and sea-level change? In order to answer these questions, the regional stratigraphic framework of the Florida Platform was assessed and compared to the changes in lithologies observed in both cores and shallow, high-resolution seismic reflection profiles, and related global oceanographic events in real time.

The first group of questions to be posed involves the detailed description of the lithologies found in the Hawthorn Group of

South Florida. Is the carbonate-siliciclastic transition on the South Florida Platform gradational or abrupt? What unique or unusual sediments occur because of the mixing of numerous lithic components of diverse origins and what processes produced these sediment types?

Evolution of the sediment types on the South Florida Platform involves correlations to global events, which requires knowledge of deposition in absolute time. When did the major change occur on the South Florida Platform causing the transition from carbonate to mixed siliciclastic and carbonate sediments? Based on known regional events, another question involving time is: Was the closure of the Gulf Trough or Apalachicola Embayment (Schmidt, 1984) by siliciclastic sediment infill the significant event allowing movement of the siliciclastic sediments to the south in the late Oligocene-early Miocene or were the siliciclastic sediments already mixed with the carbonates earlier in time (mid-Oligocene sea level event)? Finally, there has been a continuing debate (Scott, 1988; Missimer, 1992a) over the ages of the Arcadia (Hawthorn Group), Peace River (Hawthorn Group), Tamiami, and Caloosahatchee Formations for many years. Therefore, what are the ages of these formations?

A stratigraphic technique that can be used to organize complex sediments into a reasonable framework for study and comparison is sequence stratigraphy (Van Wagoner et al., 1990; Loucks and Sarg, 1993). Based upon the seismic reflection data, core data and well logs studied, can the sediments of the Hawthorn Group be placed within a sequence stratigraphic framework for comparison with regional and global sediments of equivalent ages located in other areas or to the global eustatic sea-level curve? Because of the importance of these sediments for the development of water supplies and other economic considerations, a series of questions related to mapping of sequences arises. Do third-

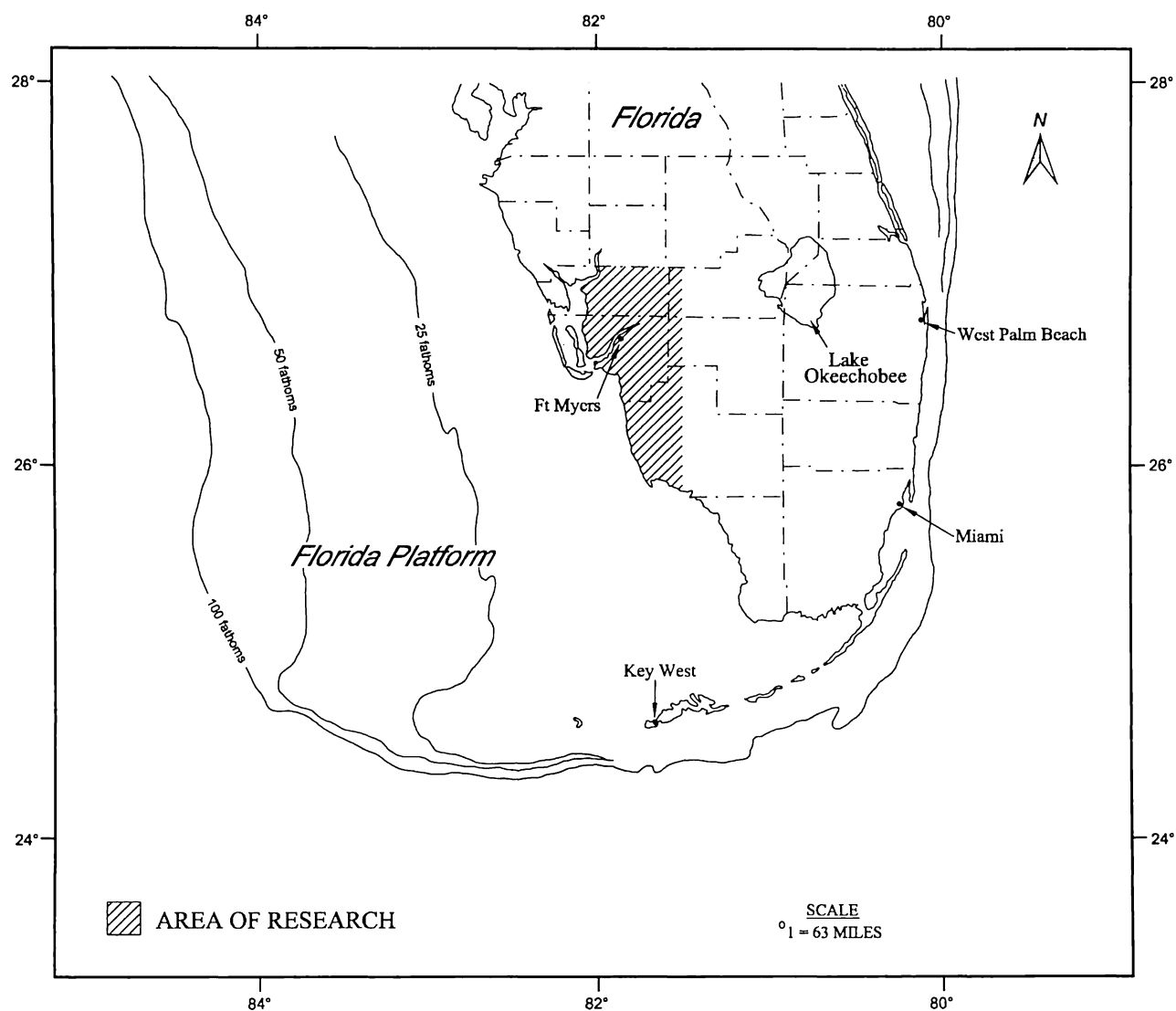


Figure 1. Map showing the southern part of the Florida Platform, the land area, shelf area, and the principal area of investigation. The investigation area is located almost in the middle of the platform, nearly on the axis.

order cycles occur in the early to middle Miocene sediments and, if so, are they areally extensive, can these cycles be mapped on a regional basis, and can the cycles be distinguished and mapped in high-resolution seismic reflection profiles?

Global and regional sea-level variations through time are of fundamental importance in producing changes in sediment types that create the stratigraphic record (Vail et al., 1977a; 1977b). There are both global and regional events that cause changes in the relative position of sea level, causing the magnitude of the changes to be quite variable at any given geographic location and producing different sediment types and thicknesses for the same time period (Vail et al., 1991). It is important to study stratigraphy in comparison to an overall global framework in order to compare one region to another. Based on the observations made on South Florida Platform sediments, 1) does the global sea-level curve of Haq et al. (1987) provide an accurate model for the history of the area?, and 2) can the global sea-level curve be refined based on new information obtained from the South Florida Platform for the late Oligocene-Miocene time frame?

A fundamental concept with regard to mixed carbonate/ siliciclastic sediment that remains to be resolved is the belief amongst many geologists that the stratigraphic contacts between carbonate and siliciclastic sediments are generally abrupt (Mount, 1984). This supposition is in conflict with Walther's Law, which suggests that within a vertical succession containing mixed sediments, records of gradational transitions between carbonate and siliciclastic facies should commonly occur. Perhaps the concept of limited mixing of end-member compositions is real or maybe the mixed sediment sequences have not been studied in sufficient detail to assess if intermediate compositional changes are common.

From a practical application point of view, the stratigraphic units on the South Florida Platform being studied as part of

this research are economically very important as future sources of water supply. Past geological studies have not defined the units in sufficient detail to allow proper definition of flow systems and calibration of regional ground water models (Stringfield, 1966; Stringfield and LaGrand, 1966; Miller, 1986; Bush and Johnson, 1988). Also, the study of the hydrogeology was limited in the past to the definition of large-scale aquifer groups. Ground-water quality information and simulations are becoming quite important. These types of investigations, aimed at predicting the long-term viability of public water supplies and assessing the movement of toxic or hazardous substances, require a much greater level of detail in geologic data compared to the past. The skeletal structure of an aquifer must be known in order to accurately predict water quality changes with time (Missimer, 1994). Answers to these fundamental questions will provide a beginning to the more detailed geologic investigations required to properly define the upper portion of the Floridan aquifer system on the South Florida Platform.

METHODS OF INVESTIGATION

Introduction

The primary problems posed for investigation are related to the significant change in sediment-type deposition on the South Florida Platform during the late Paleogene and Neogene, the documentation of the transition of a shallow marine platform from a predominantly carbonate to a mixed carbonate/siliciclastic environment, and how the platform was affected by eustatic sea-level changes. Specific questions have been posed with regard to the effect of the eustatic sea-level changes, the time of arrival of the siliciclastic sediments, the overall chronology of the sediment sequences, the cyclicity of the deposits, the source and the mode of transport of the siliciclastic sediments, and if a general deposi-

tional model can be developed to explain the patterns of deposition and the changes in sediment types.

Three primary types of investigations were made, which are: 1) investigation of the sediment types and the stratigraphic patterns of deposition; 2) investigation of the chronostratigraphy; and 3) the establishment of the sequence stratigraphy of the sediments. Each major area of investigation required a number of specific studies in order to be able to synthesize conclusions.

Lithologic and Stratigraphic Investigations

Stratigraphic investigations were made using three cores drilled by the Florida Geological Survey and a number of wells (11) located between the cores. The locations of these cores and wells are given in Figure 2. Two detailed stratigraphic sections were constructed, section A-A' being a dip section, and the other section, B-B', being constructed perpendicular to the platform dip. An additional section was constructed between the cores to provide an assessment of the continuity of sediment sequences. These sections were chosen in order to carefully evaluate the tops and bottoms of each formation and to have the ability to obtain continuous seismic reflection data either parallel to the section or cutting across it. Detailed studies of the cores and well log data allowed some general stratigraphic and lithologic characteristics to be evaluated for application to broader regional problems on the southern part of the Florida Platform.

The three cores that were studied were W-16242, W-16523, and W-17115. All three cores penetrated the full thickness of the Hawthorn Group, the principal stratigraphic unit of interest. These cores were drilled using a wire-line coring device, which allowed a high percentage of core recovery. Geophysical logs were obtained from the borehole of each core. Single-point

resistivity and natural gamma ray logs were available for all cores. In addition, core W-17115 has a neutron log and a 16/64 lateral resistivity log. Each core was studied in considerable detail by cutting the core using a rock saw and then carefully describing the lithology changes with depth using a stereoscopic microscope. The lithology changes were compared to the geophysical logs to be sure that the depth intervals written on the core boxes were correct.

Each well used to construct the primary stratigraphic sections was chosen based on the quantity and quality of data available. Nearly every one of these wells was drilled as part of a hydrogeologic investigation, which required the acquisition of detailed geologic data. Most of the wells were drilled using the reverse-air rotary technique, which allows the cuttings to be rapidly vacuumed from the borehole without contamination with drilling mud or cuttings falling into the borehole at locations above the bit. Geophysical logs were examined from each well and at a minimum, electric logs and a natural gamma ray log were available. These wells allowed the regional correlation of major stratigraphic units to be made between the cores. A listing of the site elevations and core depths is given in Table 1.

Chronostratigraphy

One of the primary problems in analyzing stratigraphy and sedimentation on the Florida Platform is the lack of accurate time control. Past definitions of many formations occurring on the Florida Platform were assigned ages based on incomplete or inaccurate paleontological data. Time stratigraphic data in this investigation was obtained using ages determined from strontium-isotope stratigraphy, magnetostratigraphy, and calcareous nannofossils (unpublished work of J. Mitchner Covington). Data from previous paleontological studies conducted on the same stratigraphic units were incorporated into the evaluation of the

Table 1. Well and Core Information.

Number ¹	Altitude		Total Depth		Location T. R. S.
	ft.	m.	ft.	m.	
Section A-A'					
W-16889	21	6.40	2712	826.6	T.42S, R.23E, S.25
LM-3509	15	4.57	1585	483.1	T.43S, R.24E, S.31
LM-1629	4	1.22	1200	365.8	T.45S, R.24E, S.17
LM-1841	14	4.27	1400	426.7	T.45S, R.25, S. 33
W-16523	11	3.35	822	250.5	T.46S, R.25E, S. 33
LM-1980	14	4.27	1306	398.1	T.47S, R.25E, S.17
CO-2317	14	4.27	3400	1036.3	T.48S, R.26E, S.35
CO-2081	10	3.05	1616	492.6	T.49S, R.26E, S.35
CO-2080	5	1.52	1608	490.1	T.51S, R.26E, S.10
W-17115	5	1.52	1040	317.0	T.52S, R.26E, S.8
CO-2271	5	1.52	3354	1022.3	T.52S, R.26E, S.8
Section B-B'					
W-16242	2	0.61	760	231.6	T.45S, R.21E, S.26
LM-3368	4	1.22	762	232.3	T.44S, R.22E, S.34
W-15487	4	1.22	662	201.8	T.45S, R.23E, S.4
LM-3484	13	3.96	760	231.6	T.44S, R.23E, S.1
LM-3509	15	4.57	1585	483.1	T.43S, R.24E, S.31
W-10761	29	8.84	450	137.2	T.41S, R.26E, S.33
Section C-C'					
W-16242	2	0.61	760	231.6	T.45S, R.21E, S.26
W-16523	11	3.35	822	250.5	T.46S, R.25E, S.33
W-17115	5	1.52	1040	317.0	T.52S, R.26E, S.8

¹ Explanation of numbers. "W" is an FGS core number. "LM" and "CO" are numbers used by the consultant who drilled the wells.

chronostratigraphy.

Perhaps the most important age dating method used was the time dependent variation of strontium isotopes in unaltered marine organisms. Most stratigraphic intervals in the cores contained some unaltered calcitic barnacles and marine mollusks, particularly oysters, and pectens. A

total of 62 strontium-isotope age determinations were made on material collected from the three cores. A majority of the age determinations (34) were made on the South Seas Plantation core (W-16242), because of the abundance of datable material and the detailed stratigraphic and lithologic analyses made on this core. The

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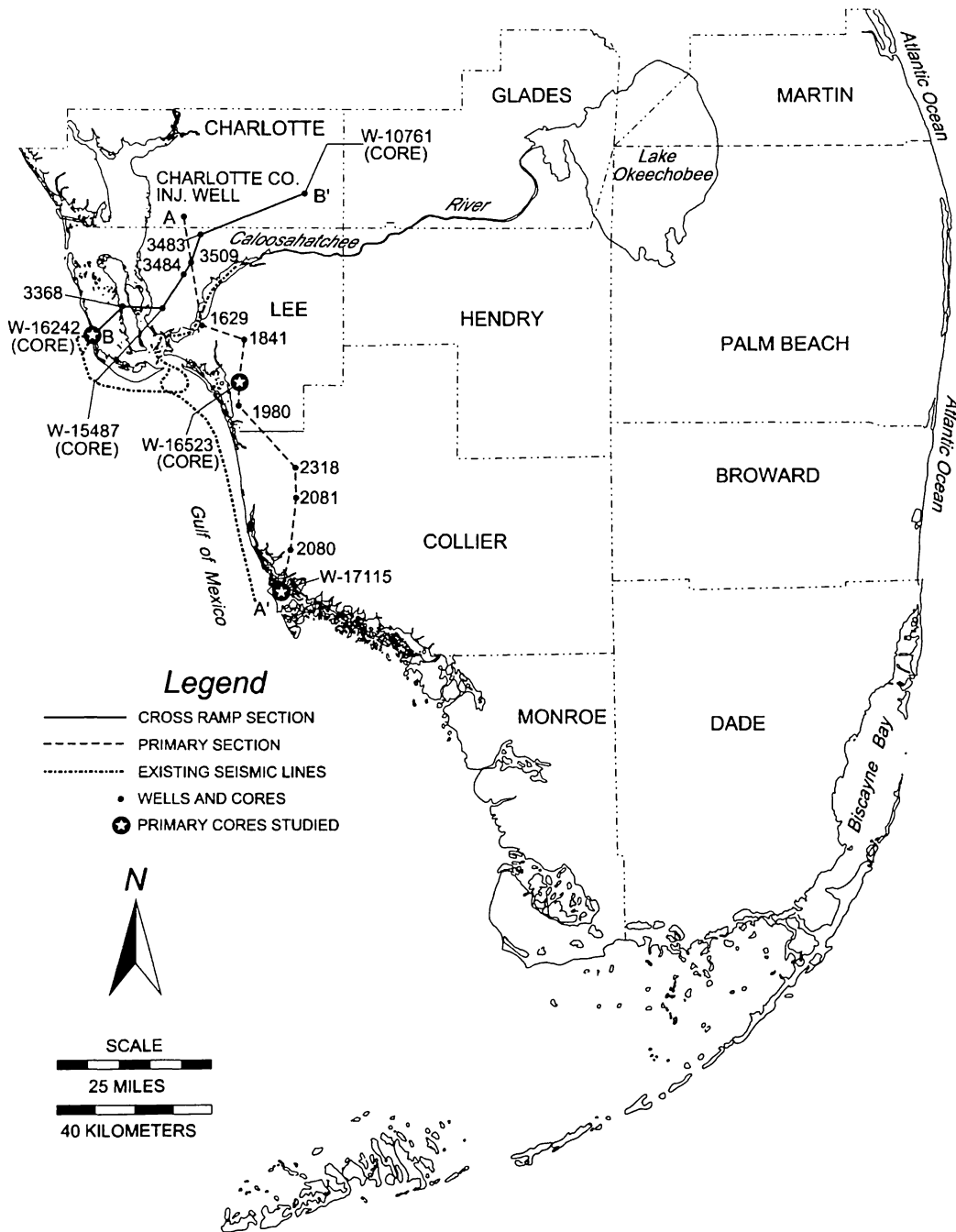


Figure 2. Map of South Florida showing the location of all cores and wells used in the investigation. The geologic section lines are shown along with high-resolution, shallow seismic reflection lines. The investigation is limited to the western part of South Florida at the approximate axis of the platform.

strontium isotope ages were determined using both the Hodell et al. (1991) and the Ostlick et al. (1994) models. Because the strontium isotope ratios were measured at the University of Florida, the Hodell et al. (1991) regression equations could be used directly with the appropriate correction. However, there is a difference in the NBS-987 number between the University of Florida and Rutgers University, where the Ostlick et al. (1994) samples were analyzed. Before the Ostlick et al. (1994) model was used for age determination, the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized. All age data were then converted to the time scale of Berggren et al. (1995b).

Detailed magnetostratigraphic data were collected from the South Seas Plantation core (W-16242). Oriented rock samples were collected from 291 intervals. Since the core was collected using a drilling rig, the only orientation of the samples that could be determined was the stratigraphic up direction. Core orientation was checked by locating geopetals in the rocks to be sure that the cores were properly oriented in the boxes. Therefore, only inclination data could be used to determine the polarity of the earth's magnetic field at the time of deposition. Magnetic measurements were made on each sample using a superconducting magnetometer. Magnetic susceptibility of each sample was measured prior to and after demagnetization. Both alternating field and thermal demagnetization methods were used to demagnetize the samples. Rock magnetization data were collected on 12 samples from the same core. All magnetic susceptibility and magnetic inclination data were collected at the Paleomagnetism Laboratory at the University of Miami (RSMAS). The rock magnetism data were collected at the Paleomagnetism Laboratory, California Institute of Technology by Dr. Donald McNeill. Magnetostratigraphic correlations were made by comparing the pattern of polarity reversals determined from the core measurements to the geomagnetic

polarity timescale (GPTS) using available biostratigraphy and Sr-isotope age tie-points.

Paleontological Age Determinations

A study of the calcareous nannoplankton was made previously on the South Seas Plantation core (W-16242) and the Koreschan core (W-16523) by J. Michner Covington of the Florida Geological Survey (Covington, 1992). Approximate stratigraphic ages were determined by comparing the overlapping ranges of several identified species in the cores to the known stratigraphic ranges of these species in the world ocean. The original age ranges for the significant species were determined from numerous radiometric dates tied to the stratigraphic occurrence of the calcareous nannofossil species.

A series of previous investigations were made on the age of many of the stratigraphic units of interest (Peck, 1976; Peck, Missimer, and Wise, 1976; Peck et al., 1977; Slater, 1978; Peck et al., 1979a; Peck et al., 1979b; Peacock, 1981; Klinzing, 1980, 1987). Most of these investigations utilized planktonic and benthic foraminifera to determine stratigraphic ages. Klinzing (1980, 1987) utilized diatoms and some calcareous nannofossils were used by Peck (1976) and Slater (1978). The data contained in these investigations were re-evaluated and incorporated into the overall effort to determine the ages of various stratigraphic units.

Seismic and Sequence Stratigraphy

About 125 km of new, high-resolution seismic reflection data were collected parallel to the major north-south stratigraphic section from Marco Island north to Sanibel Island, from the eastern tip of Sanibel Island west and north to Captiva Island immediately adjacent to core W-16242, and in the Caloosahatchee River Estuary from the Sanibel Causeway Bridge to Fort Myers

(see Figure 2 for seismic line locations). Also, about 160 km of existing high-resolution seismic reflection lines were reviewed. These lines were run by the U.S. Geological Survey as part of several water resources investigations (Missimer and Gardner, 1976).

The seismic data were collected using a variety of sources including a boomer system, a multi-element sparker, a single element sparker, and a water gun with variable pressure inputs. All of the seismic reflection data collected for this investigation were obtained using equipment on the Rice University vessel, the R/V Lonestar. The sediment velocities were estimated using well logs directly adjacent to the seismic lines and density logs from an injection well located immediately adjacent to the Macro Island core (W-17115). It was not possible to obtain velocity logs.

The sequence stratigraphy was studied using the core data, the well logs, a review of the seismic reflection data, and the correlated stratigraphic sections. The seismic record showed the overall geometry of the bedding and the major relationships of the stratigraphic units. Detailed analyses of sediment sequences in the cores allowed more detailed analysis of stacking patterns of shoaling-upward sequences separated by discontinuity surfaces.

MIXED SILICICLASTIC AND CARBONATE SEDIMENTS OF THE HAWTHORN GROUP, SOUTH FLORIDA PLATFORM

INTRODUCTION

Mixed carbonate and siliciclastic sequences can provide considerable insight into the record of eustatic sea-level changes, particularly when the sediments were deposited on a relative tectonically stable platform. Considerable interest has arisen over the past decade with regard to carbonate/siliciclastic mixtures and the replacement of regionally significant car-

bonate sequences with siliciclastic sediments or vice-versa in time and/or space (Byers and Dott, 1981; Doyle and Roberts, 1988; Budd and Harris, 1990; Harris and Lomando, 1991). Many mixed carbonate/siliciclastic sequences are cyclic or repetitive to some degree in ancient rocks, making them important in the study of sequence stratigraphy (Wilson, 1967; Picard and High, 1968; Meissner, 1972; McIlreath and Ginsburg, 1982; Brett and Baird, 1985; Mack and James, 1986; Sarg, 1988; and Shew, 1991).

It was suggested by Mount (1984) that the stratigraphic contacts between major siliciclastic and carbonate lithofacies are quite abrupt and so few examples of gradational contacts occur on shallow shelves because "(1) facies changes may have taken place through a fundamental alteration in depositional conditions on the shelf, involving either rapid migration of environments or erosion, and/or (2) the lateral transition between coexisting carbonate and siliciclastic environments was very abrupt and thus not likely to be preserved as a mixed sediment." The suggestion that "most" contacts between carbonate and siliciclastic sediment sequences are abrupt seems to conflict with Walther's Law, which suggests that within a vertical succession containing mixed carbonate and siliciclastic sediments, records of gradational transitions between carbonate and siliciclastic facies should commonly occur.

The Oligocene-Miocene stratigraphic record on the South Florida Platform provides an opportunity to view a relatively detailed example of a carbonate-siliciclastic transition compared to other regions of eastern North America, where sediments of this age are not as well preserved. The South Florida carbonate-siliciclastic transition is somewhat unique in that it is at the "end of the pipeline," or isolated from any other sources of siliciclastic sediment allowing the opportunity to assess subtle changes in depositional environments. It is the purpose of this investigation to assess

the type of carbonate-siliciclastic transition, whether it is abrupt or fully mixed, by the study of the sediment composition and facies types. Also, the hypothesis of Mount (1984) regarding the tendency of transitions to be abrupt will be tested.

Prior to Miocene time the southern portion of the Florida Platform was a carbonate platform or ramp, believed to be isolated from sources of siliciclastic sediment to the north by a deep channel known as the Gulf Trough (commonly referred to as the Suwannee Straits or the Apalachicola Embayment) (Applin and Applin, 1944; Cooke, 1945; Hull, 1962; Puri and Vernon, 1964; Schmidt, 1984; Popenoe et al., 1987; Huddleston, 1993). Previous investigations suggested that the transition of the Florida Platform from carbonate sedimentation to siliciclastic sedimentation was quite rapid (Schmidt, 1984; Scott, 1988). Because the Florida Platform is assumed to have been tectonically stable during the time period when the transition occurred (Oligocene/Miocene?) and there was between 150 and 250 m of sediment deposition in this part of the stratigraphic section, it should be a prime location for the detailed study of a major transition. Past investigations suggest that the transition occurs within the regional stratigraphic unit known as the Hawthorn Group (Puri and Vernon, 1964; Scott, 1988).

METHODS

Stratigraphic investigations were conducted by examination of three cores drilled by the Florida Geological Survey and eleven wells drilled between these cores. The locations of the cores and wells are given in Figure 2. Two stratigraphic sections were constructed, section A-A' being a dip section and section B-B' being constructed perpendicular to the platform dip. These sections were chosen in order to carefully evaluate the tops and bottoms of the major stratigraphic units and to allow the dip section to closely parallel a continu-

ous seismic reflection profile. Detailed studies of the cores and well log data were made to establish both characteristic lithofacies types and the stratigraphic sequence patterns for each major unit.

The three cores studied all penetrated the full thickness of the Hawthorn Group, which is the stratigraphic unit of primary concern. These cores were drilled using a hydraulic rotary rig equipped with a wireline coring device, which allowed a high percentage of core recovery. Geophysical logs were obtained on the borehole of each core. Single point resistivity and natural gamma ray logs were obtained for cores W-16242 and W-16523. These types of geophysical logs were obtained from the Marco Island core (W-17115) along with a neutron log and a 16/64 lateral resistivity log. Each core was studied by cutting a large portion of the core in half using a rock saw and then carefully describing the observed lithology, sedimentary structures, fauna and flora, and composition using a stereoscopic microscope. The lithologies were described and classified according to the system of Dunham (1962) with descriptive language added for the siliciclastic components. The lithology changes were routinely compared to the geophysical logs to assess the correct position of lithologies in relation to depth and the location of discontinuities.

The mineralogy of each core interval was determined not only by visual observation, but also was verified by applying dilute hydrochloric acid and/or alizarin red solution to the rock to distinguish calcite from dolomite. After some experimentation, it was determined that a 10% solution of hydrochloric acid was most effective for differentiating carbonate lithology changes. Because of the very high percentage of recovery in core W-16242 and the wide variety of lithologies found in this core, it was chosen for very detailed examination. Samples were collected from the core at 210 different depths and thin sections were made to assess detailed microfacies charac-

teristics assessing both faunal and compositional changes. In addition, 671 samples were collected and crushed into a fine powder to determine the percentage of carbonate, and for x-ray diffraction study of selected fine-grained intervals in order to determine composition. The 671 samples were analyzed for total carbonate using the "carbonate bomb" method (Müller and Gastner, 1971; Jones and Kaiteris, 1983). The method had to be modified slightly because the normal digestion time of 20 minutes for calcite and aragonite was insufficient to allow for the total dissolution of dolomite and francolite (carbonate fluorapatite). After experimentation, the contact time for dissolution was increased to two hours. A duplicate sample was run for every 12 samples analyzed. Based on the analyses of the duplicates, the precision error of the measurements averaged less than one percent. The estimated average accuracy of the measurements is about ± 2 percent based on measurements performed on standards known to be pure calcite and pure dolomite and various experiments performed by Müller and Gastner (1971). It must be noted that this method is most accurate for calcite and aragonite, but in the case of dolomite, the amount of carbon dioxide produced is greater than for calcite and aragonite. Therefore, for pure dolomite, the method yielded some carbonate percentages over 100%. However, the method still reproduced the respective carbonate percentage of the standards within a few percent. The very detailed analysis of this core allowed the development of type lithofacies to be distinguished for application to the remaining cores. All of the observed characteristics for each stratigraphic interval, including composition, sedimentary structures, fauna and flora, and rock classification, were incorporated into a series of master data matrices. These rock characteristic matrices were then used to distinguish the major and minor lithofacies.

Each well used to construct the pri-

mary stratigraphic sections was chosen based on the quantity and quality of data available and its geographic position. Nearly every one of these wells was drilled as part of a hydrogeologic investigation, which required the acquisition of detailed geologic information. Most of the wells were drilled using the reverse-air rotary method, which allowed the cuttings to be rapidly vacuumed from the borehole without contamination with drilling mud or uphole debris. Geophysical logs were used with at least a set of electric logs and a natural gamma ray log available from each well. The information obtained from these wells allowed regional correlation of major stratigraphic units between the more detailed core data.

Formation age data from the cores and continuous seismic reflection data were used to constrain the amount of time missing across unconformities and to establish the major sequence geometries. This information is described in more detail in later sections of the report.

PREVIOUS INVESTIGATIONS

The primary geographic area of investigation is the south-central part of the Florida Platform lying generally south of Lake Okeechobee to the Florida Straits (Figure 1). This area occurs in what was formerly termed the "South Florida Basin" (Pressler, 1947; Puri and Vernon, 1964; Maher, 1971) and currently is known as the Okeechobee Basin (Riggs, 1979b; Scott, 1988). The cores and wells studied in detail lie in the middle of the platform along the southwest coast of Florida, where both the Peace River and Arcadia Formations thicken significantly into the basin (Figure 3).

Stratigraphic and general geologic investigations of the Hawthorn Group began in the early part of this century because of the economic occurrence of phosphate deposits. Most detailed investigations of the stratigraphy of the Hawthorn Group were limited to the northern part of

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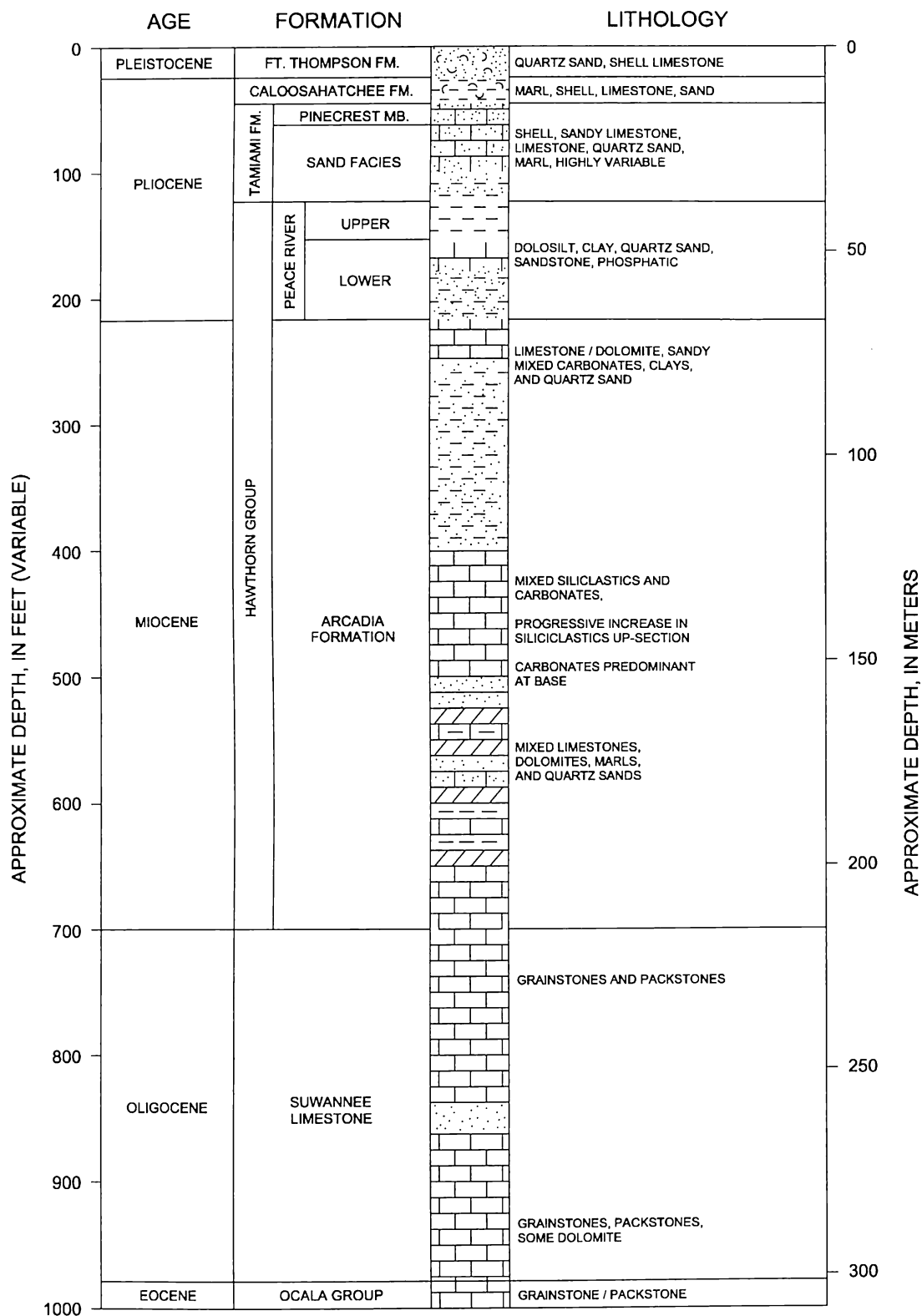


Figure 3. A general stratigraphic section for the study area based on the previous work of Scott (1988). This investigation was conducted primarily on the Hawthorn Group. The stratigraphic terminology and ages shown are based on Scott (1988) and previous investigators.

the Florida Platform, where the sediments lying above the major phosphorite ore deposits are thin. Dall and Harris (1892) were the first investigators to formally name the "Hawthorne beds" for the phosphatic sediments exposed near Hawthorne, Florida. When Matson and Sanford (1913) compiled the first comprehensive description of Florida stratigraphy, they dropped the "e" from the formation name and the Florida Geological Survey currently recognizes the formal name as "Hawthorn." A very detailed history of the evolution of the Hawthorn Group definition is given in Scott (1988). Based on the occurrence of a major regional disconformity and a change in sediment type across the disconformity, Scott (1988) elevated the Hawthorn Formation to the Hawthorn Group and, in southern Florida, subdivided it into the Arcadia Formation at the base of the section and the Peace River Formation at the top of the group (Figure 3). Since the area of investigation is located in South Florida, no further discussion of the investigations in north Florida or the evolution of the nomenclature is appropriate.

Work on the Oligocene and Miocene geology of South Florida has been limited mostly to general stratigraphic studies and studies of the regional oceanic events which caused the deposition of the massive phosphorite deposits. General stratigraphic studies of what was believed to be the Miocene in South Florida were conducted by Scott (1988) and Scott and Knapp (1987). These studies were limited to the definition and correlation of regionally mappable lithostratigraphic units. Investigations on the Suwannee Limestone and part of the Hawthorn Group were made by Cooke (1939), MacNeil (1944), Armstrong (1980), Peacock (1981), Hammes (1992), and Brewster-Wingard et al. (1997). The work by Cooke (1939) and MacNeil (1944) were regional stratigraphic studies. Armstrong (1980) and Peacock (1981) studied the biostratigraphy and

Hammes (1992) analyzed microfacies and sea level implications. These investigations were quite limited in scope and less than 50 wells and ten cores were used to define the overall stratigraphy.

A number of previous geologic investigations were conducted in the immediate vicinity of this research area. Missimer and Banks (1982) studied the stratigraphy of the Miocene and Oligocene beneath Sanibel Island and determined the depositional pattern in the Hawthorn Group to be cyclic. Hammes (1992) completed a detailed investigation of the Suwannee Limestone with work on core W-16242. Hammes (1992) investigation of the Suwannee Limestone defined a series of shallow ramp subfacies, many of which occur in the Hawthorn Group. Investigation of the Neogene seismic and sequence stratigraphy of southwest Florida was performed by Evans et al. (1989), and Evans and Hine (1991). A seismic reflection study of the upper part of the Hawthorn Group and overlying sediments was made by Missimer and Gardner (1976). This investigation lead to the interpretation that the Arcadia Formation was faulted and folded and that the upper part of the Peace River Formation was deltaic.

Although very few geologic and stratigraphic investigations of the South Florida Platform have been made to resolve large scale regional problems, a number of smaller scale studies have been made solely on the paleontology of a stratigraphic time interval or unit of interest or on the age of a unit. These investigations include the works of Gardner (1926), Cole (1934, 1941), Mansfield (1937, 1938), Applin and Jordan (1945), Akers and Drooger (1957), Gibson (1962, 1983), Shannon (1967), Hunter (1968), Akers (1972, 1974), Glawe (1974), Abbott (1978), Klinzing (1980), Hoenstine (1988), MacFadden et al. (1991), Brewster-Wingard et al. (1997).

Investigations of the regional develop-

ment of phosphatic sediments in the Hawthorn Group have related global oceanic events and the change in current patterns to the Miocene evolution of the Florida Platform. These investigations include Compton et al. (1993), Riggs (1979a, 1979b, 1980, 1984), and Synder et al. (1988). Specific hypotheses have been presented with regard to the origin of the dolomite within the Hawthorn Group (Prasad, 1985; Compton et al., 1994).

Most previous work on the Florida Platform has been on carbonate depositional patterns and sedimentation. A recent investigation of mixed siliciclastic/carbonate sedimentation shows part of the regional sedimentation pattern developed in this research (Warzeski et al., 1996; Cunningham et al. 1998).

GEOLOGIC AND STRATIGRAPHIC SETTING

Stratigraphy

The Hawthorn Group occurs regionally beneath most of the Florida Platform with the exception of areas located in and around the Ocala High in west central Florida (Puri and Vernon, 1964). In southern Florida the Group is subdivided into two formations, the Arcadia and the Peace River Formation, following the nomenclature of Scott (1988). According to the literature, the Hawthorn Group is underlain by the Suwannee Limestone and overlain by the Tamiami Formation (Figure 3).

There has been considerable debate over the past 40 years with regard to the formation boundaries and sediment characteristics by which to recognize the formation boundaries as rock stratigraphic units in South Florida (Missimer, 1978; Missimer and Banks, 1982; Scott and Knapp, 1987; Scott, 1988). Missimer (1978) proposed that the upper boundary of the Hawthorn

Formation (at that time) be located on a major regional, disconformity, which separates a section of predominantly siliciclastic sediments from an underlying mixed carbonate/siliciclastic unit. This easily mapped boundary was chosen because it represented a major lithology change with the probability of a considerable amount of time missing. Missimer and Banks (1982) utilized the definition of the overlying Tamiami Formation following the concepts presented by Hunter and Wise (1980a, 1980b), who removed the Peace River Formation sediments and restricted the Tamiami Formation to the originally described sandy limestone. Wedderburn et al. (1982) also utilized the restricted definition of the Tamiami Formation. Because of the lithologic change across the disconformity and the restricted stratigraphic position of the Tamiami Formation (along with many other inconsistencies), Scott (1988) elevated the Hawthorn Formation to Group status, thereby creating a more consistent and mappable section throughout Florida.

Formation Boundaries

Suwannee - Arcadia

The contact between the Arcadia Formation and the underlying Suwannee Limestone is distinctive throughout the study area. The basal facies of the Arcadia Formation is generally a sandy, phosphatic, wackestone and the uppermost facies of the Suwannee Limestone is a foraminiferal packstone or grainstone lacking mud and/or any significant concentration of phosphorite, and containing distinctly less quartz sand than above (Plates 1, 2, and 3). In core W-16523, a thin clay layer marks the disconformity (Plate 2). A marked reduction in gamma ray activity across the formation contact can be distinguished in natural gamma ray logs in all cores and wells studied.

Arcadia - Peace River

Throughout the study area, the contact between the Peace River and Arcadia formations within the Hawthorn Group is a distinct disconformity between a sandy, highly phosphatic, dolomitic mud and an underlying sandy, phosphatic wackestone. In core W-16242 and the wells in northern Lee County, the uppermost part of the Arcadia Formation is dolomitic and in the south it is calcitic. Quartz gravel, phosphorite pebbles, and marine vertebrate fossils commonly occur in the detritus above the disconformity. This contact is always distinctive in a gamma ray log, where a peak is caused by the large accumulation of phosphorite, which contains relatively greater concentrations of uranium and other radioactive trace elements (see Plates 1, 2, and 3).

Peace River - Tamiami

The stratigraphic contact between the Tamiami Formation and the Peace River Formation (upper part of the Hawthorn Group) in the northern part of the study area is clear and mappable. In core W-16242 (Plate 1) and areas to the west, the base of the Tamiami Formation is a quartz sand and shell facies or a sandy, phosphatic, calcitic wackestone (Missimer, 1992b) and the top of the Peace River Formation is a dolomitic, clayey quartz silt with a distinct green color. In the southern part of the study area, the Tamiami Formation is a sandy limestone facies and the Peace River Formation is a quartz sand and shell unit commonly containing some dolomitic cement. In the W-17115 core (Plate 3), the contact is not distinct, but is placed on the occurrence of a disconformity with an underlying beach subfacies that has been dolomitized.

Age of the Hawthorn Group and Bounding Formations

Within the past 10 years a considerable amount of new information has been obtained on the age of the Neogene and upper Paleogene stratigraphic section beneath the South Florida Platform. The ages of most major stratigraphic units were determined in the past by rather crude paleontological correlations to stratigraphic units with better age control. A detailed analysis of the age of the stratigraphic units of interest is presented later in this dissertation.

For many years the ages of the stratigraphic units in south Florida conformed to those assigned by Parker et al. (1955), which were as follows: the Suwannee Limestone was Oligocene, the Hawthorn Formation was middle Miocene, the Tamiami Formation was late Miocene, and the younger units were assigned to the Pleistocene. Recent stratigraphic investigations by Scott (1988), COSUNA (1988), Missimer (1992b), Jones et al. (1991), Hammes (1992), Mallinson and Compton (1993), Compton et al. (1993), and Brewster-Wingard et al. (1997) have helped constrict the major stratigraphic units to more accurate ranges in age. The age ranges of the Suwannee Limestone, the Hawthorn Group, and the Tamiami Formation will be discussed later in the report.

VARIATIONS IN COMPOSITION OF SEDIMENT

Total Carbonate Variation: Results

Many of the fundamental questions posed with regard to mixed carbonate/siliciclastic sediment sequences center around variations in composition of the sediment. All compositional data are located in a Florida Geological Survey repository and in Plates 1, 2, and 3. Samples were collected from all formations in core W-16242,

despite the primary interest in the sediments of the Hawthorn Group, in order to make overall stratigraphic comparisons. A comparison of the average total carbonate concentration in all formations from Holocene to early Oligocene is given in Table 2.

There is a decrease in the percentage of total carbonate from the Suwannee Limestone up-section to the lower part of the Peace River Formation, and a slight increase in total carbonate in the upper part of the Peace River Formation. The trend toward increase in total carbonate continues through the Tamiami Formation and peaks in the Caloosahatchee Formation. The total carbonate decreases through the Fort Thompson Formation and into the Holocene (Figure 4).

From the base of the Suwannee Limestone to the Miocene-Pliocene boundary within the Peace River Formation, the predominant portion of the non-carbonate fraction of the sediment is quartz sand. There are a few minor units containing a

high percentage of clay within the Arcadia Formation. Also, there is a significant amount of glauconite and a trace of sulfide minerals within the Arcadia Formation. It is very important to note that quartz sand occurs in virtually every sediment facies within both the Suwannee Limestone and the Arcadia Formation. A mix of quartz sand and silt, along with clay, form the non-carbonate portion of the upper Peace River Formation. Quartz sand is the predominant non-carbonate sediment component within the remaining Neogene formations.

Variation in the total carbonate percentage can be used to help define discontinuity surfaces and sequence boundaries within mixed carbonate/ siliciclastic sediments (Plates 1, 2, and 3). Starting at the base of the stratigraphic section in core W-16242, the variation in the total carbonate percentage has a different interpretation in different stratigraphic units.

Within the Suwannee Limestone, the

Table 2. Comparison of Total Carbonate Percentages by Formation in the South Seas Plantation Core (W-16242)

Formation	Average Percentage	High	Low	No. Samples	Standard Deviation ²
Suwannee Limestone	91.0 ¹	98.1	64.9	17	8.18
Arcadia Formation	76.4	100.00	4.7	370	20.71
Miocene Section	29.5	68.4	5.3	15	20.70
Pliocene Section	41.5	82.8	8.0	162	18.36
Peace River Formation	40.5	82.8	5.3	177	18.69
Tamiami Formation	50.2	82.8	13.0	63	18.33
Caloosahatchee Formation	82.4	88.5	75.7	19	5.29
Fort Thompson Formation	51.8	84.8	16.6	7	25.69
Holocene	35.9	97.4	4.5	18	30.96

¹ Likely average would be about 95% if numerous samples collected (Hammes, 1992).

² Sample standard deviation.

FLORIDA GEOLOGICAL SURVEY

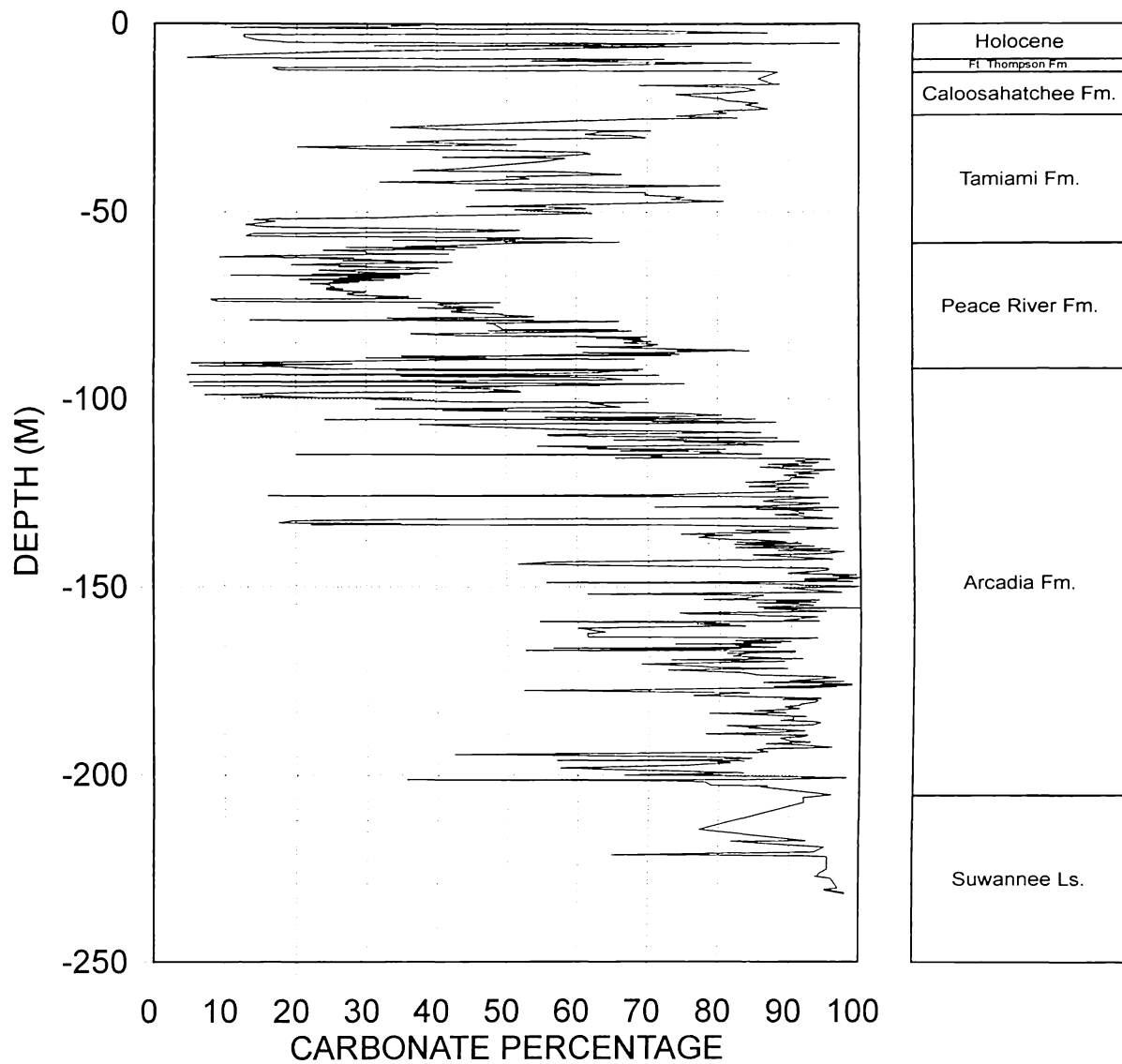


Figure 4. Variation of total carbonate percentage with depth in core W-16242 based on 760 measurements. There is an overall trend of decreasing carbonate percentage with decreasing age going up-section from the Suwannee Limestone to the late Pleistocene formations (with exception of the Caloosahatchee Formation). The extreme changes in carbonate percentage mark subfacies boundaries and commonly occur at sequence boundaries lying on regional disconformities. Depths are below land surface.

lowest total carbonate percentages occur at discontinuity surfaces (Figure 4). Based on past literature (Puri and Vernon, 1964), there is little if any quartz sand or other non-carbonate sediments in the Suwannee Limestone, but virtually all sediment intervals in core W-16242 contain some non-carbonate sediment (Figure 4). The variation in carbonate percentage provides assistance in interpreting sequence boundaries, changes in water depth, changes in subfacies, and shoaling-upward sequences within the Arcadia Formation (Figure 5). Based on the variations in total carbonate percentage measured within the Arcadia Formation, there is a general overall upward increase in the siliciclastic component with abrupt changes in the upper part of the Arcadia Formation. The relationship between the carbonate and non-carbonate components, within shoaling-upward sequences, is presented later in this bulletin. Total carbonate variation in the Peace River Formation shows the distinct boundary between the Miocene sands in the lower three meters of the formation and the increase in carbonate at the Miocene-Pliocene contact located in this core at about 88.4 m (Figure 6). Within the upper part of the formation, the total carbonate decreases with depth in a given bed and sand lags occur at the top of shoaling-upward sequences, such as at 74 m (Figure 6). It is quite apparent from the carbonate data presented that the siliciclastic component of the sediment in all carbonate/siliciclastic units observed is mixed within virtually all types of carbonate depositional environments and many contacts between facies are gradational. This conclusion directly conflicts with the hypothesis of Mount (1984), who stated that there are few examples of truly mixed carbonate/siliciclastic sediment sequences in the stratigraphic record. Beginning at the base of core W-16242, it is observed that the

Suwannee Limestone contains a minor percentage of quartz sand throughout the unit, which confirms a similar observation made by Hammes (1992) in several other cores located to the north. The siliciclastic sediment component within the Arcadia Formation is mixed with the carbonate component throughout the unit, but does show some abrupt, nearly pure compositional contrasts at many sequence boundaries. Siliciclastics and carbonates are completely mixed within the Peace River Formation. All of the other Neogene formations within the core also show thorough mixing of carbonate and siliciclastic sediments within the units. Of the six ancient formations studied, and the Holocene sequence, all of the units contain carbonate and siliciclastic sediments that are thoroughly mixed in terms of overall composition.

Variations in Carbonate Mineralogy

Introduction

The two primary carbonate minerals of interest in this discussion are calcite and dolomite. Aragonite commonly occurs in the upper part of the stratigraphic section in some Pliocene (Pinecrest Member of the Tamiami Formation), Pleistocene and Holocene sediments, but this mineral was not found within the Hawthorn Group in any of the three cores studied. Aragonite has been found recently within the Hawthorn Group stratigraphic section in a core drilled at Key West (Cunningham et al., 1998). Another carbonate mineral, francolite, commonly occurs in these sediments, but will be discussed separately under variations in phosphorite. The variation of the carbonate mineralogy is quite important, because significant changes in the mineralogy commonly mark sequence boundaries and aid in stratigraphic interpretation (Missimer, 1978; Missimer and Banks, 1982; Scott, 1988). Determinations

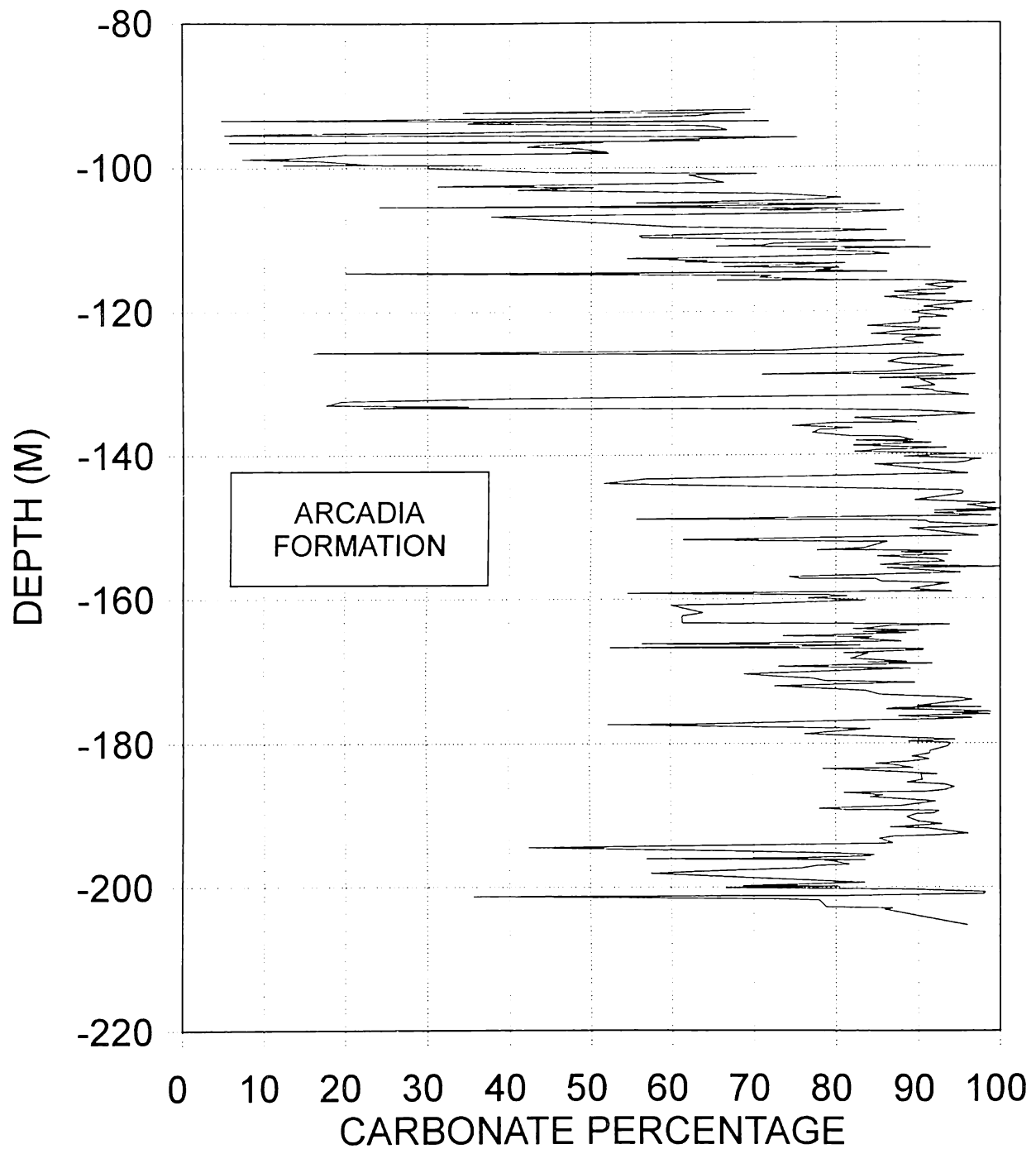


Figure 5. Variation of total carbonate percentage within the Arcadia Formation in core W-16242. Total carbonate percentage ranges from less than 5% to 100% in the Arcadia Formation. In the lower part of the formation, the lower total carbonate percentages occur at coarse sediment accumulations or at disconformities. In the upper part of the formation, the lower carbonate percentages occur in clay deposits or sandy deposits (quartz sand). The graph indicates that the composition of the formation is a mix of both carbonate and siliciclastic sediments in the entire stratigraphic section. Depths are below land surface.

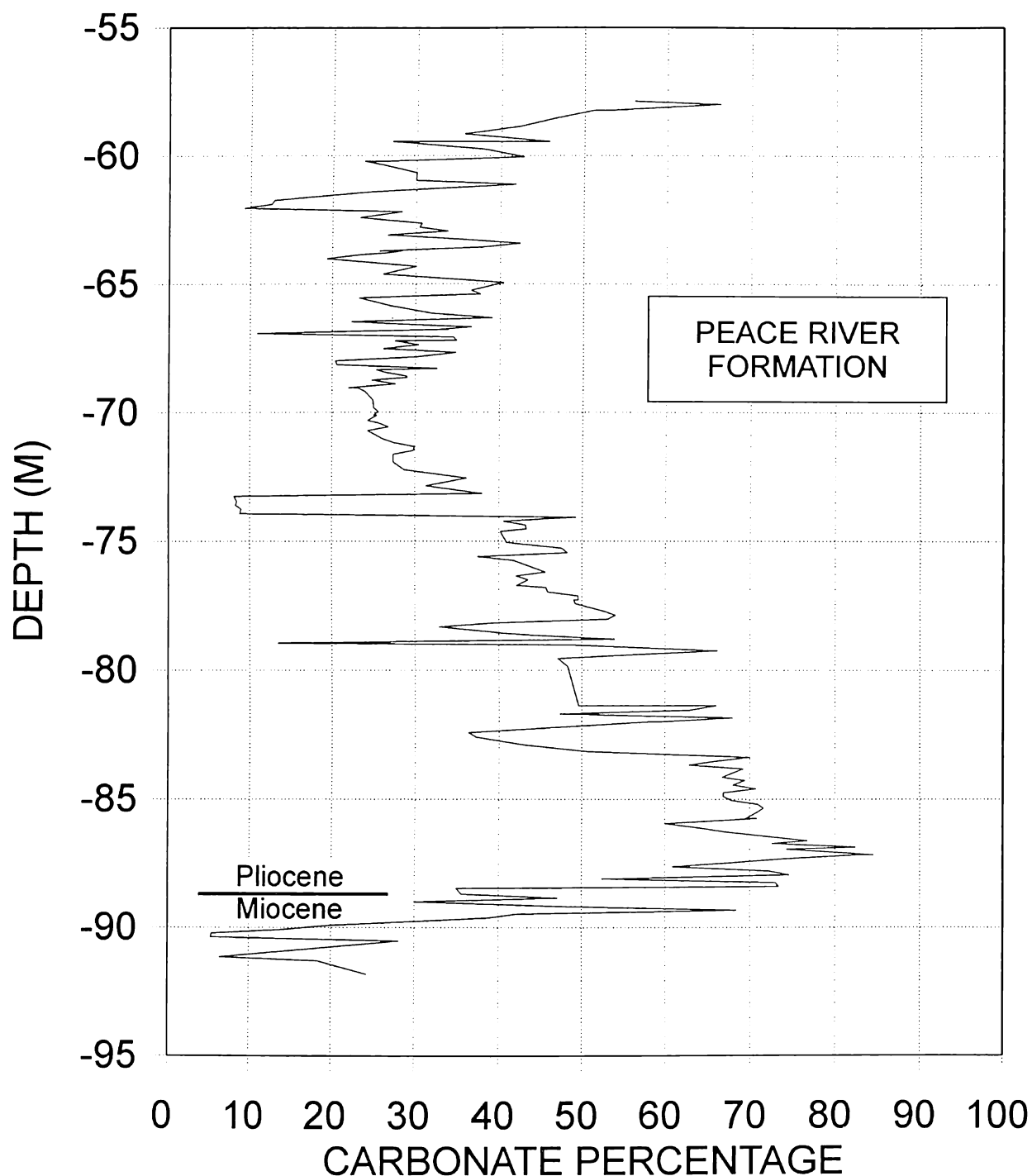


Figure 6. Variation of total carbonate percentage in the Peace River Formation in core W-16242. The total carbonate is low at the base of the formation and increases to a high at about 87 meters, then decreases to about 70 meters. In the upper 10 meters, the total carbonate varies considerably. The lower three meters of the formation is a quartz sand. The predominantly silty, angular-bedded sediments lie above the basal sand. Depths are below land surface.

of the carbonate mineralogy were made using X-ray diffraction in the fine-grained mixed sediments of the Peace River Formation in core W-16242, staining of thin sections from the Arcadia Formation in core W-16242, and by staining and application of 10% hydrochloric acid in the other cores.

Large Scale Variation in Dolomite Occurrence

Dolomite is the predominant carbonate mineral within the Hawthorn Group in North and Central Florida as well as geographic areas located immediately north of this study area (Prasad, 1985; Scott, 1988; Weedman et al., 1993; Compton et al., 1994; Brewster-Wingard et al., 1997). However, the percentage of dolomite in the Hawthorn Group decreases dramatically from north to south into the basin. Calcite is the predominant carbonate mineral within the underlying Suwannee Limestone, but dolomite does occur within specific stratigraphic intervals, particularly near the base of the formation in Collier County (see well log of CO-2318). Calcite is the predominant mineral in the sediment occurring stratigraphically above the Hawthorn Group. The occurrence of dolomite is quite rare in late Pliocene and Pleistocene sediments of southern Florida.

Variation in Carbonate Mineralogy in the Arcadia Formation

A distinctive change in the carbonate mineralogy of the Arcadia Formation occurs from the north to south across the area of investigation. Dolomite is the predominant carbonate component (64%) of the stratigraphic section in the South Seas Plantation core (Plate 1). To the south, the percentage of dolomite in the stratigraphic section reduces to only 17% in the Koreshan core and 32% in the Marco Island core (Table 3). Calcite is the predominant carbonate mineral within the Arcadia

Formation in the southern part of the study area. It occurs as primary mud, a micritic cement, a sparry cement, and as skeletal grains.

Five different types of dolomite were recognized based on textures. These dolomite types are: 1) microcrystalline dolomite (non-mimetic); 2) microcrystalline dolomite (mimetic); 3) sucrosic dolomite; 4) microsucrosic dolomite; and 5) floating rhombs. The most common dolomite type is the microsucrosic dolomite, which is fabric destructive. Commonly, dolomitization is selective with calcitic skeletal grains remaining unaltered in the dolomitized rock. In certain cases, dolomitic cements occur within primarily calcitic sediments. Dolomite rhombs commonly occur within predominantly calcitic sediments. In a few cases, hard dolomitic rocks contain borings infilled with friable calcitic mud. There is a common association between the occurrence of hard, dense, relatively thin dolomite units and the occurrence of phosphorite crusts, pyrite, and glauconite.

Variation of Carbonate Mineralogy in the Peace River Formation

Although the Peace River Formation consists largely of siliciclastic sediments with variable proportions of quartz and clay minerals, there is a significant carbonate component (Figure 6). The predominant carbonate mineral is calcite. The percentage of total carbonate ranges from 5.3 to 82.8% and averages 40.5% (Table 2). In core W-16242, dolomite is the predominant carbonate mineral at the top of the section and calcite is predominant in most of the lower section (Figures 7 and 8). The highest percentages of dolomite occur in the deltaic facies (subfacies 14) between 57.5 and 62.5 m below surface (see description of subfacies 14). The dolomite distributed throughout subfacies 14 consists mostly of silt-sized rhombs, which "float" in the

Table 3. Comparison of the calcite and dolomite occurrence in the Arcadia Formation in cores W-16242, W-16523 and W-17115 (north to south).

Core Number	Thickness of Section		Percentage Calcite ¹	Percentage Dolomite ¹
	(feet)	(meters)		
W-16242	374	114	36	64
W-16523	608.2	185.4	83	17
W-17155	518	157.9	68	32

¹ Percentage of predominant calcite and dolomite in stratigraphic section. Measurements or determinations were made by staining, direct observation, or x-ray diffraction on the entire length of each core.

mixed sediment. Based on the stratigraphic pattern of occurrence in relation to the graded beds in the upper part of the section, the dolomite appears to be hydraulically sorted. The percentage of calcite increases dramatically below the 74 m depth, which lies at a probable sequence boundary. Also, the abundance of benthic foraminifera and ostracods increases at this depth. In the lower three to four m of the section, within the Miocene siliciclastic sequence, the dolomite percentage is high in comparison to the calcite percentage. At the base of the Peace River Formation, the accuracy of the dolomite/calcite percentages is not as great because of the high percentage of francolite occurring near the disconformity with the underlying Arcadia Formation.

The occurrence of dolomite in the Miocene siliciclastic section is more common in the Marco Island core (W-17115) to the south, in which the lower part of the Peace River Formation is greatly expanded in thickness. In this core, several of the packstone and grainstone subfacies are selectively dolomitized (Plate 3). Since the principal carbonate grains within the predominantly siliciclastic sediments are skeletal grains, being mostly mollusk shells and foraminifera, much of the calcite occurs as skeletal grains with some calcitic mud

Variation in Francolite (Phosphorite) Occurrence

Francolite is the carbonate phosphorite mineral which commonly occurs throughout the stratigraphic column above the Suwannee Limestone. Some minor occurrences of blackened discontinuity surfaces, which may contain some francolite, do occur within the Suwannee Limestone. However, the occurrence of major phosphorite deposits begins in the Hawthorn Group on the South Florida Platform.

There are two types of francolite deposits observed in the cores. The most common francolite occurrence is in nodular form with peloids, some coated grains, fecal pellets, intraclasts, and skeletal grains being phosphatized. The second type of phosphorite occurrence is in the form of a crust, which commonly formed on discontinuity surfaces and on marine hardgrounds. The formation of francolite in the Hawthorn Group is described in detail by Riggs (1979a; 1979b; 1980; 1984), Compton et al. (1990), and Compton et al. (1993).

The percentage of phosphorite on the southern part of the Florida Platform is generally lower compared to the northern part of the platform. Detailed work by Compton et al. (1993) on core W-10761 (see section A-A'), showed phosphorite concentrations ranging between 0 and 100% with an average concentration within the

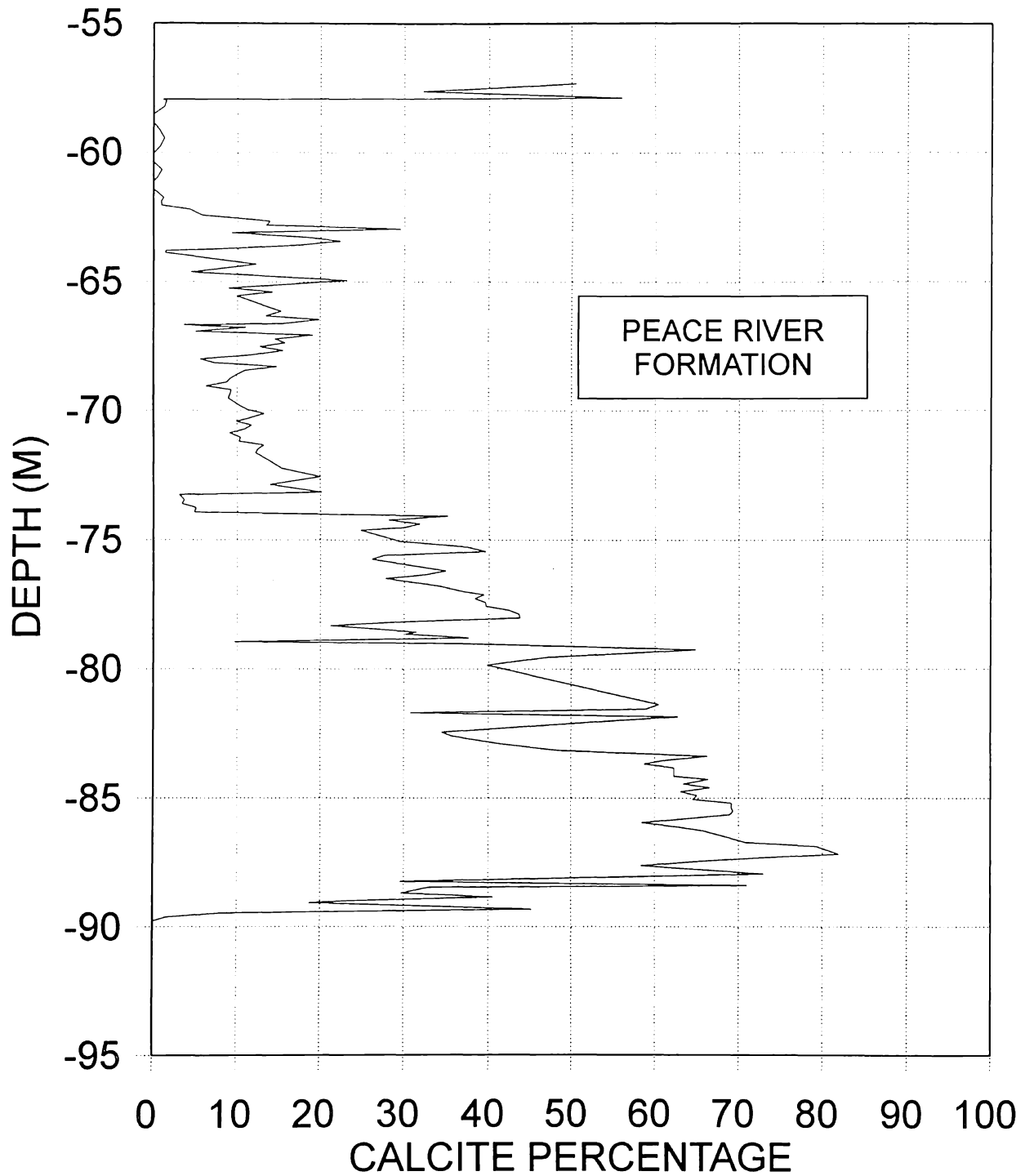


Figure 7. Calcite percentage with depth in the Peace River Formation in core W-16242. The sharply lower calcite percentages within individual beds, from about 75 meters to the base of the formation, correspond to high concentrations of quartz sand. Within the upper part of the Peace River Formation (all but lower three meters), the percentage of calcite increases with depth. The calcite is mostly silt-sized material, some mud, and some skeletal grains, mostly foraminifera and ostracods. The calcite percentage was measured using x-ray diffraction (see methods). Depths are below land surface.

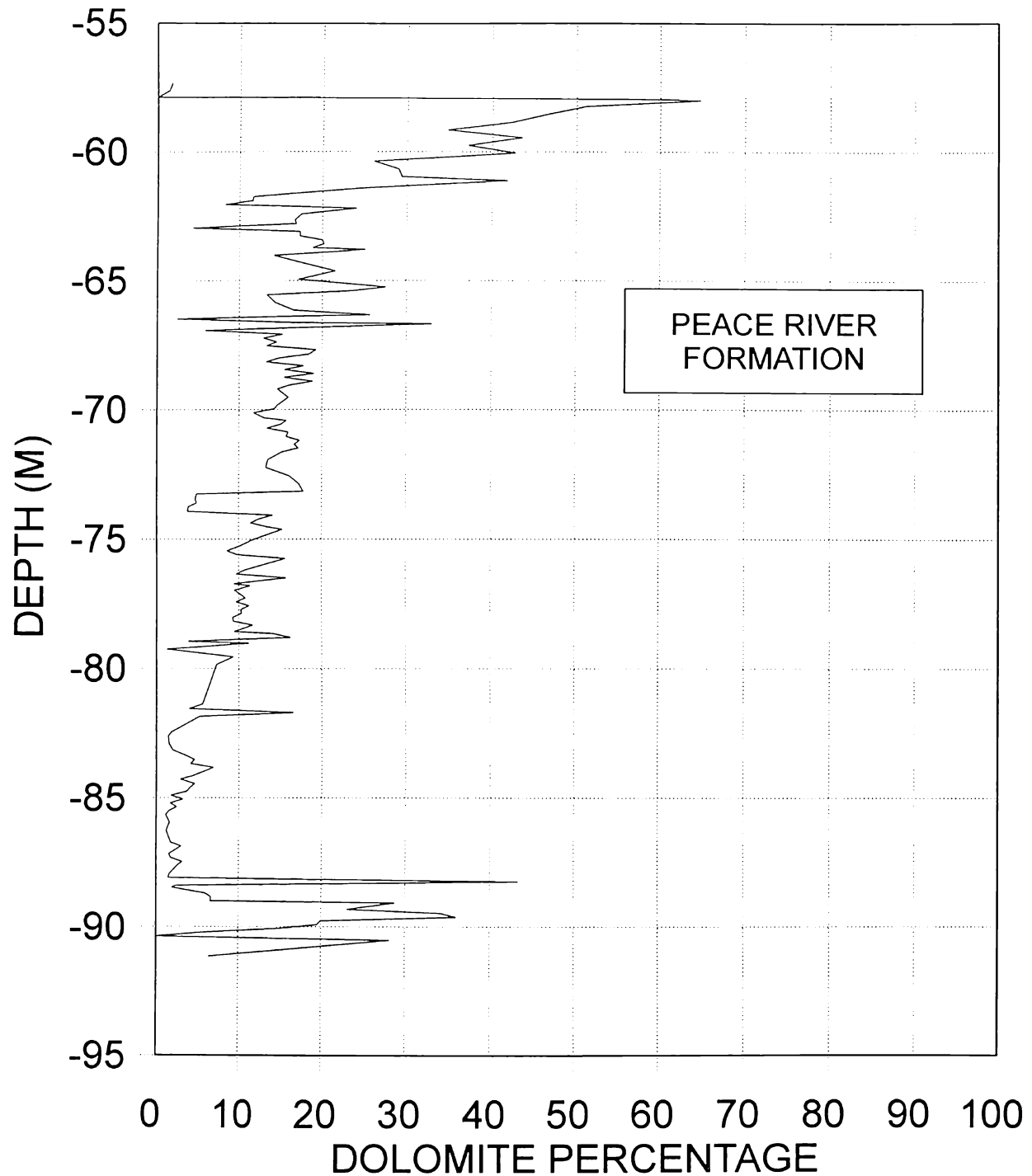


Figure 8. Dolomite percentage with depth in the Peace River Formation in core W-16242. The dolomite grains are detrital rock fragments in the lower subfacies in the lowermost three meters of the formation and exclusively silt-sized rhombs in the upper subfacies. The percentage of dolomite decreases throughout the upper part of the Peace River Formation. The dolomite percentage was measured using X-ray diffraction (see methods). Depths are below land surface.

Arcadia Formation of about 20%. It is also important to note that very little phosphorite was found in the upper part of the Peace River Formation in core W-10761. Compton et al. (1993) also found a direct correlation between natural gamma ray activity and the percentage of phosphorite. The percentage of phosphorite in cores W-16242, W-16523, and W-17115 was estimated under the microscope using visual comparison charts. A direct estimation using the gamma ray logs was not used because of recent data generated by Green (1994) who found a considerable quantity of uranium and other radioactive isotopes are contained within the bulk carbonate rock in the Hawthorn Group along with the radioactive isotopes contained within the phosphorite nodules. Therefore, direct use of the gamma ray logs for estimation purposes will tend to yield francolite percentages higher than actual occurrence.

The francolite percentage in core W-16242 ranged from 0 to 100% with an average of less than 1% in the Peace River Formation and about 10% in the Arcadia Formation (see Plate 1). The highest percentages in all cores are associated with lag deposits in the lower part of the Peace River Formation near the disconformity with the underlying Arcadia Formation and in lag deposits and primary phosphorite deposition zones within the Arcadia Formation. (Note: Primary phosphorite deposits were "crusts" within the sediments, whereas nodular phosphorite can be either primary or transported.) The francolite percentage in core W-16523 ranged from 0 to 100% with an average of about 5% in the Peace River Formation (mostly lower section) and about 7.5% in the Arcadia Formation (see Plate 2). The francolite percentage in core W-17115 ranged from 0 to 100% with an average of one to two percent (only lower section of formation) and less than 5% in the Arcadia Formation (see Plate 3). Based on the observed francolite percentages in the cores, the trend for reduced phosphorite

deposition moving from north to south on the platform continues through the area investigated.

There is a definite tendency for phosphorite lag deposits to form at discontinuity surfaces, particularly in the open marine, inner and outer ramp subfacies. Although the significant accumulations of francolite commonly mark sequence boundaries, they also occur within sequences as primary deposits and as storm lags. Therefore, the occurrence of accumulations of francolite at any stratigraphic interval must be evaluated in terms of the overall characteristics of the sediment sequence.

Although francolite formed during deposition of the Hawthorn Group, the nodules are quite resistant to weathering and the francolite nodules are reworked upward through the entire Neogene stratigraphic section. Accumulations of phosphorite nodules can also be used to help locate sequence boundaries within the younger formations, such as the Tamiami and Caloosahatchee Formations.

Non-carbonate Sediment Composition Variation

Introduction

There are three principal components of the non-carbonate portion of the Hawthorn Group sediments. These components are quartz, clay minerals, and a series of trace minerals with pyrite and glauconite being of most significance. The larger scale occurrence of the siliciclastic minerals within the predominantly carbonate Arcadia Formation is not random, but is directly related to changes in the depositional environment caused by sea-level changes. Bed-scale variations in quartz sand occurrence may be related to lag deposits or minor stratigraphic discontinuities.

There is a distinctive increase in the siliciclastic sediment percentage in the

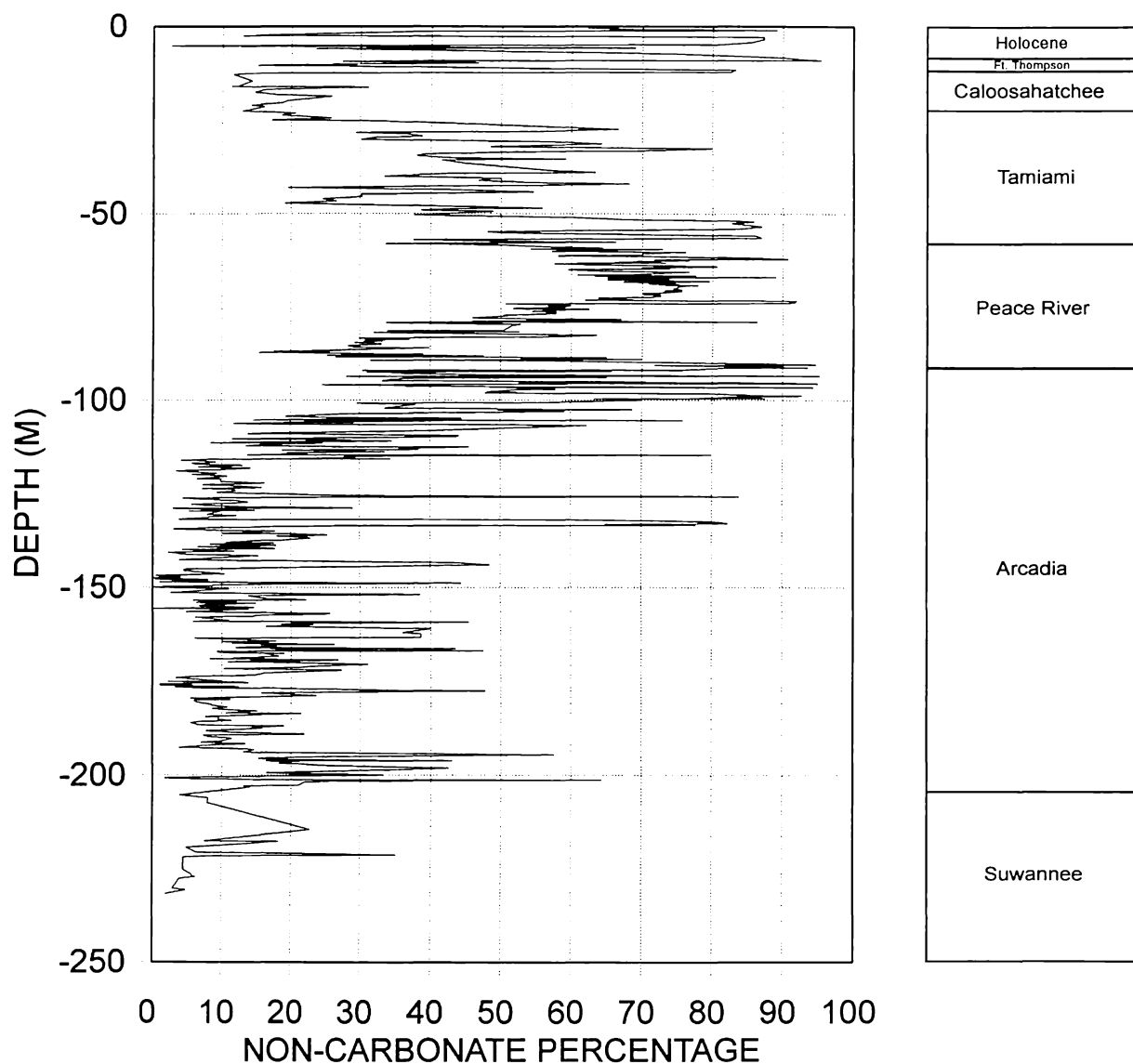


Figure 9. Non-carbonate sediment percentage with depth in core W-16242 based on 760 analyses. The age of the sediments ranges from Oligocene to the Holocene. There is a general increase in non-carbonate or siliciclastic sediment from the bottom to the top of the core. The siliciclastic component of the Caloosahatchee Formation is lower and does not follow the general trend. The non-carbonate sediment percentage was determined by subtraction of the carbonate percentage from the total. Figure 9 is the inverse of Figure 4. Depths are below land surface.

stratigraphic section moving from the Suwannee Limestone upward into the Arcadia Formation (contact at about 206 m in Figure 9), with a substantial increase in the upper Arcadia. After deposition of the Suwannee Limestone, all sediments deposited on the South Florida Platform had a significant percentage of non-carbonate sediment, which is thoroughly mixed with the carbonate component.

The non-carbonate part of the sediment in the Suwannee Limestone in core W-16242 shows a rather irregular variation, which may be a function of the small number of samples collected for analysis or may be a function of diagenesis (Figure 9). The non-carbonate portion of the sediment contains mostly very fine quartz sand with a minor quantity of terrigenous clay and another component consisting of siliceous replacement of echinoid grains.

The non-carbonate component of the sediment in the Arcadia Formation shows an increasing percentage going up-section in core W-16242 (Figure 10). Nearly 50% of the sediment in the upper 30 m of core W-16242 is non-carbonate sediment. This trend in up-section increased siliciclastic sediment deposition occurs in each of the Arcadia Formation cores.

Within the Peace River Formation, siliciclastic sediment becomes the predominant component of the stratigraphic section (Figure 11). The lower Peace River Formation sediments, below 88.5 m in Figure 11, are mostly siliciclastic deposits with compositions being nearly 100% non-carbonate in many stratigraphic intervals. In the upper part of the Peace River Formation, the siliciclastic component of the sediment ranges mostly between 70 and 80% and decreases to between 30 and 40% in the lower part of this sequence. There is a change in the overall pattern of sedimentation within the Peace River Formation from north to south with the upper subfacies becoming less significant. The fine-grained, upper subfacies thins sig-

nificantly between Captiva Island and Koreshan and does not exist in the Marco Island core. The subfacies terminates at about the Lee-Collier county line.

Variation in Quartz Sand Occurrence

Quartz sand is the primary component of the non-carbonate portion of the sediment throughout the Late Paleogene and Neogene section on the South Florida Platform. Terrigenous clays occur as thin, laminated deposits in the upper Arcadia Formation, as a minor component of the muddy carbonate deposits, and in the Peace River Formation. The percentage of quartz sand was determined for nearly every stratigraphic interval in the three cores intensely studied (see Plates 1, 2, and 3). A more detailed analysis of the quartz silt percentage of the fine-grained sediment within the Peace River Formation in core W-16242 was attempted using X-ray diffraction techniques. This analysis method was unsuccessful because the clay fraction of the sediment tended to greatly and inconsistently interfere with the intensity of the quartz peak and a calibration equation could not be developed. The quartz percentages were estimated using visual comparison charts and microscopic examination along with the total carbonate measurements (core W-16242). It is quite important to note that quartz sand and the carbonate sediment component are thoroughly mixed in each formation and within each and every depositional environment in the entire Neogene section.

The percentage of quartz sand in the Arcadia Formation generally increases in each core from the base to the top of the formation (Plates 1, 2, and 3). There is a distinctive reduction in the overall content of quartz sand within the formation from north to south moving away from sources to the north. In core W-16242, the percentage of quartz sand averages between 10 and 20% in the lower part of the formation and over 50% in the uppermost part of the for-

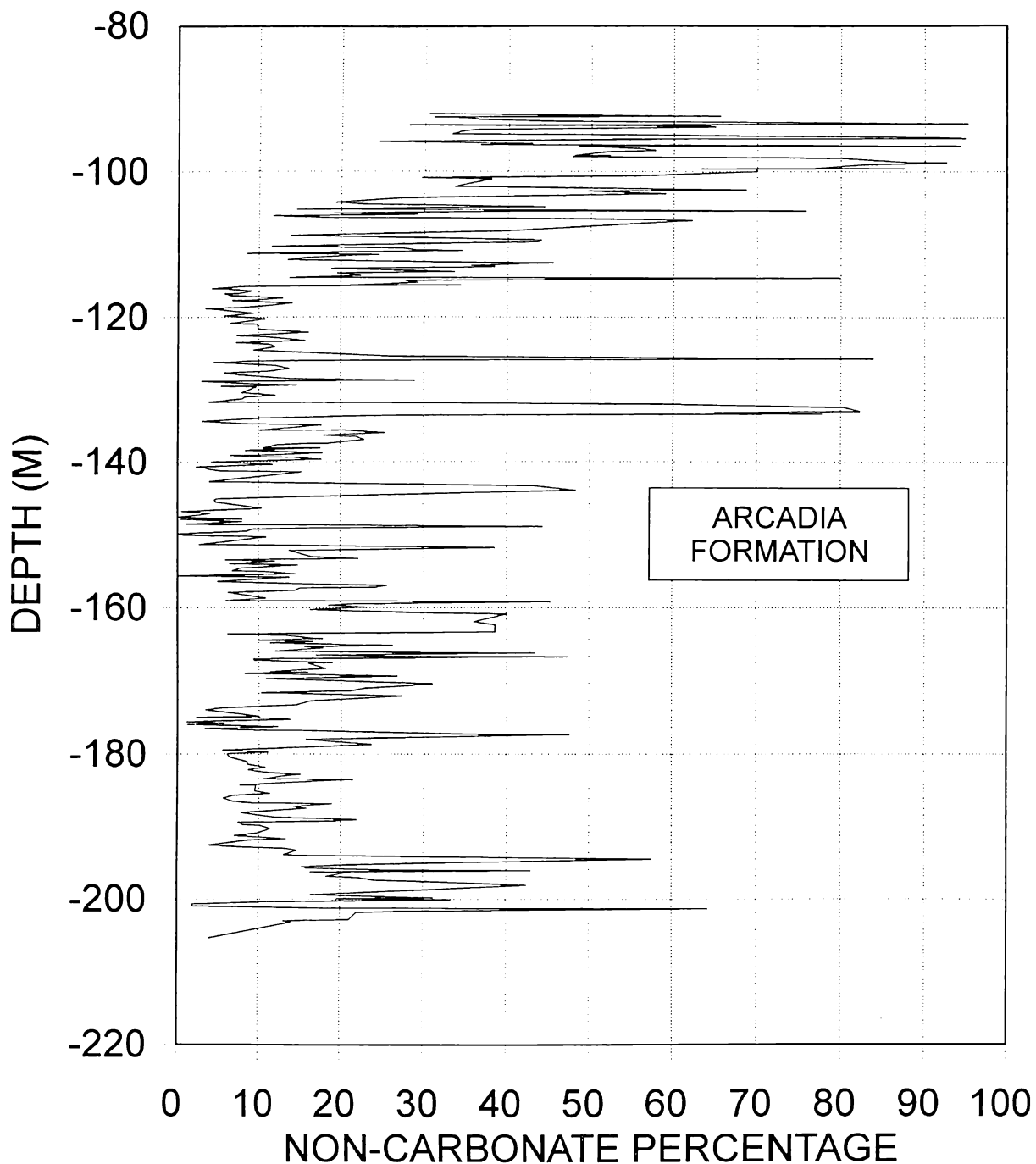


Figure 10. Non-carbonate sediment percentage with depth in the Arcadia Formation in core W-16242. . In this mixed carbonate/siliciclastic unit, there is some non-carbonate sediment in virtually all depositional environments found in the section. There is a general increase in non-carbonate sediment percentage from the bottom to the top of the formation. The spikes of high non-carbonate sediment percentage in the lower part of the formation commonly correspond to disconformities and sequence boundaries. The overall percentage of non-carbonate sediment increases abruptly in the upper Arcadia Formation at about 117 meters. Depths are below land surface.

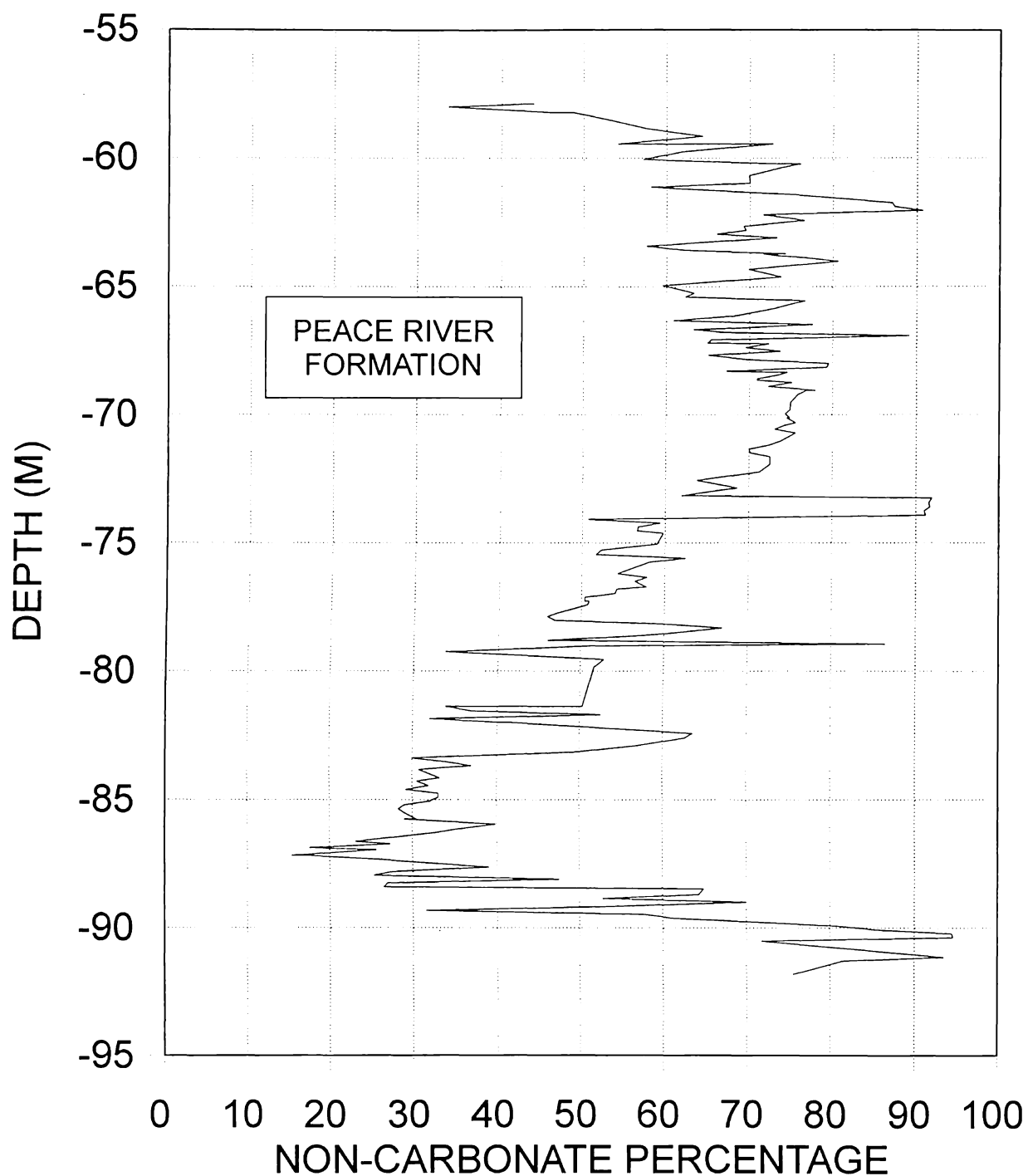


Figure 11. Non-carbonate sediment percentage with depth in the Peace River Formation in core W-16242. Note that the base of the formation has a high non-carbonate sediment percentage associated with the quartz sand section in the lowermost three meters of the core. There is a general upward increase in the non-carbonate sediment percentage within the upper subfacies. Relatively thin intervals with high non-carbonate sediment percentages are commonly quartz sand beds, for example between 73 and 74 meters. The bottom of the formation is at 91.74 meters and the top is at 57.91 meters. The non-carbonate portion of the sediment was determined by subtraction of the total carbonate measured from unity. Depths are below land surface.

mation (Plate 1). There is at least 5% quartz sand in nearly every type of depositional environment. The percentage of quartz sand is significantly lower in core W-16523 (Plate 2). In the lower part of the formation, the percentage of quartz sand averages less than 10% and there are many stratigraphic intervals, where there is only a trace of quartz sand. The overall average percentage of quartz sand is less than 20% in the upper part of the section. The percentage of quartz sand is significantly lower throughout the formation (Plate 3). In core W-17115, through the lower part of the formation, there are many stratigraphic intervals wherein only a trace of quartz sand was observed in the formation. In the upper part of the formation the overall percentage of quartz sand averages less than 5% with a few intervals having up to 25%.

The quartz-rich part of the Peace River Formation consists of a number of subfacies. The lower Peace River Formation in core W-16242 is predominantly quartz sand. In core W-16523 to the south, the lower part of the Peace River is also predominantly quartz sand with some terrigenous mud. Most of the sand deposits contain medium-to-fine grained, well-sorted quartz sand, occurring as laminated or bioturbated deposits. The lower Peace River Formation section in core W-17115 is also predominantly quartz sand. However, some of the deposits contain quartz gravel and discoid quartz pebbles.

Variation in quartz content with depth in the Peace River Formation is quite complex. Approximate percentages of quartz sand with depth in cores W-16242, W-16523, and W-17115 are shown in Plates 1, 2, and 3. The upper section contains a significant percentage of quartz, which is silt-sized along with sand-sized quartz. The highest percentage of quartz silt occurs near the top of the stratigraphic section in cores W-16242 and W-16523. Quartz sand occurs in the lower part of the beds throughout the upper part of the sequence and as lag deposits.

The percentage of quartz sand in the Tamiami, Caloosahatchee, Fort Thompson, and Holocene formations in core W-16242 was approximated by subtraction of the total carbonate measurements from unity (Figure 9). Quartz sand percentage ranges from about 5% to about 95%. The average quartz sand percent-age is over 50% in the Holocene, Fort Thompson, and Tamiami Formation sediments and is only about 20% in the Caloosahatchee Formation.

Variation in Clay Occurrence

Deposition of terrigenous clay is limited to the upper part of the Arcadia Formation, the angular-bedded subfacies in the upper part of the Peace River Formation and to a laminated subfacies occurring within the lower part of the Peace River Formation. A trace of clay was found in the outer shelf facies. The exact percentage of clay minerals within the sediments was not measured, although an attempt to quantify the relative percentages of carbonate minerals, quartz and clay was made using X-ray diffraction techniques. This method did not yield reliable data because the clay minerals interfered with the intensity of the quartz peak in an irregular manner.

The composition of clay minerals within the Hawthorn Group has been studied in considerable detail by Weaver and Beck (1977; 1982). Some work on the clay mineralogy of the subfacies showed the clays to be mostly palygorskite (attapulgitite) and montmorillonite (smectite). The clay mineralogy of the sediment sequence in the upper part of the Peace River Formation is more complex with a greater variety of clay minerals, including palygorskite, sepiolite, and montmorillonite (smectite) (Green, 1994). The mineralogy of the clays was studied by the Florida Geological Survey (X-ray diffractograms), Scott (1988), Green (1994), Peck et al. (1979b), and other inves-

tigators. A trace of feldspar was also present, but is not considered significant because only a few grains were noted in two thin sections.

Variation in Glauconite Occurrence

Glauconite occurs within the Arcadia Formation primarily as sand-sized, well-rounded grains. It also occurs as thin lenses of material that are up to 10 mm in length and about two to five mm in thickness associated with other sediment particles. The glauconite grains are light green in color and are commonly magnetic. The well-rounded grains are interpreted to be fecal pellets that have undergone verdissment, while the "lenses" may be primary glauconite or clay that has been altered. Although glauconite grains occur in a number of different depositional environments within the Arcadia Formation, the greatest abundance of grains occurs within muddy, bioturbated subfacies (Tables 4 and 5). The lenses of what may be primary glauconite occur only in the inner and outer ramp subfacies primarily in relatively deep water (see inner and outer shelf subfacies description). Using the classification of Odin and Fullager (1988), the most common grains occur in the granular habit as "1.2 Fecal grains" with some occurrences of the film habit in association with "2.2 Hardground" or "2.3 Diffuse habit." All occurrences of glauconite grains observed in the thin sections of core W-16242 are listed in Table 4.

Based on the research of Odin and Fullager (1988), the presence of glauconite commonly indicates deeper, cooler water, but with a wide distribution of latitudinal occurrences. There is some agreement with a slightly cooler water temperature when the occurrence of "primary" glauconite is compared to the oxygen isotope curve for core W-16242 (see section 3). However, the overall climate is still interpreted to be subtropical based on the flora and fauna pres-

ent in the sediments. The most abundant occurrence of glauconite does correspond closely to the maximum flooding of the South Florida Platform, which occurred in the Burdigalian and Langhian (Miocene).

COMPOSITION INFLUENCE ON INTERPRETATION OF SEDIMENT FACIES

Introduction

Hawthorn Group sediments vary greatly in composition within all scales of stratigraphic units ranging from lamination-scale to bed-scale to subfacies-scale to sequence-scale. Siliciclastic particles are completely mixed with carbonate particles in virtually each depositional environment. Therefore, the occurrence of particle types cannot be used for interpretation of depositional environment without the addition of primary sedimentary structures and the occurrences of faunal effects on the sediments, such as bioturbation. This discussion relates to depositional environments in a mixed siliciclastic/carbonate ramp model, which is the most probable geometry for the South Florida Platform (see Suwannee Limestone ramp model from Hammes, 1992).

Siliciclastic Components

Quartz

There are some general concepts that were used to interpret depositional relationships of the sediment types based on composition. Quartz sand is pervasive throughout all of the depositional environments, but the processes of transport are limited and cause specific concentrations and grain-size distributions that constrain depositional environment interpretations. Within the Hawthorn Group, quartz occurs as bedded or disseminated silt-sized particles, as bedded or disseminated sand-sized particles, and as bedded or disseminated

Table 4. Occurrence of glauconite in core W-16242
(Note: R = Rare, A = Abundant)

Depth (ft)	Depth (m)	Description of Glauconite	Abundance	Subfacies
301-304.5	91.74-92.81	Rounded size-sized grains	R	8
304.5-305.7	92.81-93.18	Rounded size-sized grains	R	4,3,1
307.5-312.3	93.73-95.19	Rounded size-sized grains	R	3
313.5-321.5	95.55-97.99	Rounded size-sized grains	R	7
326.5-327(?)	99.52-99.67	Rounded size-sized grains	R	8
349.9-362.6(?)	106.65-110.52	Rounded size-sized grains	R	8
427.5-432	130.30-131.67	Rounded size-sized grains	R	6
476-484	145.08-147.52	Rounded size-sized grains	R	10
498-503	151.79-153.31	Rounded size-sized grains	R,A ¹	10
505.8-520.5	154.17-158.65	Rounded size-sized grains	R,A ¹	10
520.5-523.5	158.65-159.56	Rounded size-sized grains	R,A ¹	8,9
523.5-533	159.56-162.46	Rounded size-sized grains	R	9
533-536.5	162.46-163.53	Rounded size-sized grains	R	9
537-540.8	163.68-164.83	Rounded size-sized grains	R	9
540.8-546	164.83-166.42	Grains & lenses (primary)	A	9,10
546.5-553.5	166.57-168.71	Grains & lenses (primary)	A	9,10
553.5-554	168.71-168.86	Rounded sand-sized grains	R	3,1
564-568	171.91-173.13	Rounded sand-sized grains	R	11
574-574.4	174.96-175.08	Coarse sand-sized grains	A	1,4
574.4-575.2	175.08-175.32	Rounded sand-sized grains	R	9
578-580	176.17-176.78	Grains & lenses (primary)	A	3
588-588.4	179.22-179.34	Rounded sand-sized grains	R	3,1
590-591.3	179.83-180.23	Rounded sand-sized grains	R	9
602.15-608.2	183.54-185.38	Rounded sand-sized grains	R	9
643.2-656	196.05-199.95	Rounded sand-sized grains	R	3,7
657.2-660.2	200.31-201.23	Rounded sand-sized grains	R	7,3

¹ Abundant grains are concentrated in thin intervals.

gravel or pebbles.

Most occurrences of quartz pebbles found in the cores studied were in either bedded units containing shell fragments, interpreted as beach deposits, near the more-prominent disconformities, interpreted as erosional concentrations, or in burrows occurring within muddy sediments, interpreted as storm transport lag deposits (similar to the skeletal deposits in burrows of Florida Bay described by Tedesco and Wanless, 1991). When gravel or pebble-sized quartz occurs in bedded sediment, the processes required to transport are limited to either stream flow or wave-generated movement on beaches. Erratic quartz pebble occurrence can occur via floating trees in tropical environments or can be the result of storm-transport into lower energy environments, such as removal from beaches into tidal flats (filling burrows).

The occurrence of concentrated quartz sand also provides some limitation on environmental interpretation. Bedded quartz sands that are reasonably well sorted occur almost excessively in beach or dune environments. The occurrence of quartz sand in the absence of primary bedding and with a mud component, whether clay or carbonate, also limits environmental interpretation based on the relative concentration of mud in the sediment. However, if the sand concentration is very high then the depositional environment interpretation is limited to either shallow shelf, or well-flushed intertidal. The interpretation of sand and mud deposits being in river channels or deltas must also be considered. In all cases, the depositional environment must be interpreted using a combination of sediment composition, sedimentary structures, and biological indicators (for example the occurrence of oysters that live exclusively in a lagoon). The definition of a subfacies cannot be based solely on the physical compositions of the sediment.

Disseminated quartz sand occurs throughout nearly every rock type in the Hawthorn Group. The occurrence of quartz

sand in relatively low concentrations bears little significance to the environmental interpretation, because it is an inert particle within a carbonate environment, and natural processes can cause transport into a very wide variety of depositional environments.

The occurrence of quartz silt presents a wide variety of interpretations that could involve several different transport mechanisms. The large-scale structure of bedding patterns and the compositional variations, in both the horizontal and vertical dimensions, bear significance in interpretation, as well as the occurrence of fauna within the sediment.

Clay

The occurrence of clay in a primarily carbonate environment is relatively rare and has distinctive implications concerning deposition environment. Continuously turbid water with suspended clay particles commonly precludes carbonate deposition, particularly in reefal settings. Bedded or laminated clay deposits can only occur where the clay particles have sufficient time to settle from the water column and are undisturbed by currents, storm activity, or bioturbation.

If the clay is mixed with carbonate sediment in thick beds without bioturbation, there is an implication that sedimentation was relatively rapid and the source of sediment was relatively close. Some typical environmental interpretations include a tropical estuarine system with considerable stream-transport of the terrigenous sediment component or an open-shelf deposit related to some type of delta. If sedimentation was not rapid, the bedding features would not be preserved because of bioturbation. The proximity to the source stream can be determined by the fossil types in the sediment, whether they are predominantly open marine or brackish-water species.

Nearly compositionally pure clay deposits occur within a mixed

siliciclastic/carbonate ramp setting only in a few depositional environments. Laminated or thinly-laminated clay deposits can be deposited and preserved only in environments such as deep lagoons and certain tidal flats. Deep, lagoonal laminated-clay deposits, in order to be preserved without substantial bioturbation, would have to either be relatively thin with preservation caused by early covering by storm deposits or be relatively anoxic, deep-water deposits containing organic matter, an environment non-conducive to benthic infauna. Tidal flat deposits containing laminated clays may or may not be bioturbated to a large degree with primary bedding destroyed based on the rate of deposition and specific environmental conditions. Special circumstances could allow bedding preservation when rapid burial occurs.

Disseminated clay does not usually occur in shallow water carbonate deposits, because of the problem of carbonate-organism productivity loss caused by water clarity reduction. The occurrence of disseminated clay in a mixed environment implies relatively calm water with sediment mixing, such as intertidal and shallow lagoonal environments with pervasive bioturbation.

The very occurrence of clay deposits in a mixed system places constraints on the environmental interpretation. Utilizing information from primary sedimentary structures (bedding types and form) and the fauna, depositional environments containing clay can be interpreted with reasonable certainty.

Other Non-Carbonate Components

There are a number of other non-carbonate grain types that occur within the Hawthorn Group that produce some, but less significant, implications concerning depositional environment. These sediment types include: glauconite, pyrite, iron oxide, and potassium feldspar.

Glauconite occurrence was discussed

earlier in the text and yields some implications for environmental setting. There are two types of glauconite grains found in sediments of the Arcadia Formation, which are sand-sized, rounded grains of "secondary" glauconite. These grains occur throughout a variety of sediment types and are transported like quartz sand and phosphorite grains of similar size. But unlike quartz and phosphorite, they can only be transported short distances because they are easily abraded. The other glauconite type is lenticular "lenses" of altered clay or "primary" glauconite. The sand-sized glauconite occurs in predominantly muddy environments within a wide range of depositional settings. The lenticular glauconite occurs primarily in wackestones containing open-shelf mollusk assemblages.

Pyrite occurs in some of the sediments containing both carbonate mud and clay and in the predominantly carbonate wackestones. The occurrence of pyrite in the sediments implies a reducing environment, which may be related to primary phosphate deposition (Compton et al., 1990). There is no specific depositional environment implication other than anoxic condition in the sediment.

Iron oxide occurrence is rare in Hawthorn Group sediments. There are several laminated crust deposits that contain some iron oxide staining of carbonate grains. The iron oxide occurrence implies some atmospheric exposure.

Within the siliciclastic sediment component, some potassium feldspar grains were identified. These grains are quite rare and only imply that a terrigenous sediment source was present. Since potassium feldspar is relatively resistant to weathering, the occurrence of a few grains bears no significance in terms of transport duration or depositional environment. Potassium feldspar has been found in northeast Florida beach sands (Martens, 1935).

Carbonate Components

Introduction

Carbonate sediment composition on a shallow ramp is controlled by hydrodynamic factors, such as currents, wave activity, and overall energy level of the environment. The principal carbonate sediment components found on the southern Florida Platform are skeletal, mud, and non-skeletal particles, such as intraclasts, phosphorite nodules, lumps, and peloids. In terms of the hydrodynamic properties of the sediments, the size and shape of the particles is affected by processes similar to the siliciclastic sediment components. The sand-sized skeletal and non-skeletal sediments occupy the same depositional environments as quartz sand. Larger skeletal particles concentrate where there is sufficient current or winnowing processes to allow transport or concentration. An exception is larger non-skeletal fragments, which can be trapped in low energy environments and may not be transported far from the point of origin. Carbonate muds are deposited in areas where there is enough time to allow sediment to settle from the water column. Some of the depositional environments for the muds are similar to clays. In terms of sediment transport, carbonate sediments differ from siliciclastic sediments in that most siliciclastic sediment components are transported onto the platform, while carbonate sediment are produced locally with a relatively short component of transport.

The mixed sediments of the Hawthorn Group are described using the classification of (Dunham, 1962). Siliciclastic sediment components are used as modifiers of the primary carbonate rock type. An example would be a sandy skeletal packstone, which is a skeletal packstone with a quartz sand component. Various descriptive schemes have been used to describe these sediment

types, but all suffer from flaws in implied interpretation. The descriptive terms used herein to identify these mixed sediments are solely descriptive, without interpretative implications. The four principal classes of carbonate sediments: grainstones, packstones, wackestones, and mudstones, all are deposited within specific depositional environments. The carbonate sediment type does bear on the interpretation of depositional environment in the Hawthorn Group.

Grainstone

Grainstones do not contain any mud and therefore are thoroughly winnowed or had no mud at the production/accumulation site. Based on the detailed description of the sediments of the Hawthorn Group, there are few examples of predominantly carbonate grainstones, while there are numerous nearly pure quartz sand deposits. Grainstones can occur on beaches, in offshore bars within a strong current regime, in dunes, in storm lag deposits, in some lagoons, and on continental slopes. Differentiation between these types of environments was accomplished by assessing the sedimentary structures within the sediment in combination with the composition, grain size, and sorting of the sediment. A thinly laminated or bedded grainstone can be interpreted as a beach deposit, a dune or an offshore bar. If the sediment is thinly laminated, nearly all sand-sized, is well-sorted, and does not contain large sediment particles, it is interpreted as a dune deposit. If the grainstone contains larger skeletal particles, some pebbles, is laminated, and well sorted, it is interpreted as a beach deposit. If the grainstone is laminated, well-sorted, predominantly sand-sized, and contains some evidence for bioturbation, it is interpreted as a bar deposit. If the grainstone is thickly-bedded, contains a variety of sand-sized and larger particles (particularly skeletal particles and phosphate nodules), and is bioturbated, it is

interpreted as a shelf deposit. The interpretation is strengthened by the occurrence of siliciclastic components. For example, if a grainstone is bedded, contains principally skeletal grains, and discoid quartz pebbles, the deposit is interpreted as a beach deposit, because it is the environment with sufficient energy to remove any mud and to transport both the skeletal sands and quartz pebbles. The identification of depositional environments in which grainstones is deposited are subject to some variation in interpretation, but the limited number of depositional environments allows greater certainty in interpretation.

Packstone

Packstones are grain-supported and contain some mud. There are a number of deposition environments on a shallow ramp that can produce packstones. These environments include: intertidal flat areas adjacent to tidal inlets (reasonably well-washed), offshore bars, nearshore seaward of beach deposits, and various types of lag deposits, including emergent storm ridge deposits within restricted water bodies and in submergent settings over broad areas of the shelf. There are also some primarily biogenic deposits that form packstones, such as certain oyster bars, Sabellarid "reef" deposits, and the *Hyotissa* deposits in the deep shelf area (Meeder, 1987). The interpretation of the depositional environments of packstones must include analyses of both sedimentary structure and the biogenic composition of the sediment.

Wackestone

Wackestones are deposited in a variety of different environments on a shallow ramp setting. The lithology is only negative evidence concerning what the depositional environment cannot be rather than what it was. Mud-supported carbonate sediments are deposited where there is sufficient time to allow mud to settle out of the

water column and where the sediment is not winnowed by wave action or strong currents. Wackestones may occur from supratidal to intertidal to lagoonal to shallow or deep open-shelf environments. In order to interpret the depositional environment of a wackestone, it is necessary to assess both the sedimentary structures contained within the sediment and the composition of the faunal assemblage.

Few of the wackestones found in the Hawthorn Group retain bedding features. Wackestones that are laminated, fine-grained, and contain some other features, such as intraclasts, are interpreted to be supratidal deposits. Wackestones having thick beds, partially bioturbated, with some quartz sand and a shallow water restricted faunal assemblage are interpreted to be intertidal deposits. Many wackestones contain oysters and interbedded terrigenous material, which is further evidence for intertidal deposition. Wackestones containing dark-colored organic material, heavy bioturbation with no distinguishable bedding, and a restricted assemblage of mollusks or other fauna and/or some grass root structures are interpreted to be lagoonal. Wackestone deposited on the open-shelf rarely contain any primary bedding features, because they are heavily bioturbated. Thicker wackestone deposits, those over one meter, that contain some packstone lag deposits must be deposited in the inner shelf where storm wave drag on the bottom sediments is a significant process. The most diagnostic feature separating inner and outer shelf wackestones is the faunal assemblage. The models used to interpret the faunal assemblage with regard to water depth are discussed later in the text.

In the mixed carbonate/siliciclastic sediments of the Hawthorn Group, the relative quantity of quartz sand can be used to simplify the interpretation between inner and outer shelf depositional environments. High percentages of quartz sand in a wackestone containing an open-shelf fau-

nal assemblage are interpreted to be an inner shelf deposit, because the sand is not likely to be transported in the deeper shelf environment. Interbedded wackestone and quartz sand deposits with an open-shelf faunal assemblage are interpreted to be inner shelf deposits. The occurrence of quartz sand and phosphorite lag deposits is most common in inner shelf deposits. Lag deposits are also observed in wackestones that are interpreted as outer shelf deposits. These deposits may represent shoaling of water during some minor sea-level change or may be the result of strong hurricane drag in deeper water. Because of the very heavy bioturbation of shelf wackestones, the bulk composition of the sediments is not a reliable indicator of depositional environment, because shallow shelf sands fill deep burrows in outer shelf deposits.

Interpretation of depositional environments of wackestone deposits is most difficult and must be based on composition, sedimentary structures, and the faunal assemblages found in the sediments. Upon completion of the interpretations of these environments, the overall stratigraphic sequence was assessed to check for obvious interpretation errors.

Mudstone

Mudstones occur within a very limited number of depositional environments in a shallow ramp setting. Nearly pure clays and mudstones accumulate where there is a minimum effect of currents and wave activity that tend to keep the fine sediment in suspension. Mudstones are deposited in lagoons, intertidal flat areas at distance from tidal inlets, or in supratidal environments. Differentiation between these depositional environments is accomplished by assessing the sedimentary structures and faunal assemblage within the sediments. All of these environments, however, share the characteristic of occurring in restricted waters.

Mudstone deposits commonly retain

bedding in the form of thin laminations or thin beds. Within the Hawthorn Group, the carbonate mudstones are commonly associated with laminated clay deposits. Where the mudstones are associated with dark-colored clays containing thin laminations, they are interpreted to be lagoonal deposits. Mudstones containing some preserved bedding, some bioturbation, and a variety of very shallow water fauna are interpreted to be intertidal deposits. Mudstones containing some preserved bedding, fenestral pore features, some small to medium-sized intraclasts, and a paucity of infauna are interpreted to be supratidal deposits.

Mudstones are also deposited in the lee of emergent land masses occurring on carbonate platforms. An example of this shelf occurrence is the mud deposits of Andros Islands in the Bahamas (Hardie, 1977). Many of these mud deposits are quite bioturbated, mixed with infauna and flora. Although some of the mudstones found within the Hawthorn Group could be interpreted to be similar to the leeward mud accumulations, the characteristics of the sediments show greater evidence of lagoon-al, intertidal, or supratidal deposition.

FAUNAL OCCURRENCE AND INTERPRETATION OF WATER DEPTH

Introduction

The faunal characteristics of mixed carbonate and siliciclastic sediment depositional patterns in Tertiary shelf deposits are not well documented. Most descriptions of faunal occurrence with water depth in a shelf setting are for predominantly carbonate environments, such as those found in the Mediterranean (Frost, 1981; Buxton and Pedley, 1989), the Arabian Gulf (Purser, 1973), and the Florida Platform (Hammes, 1992). The carbonate/siliciclastic deposits of the Holocene on the west Florida shelf are one of the few mixed sediment sequences documented (Doyle, 1979;

Doyle and Sparks, 1980).

Faunal Characteristics and Water Depth

Biological characteristics of relatively shallow water are not consistent throughout the world, because of climatic, current, and natural faunal variations. Therefore, in order to draw some comparisons between the variations in biota found within the Hawthorn Group and water depth, these characteristics must be compared to other documented faunal assemblages within the general range of climatic conditions believed to have occurred at the time these sediments were deposited.

Some of the most significant faunal assemblages that are used for comparison, include: 1) restricted-water species, 2) shallow shelf assemblages, including coral, algal, and mollusks, 3) known deep shelf species, such as some deep-water oysters, and 4) depth tolerant species, such as some families of bryozoans and mollusks. The relative abundance of various types of organisms within a sediment subfacies is also significant.

DESCRIPTION OF THE HAWTHORN GROUP SUBFACIES

Introduction

Examination of the three cores revealed a large number of microfacies based on lithic, faunal, floral composition, and sedimentary structures. The microfacies were grouped into 92 categories, but the extreme compositional variation could have allowed more than 200 categories to be described. The microfacies were then grouped into 14 primary subfacies with each subfacies being interpreted to represent a specific depositional environment based on water depth, salinity, and water movement, as controlled by wave energy and current velocities (Table 5).

Subfacies Descriptions

Introduction

Each of the 14 subfacies exhibit specific characteristics that allow them to be interpreted to have been deposited in a specific depositional environment. A summary of the characteristics of each subfacies is given in Table 5. For each subfacies, there is a list of microfacies facies types found within the subfacies with the most abundant lithic type listed first and the least abundant type listed last.

All grain types found within the subfacies are listed in order from greatest to least abundant. The matrix material is described for each subfacies in order of abundance. All sedimentary structures found within the subfacies are also listed in order of common occurrence. The subfacies are described in terms of where in the Hawthorn Group they occur and how common they are in terms of the overall stratigraphic section. In order to define some scale for the grain size of the components and the range in thickness of the unit, ranges are listed for each of these characteristics. A brief description of the characteristics of each subfacies is given to reveal the most diagnostic features. The diagnostic features considered to be most important are highlighted with bold type on the table.

Subfacies 1

Subfacies 1 consists of a series of microfacies that are either laminated, brecciated, or contain coarse grains with poor sorting. The occurrence of this subfacies is most common at stratigraphic breaks, commonly correlating with abrupt increases in the percentage of siliciclastic grain types. Occurrences of this subfacies are characteristically thin with a range from 15 to 60 cm. The most common grain type is quartz sand followed by mollusks, intraclasts, peloids, phosphate nodules, and quartz gravel. In

the predominantly carbonate portions of the Arcadia Formation (near the base), sub-facies 1 commonly occurs as a laminated crust and is often selectively dolomitized (Figure 12). Within parts of the upper Arcadia Formation, subfacies 1 is characterized by the occurrence of coarse pebble-sized phosphate nodules at boundaries between distinct changes in lithology. Subfacies 1 is one of the only subfacies types to have preserved bedding in the form of thin laminations and laminations. Although this subfacies occurs commonly throughout the stratigraphic section of the

Hawthorn Group, it constitutes only a small portion of the section.

Subfacies 2

Subfacies 2 is characterized by the overall lack of mud, the occurrence of quartz sand, gravel, and skeletal carbonates with a relatively large grain-size average diameter compared to other sediment subfacies, and the preservation of bedding with thin laminations, laminations, and cross beds. Virtually all carbonate and siliclastic grain types occur in subfacies 2

Table 5. Subfacies Type Descriptions and Microfacies Grouped within each Subfacies (Bold indicates primary features).

Subfacies No.	Subfacies 1.	Subfacies 2.
Subfacies Properties:	Brecciated and laminated packstones	Laminated sands and sandy packstones
Microfacies Types: (In order of abundance)	a. Sandy packstone (sandstone) b. Sandy brecciated packstone c. Intraclast packstone d. Brecciated packstone e. Sandy interclast packstone	a. Medium to fine-grained quartz sand b. Quartz gravel and sand c. Quartz sand and skeletal grains d. Sandy molluscan grainstone e. Sandy molluscan packstone f. Quartz pebbles and sand g. Molluscan grainstone h. Molluscan packstone
Grain Types: (in order of abundance)	Quartz sand Mollusks Intraclasts Peloids Phosphorite Nodules Quartz gravel	Quartz sand Mollusks Phosphorite nodules (peloids, intraclasts) Quartz gravel Lithoclasts Quartz pebbles Corals Red algae Bryozoans Vertebrates
Matrix:	Micrite, microspar Microsucrosic dolomite	None, micrite, sparite, microsucrosic dolomite
Size of Grains:	0.1 to 2.5cm	0.1 to 2.5cm
Sedimentary Structures: (in order of abundance)	Laminations Thin laminations Brecciation Poor sorting Sand and shell lenses	Laminations Interbedding (skeletal grains and quartz) Well sorted (no mud) Thin laminations Cross-stratification
Occurrence:	Lower Peace River Formation, Arcadia Formation (most common in lower)	Lower Peace River Formation
Thickness of Strata:	15 to 60cm	3 to 10m

Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 3.	Subfacies 4.
Subfacies Properties:	Laminated sandy mudstone/ wackestone	Quartz sand/sandy molluscan grainstone/packstone/ wackestone
Microfacies Types: (In order of abundance)	a. Sandy dolomite mudstone b. Sandy dolomite wackestone c. Sandy dolomitic, red algae wackestone d. Sandy microsucrosic dolomitic, molluscan, red algae wackestone e. Sandy intraclast, dolomitic mudstone f. Sandy intraclast, dolomitic wackestone g. Sandy calcitic, clayey molluscan wackestone h. Sandy calcitic red algae mudstone (floating dolomitic rhombs) i. Sandy calcitic, molluscan, ostracod wackestone (floating dolomite rhombs) j. Sandy calcitic, molluscan, red algae wackestone k. Sandy calcitic, molluscan, mudstone l. Sandy calcitic, molluscan, organic wackestone (floating dolomite rhombs) m. Sandy calcitic, intraclasts, phosphorite molluscan wackestone	a. Medium to fine-grained quartz sand b. Quartz sand and mollusk shell grainstone c. Quartz sand, mollusks, and intraclast grainstone d. Sandy molluscan grainstone e. Sandy molluscan packstone f. Sandy molluscan wackestone
Grain Types: (in order of abundance)	Quartz sand (medium to very fine) Phosphorite Organics Mollusks Intraclasts of mud Red Algae	Quartz sand Phosphorite Mollusks, bivalves and Gastropods Intraclasts Peloids Red algae (rare)
Matrix:	Micrite Microcrystalline dolomite Microsucrosic dolomite Carbonate mud	None, micrite, microsucrosic dolomite Carbonate mud Clay
Size of Grains:	0.04mm to 5mm	0.1 to 10mm

Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 3.	Subfacies 4.
Sedimentary Structures: (In order of abundance)	Laminations Thin laminations (algal) Intraclasts Lithoclasts/brecciation Mud cracks Burrows Fenestral pores	Burrows (mud or sand infilled) Root molds Thick beds Isolated quartz sand and shell deposits Shell beds Laminations (rare)
Occurrence:	Peace River Formation, Lower part of Arcadia Formation	Peace River Formation
Thickness of Strata:	20cm to 3m	1 to 10m

Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 5.	Subfacies 6.
Subfacies Properties:	Laminated clay	Laminated microsucrosic dolomitic mudstone/wackestone
Microfacies Types: (In order of abundance)	a. Thinly laminated clay b. Laminated dolomitic clay c. Sandy, laminated dolomitic clay	a. Microsucrosic dolomitic mudstone b. Sandy microsucrosic dolomite mudstone c. Sandy microsucrosic dolomitic wackestone d. Sandy microsucrosic dolomitic skeletal wackestone
Grain Types: (in order of abundance)	Quartz silt Dolomite (floating rhombs) Very fine quartz sand Phosphorite (very fine sand-sized) Organic material	Microsucrosic dolomite Quartz silt Very fine quartz sand Very fine phosphorite sand Red algae (sand sized grains) Mollusks (sand sized grains)
Matrix:	None, microsucrosic dolomite Clay	Microsucrosic dolomite cement Clay
Size of Components:	0.02 to 0.5mm	0.02 to 0.5mm
Sedimentary Structures: (in order of abundance)	Thin laminations Laminations Burrows (minor) Root structures (minor)	Laminations Burrows
Occurrence:	Upper Arcadia Formation	Arcadia Formation - always above subfacies 5
Thickness of Strata:	1 to 2m	1 to 3m

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Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 7.	Subfacies 8.
Subfacies Properties:	Muddy quartz sand and mollusks, muddy-sandy molluscan wackestone	Quartz sand and mollusks, muddy
Microfacies Types: (In order of abundance)	a. Muddy quartz sand, medium to fine b. Muddy quartz sand and mollusks (lagoonal species, i.e. oysters) c. Muddy-sandy molluscan wackestone (lagoonal species) d. Sandy, intraclastic molluscan wackestone e. Quartz sand f. Quartz sand and shell g. Molluscan packstone (oysters, barnacles)	a. Fine to very fine quartz sand b. Muddy quartz sand c. Muddy molluscan quartz sand d. Molluscan quartz sand e. Molluscan, red algae quartz sand f. Red algae quartz sand g. Molluscan, red algae, echinoid quartz sand
Grain Types: (in order of abundance)	Quartz sand, medium to fine Clay Dolomitic mud Mollusks (lagoon and open marine) Intraclasts Phosphorite sand and gravel Red algae (rare)	Quartz sand Quartz silt Phosphorite sand and gravel Mollusks (open-marine species) Red algae Echinoids Glauconite (detrital)
Matrix:	Micrite, microsucrosic dolomite	No cement, some clay Lime mud
Size of Grains:	0.2 to 5cm	0.04mm to 2cm
Sedimentary Structures: (in order of abundance)	Burrows Isolated sand and shell lenses or beds Thin beds (rare)	Burrows Interbedding Isolated sand and shell beds
Occurrence:	Tamiami Formation, Peace River Formation (lower)	Lower Peace River Formation, Upper Arcadia Formation
Thickness of Strata:	1.5 to 6m	1.5 to 10m

Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 9.	Subfacies 10.
Subfacies Properties:	Sandy molluscan skeletal wackestone	Sandy molluscan, echinoid, bryozoan, wackestone
Microfacies Types: (In order of abundance)	a. Sandy molluscan packstone b. Sandy molluscan wackestone c. Sandy molluscan, red algae packstone d. Sandy molluscan, red algae wackestone e. Sandy molluscan, benthic foraminiferal packstone f. Sandy molluscan, benthic foraminiferal, echinoid wackestone g. Sandy molluscan, benthic foraminiferal, red algae, echinoid wackestone h. Sandy molluscan, coralline, packstone i. Sandy molluscan, coralline, red algae, wackestone	a. Sandy molluscan, echinoid bryozoan packstone b. Sandy molluscan, echinoid, bryozoan wackestone c. Sandy molluscan, rhodolith, bryozoan wackestone d. Sandy molluscan, bryozoan wackestone e. Sandy molluscan, bryozoan, echinoid, foraminiferal wackestone f. Sandy molluscan, bryozoan, echinoid, foraminiferal packstone g. Sandy molluscan, bryozoan, echinoid, foraminiferal, red algal wackestone
Grain Types: (in order of abundance)	Mollusks (bivalves and gastropods) Quartz sand (fine to very fine grained) Phosphorite (sand-sized to gravel) Bryozoans Corals Benthic foraminifera Red algae Ostracods Green algae Glauconite (detrital) Pyrite	Mollusks Bryozoans Echinoids Phosphorite Quartz sand (fine to very fine) Benthic foraminifera Ostracods Planktonic foraminifera Glauconite (detrital and primary) Marine vertebrates
Matrix:	Micrite, sparite, microcrystalline dolomite, microsucrosic dolomite Carbonate mud	Micrite, microcrystalline (mimetic) dolomite, microsucrosic dolomite Carbonate mud
Size of Grains:	0.1 to 5cm	0.1 to 25mm
Sedimentary Structures: (in order of abundance)	Burrows Boring (into skeletal grains) Isolated sand and shell accumulations Lenses of sand in mud Thin bedding (rare)	Burrows Marine hardgrounds Lamination Thin bedding Isolated sand and shell accumulations
Occurrence:	Major facies of Arcadia Formation, Caloosahatchee Formation	Arcadia Formation
Thickness of Strata:	10cm to 15m	0.5 to 4m

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Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 11.	Subfacies 12.
Subfacies Properties:	<i>Hyotissa</i> packstone (wackestone)	Molluscan wackestone (no significant quartz sand)
Microfacies Types: (In order of abundance)	a. Sandy <i>Hyotissa</i> , molluscan wackestone b. Sandy <i>Hyotissa</i> , molluscan, bryozoan wackestone c. Sandy <i>Hyotissa</i> , molluscan packstone	a. Molluscan wackestone b. Molluscan, echinoid wackestone c. Molluscan, bryozoan wackestone d. Molluscan, foraminiferal wackestone e. Molluscan, foraminiferal packstone
Grain Types: (in order of abundance)	<i>Hyotissa</i> Quartz sand (medium to very fine) Phosphorite (sand to gravel sized) Carbonate mud Mollusks Bryozoans Glauconite	Mollusks Echinoids Bryozoans Phosphorite Quartz sand (minor, low percentage) Foraminifera (benthic and planktonic)
Matrix:	Micrite, microsucrosic dolomite	Micrite, microsucrosic dolomite Carbonate mud
Size of Grains:	0.1 to 30cm	0.04mm to 2cm
Sedimentary Structures: (In order of abundance)	Boring	Burrows Laminations (rare)
Occurrence:	Arcadia Formation (middle to upper) Tamiami Formation	Arcadia Formation
Thickness of Strata:	0.5 - 2m	0.5 - 2m

Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 13.	Subfacies 14.
Subfacies Properties:	Bryozoan wackestone (minor quartz sand)	Mixed siliciclastic/carbonate clay, graded bed
Microfacies Types: (In order of abundance)	a. Bryozoan wackestone b. Bryozoan, molluscan wackestone c. Clayey bryozoan wackestone	a. Silty mudstone b. Clayey mudstone c. Sandy, clayey, wackestone d. Sandy, clayey, foraminiferal wackestone e. Sandy, clayey, foraminiferal, ostracod wackestone f. Sandy, clayey, foraminiferal, diatom wackestone g. Clayey, foraminiferal mudstone h. Clayey, foraminiferal, diatom mudstone i. Silty, clayey, foraminiferal wackestone j. Sandy, molluscan, clayey, wackestone k. Silty, clayey, molluscan, echinoid wackestone l. Quartz sand m. Foraminiferal quartz sand
Grain Types: (In order of abundance)	Bryozoans Mollusks Phosphorite (very fine sand sized) Quartz sand (very fine, rare) Clay	Dolosilt Calcite silt Clay Quartz silt Quartz sand (medium to very fine) Benthic foraminifera Mollusks Phosphorite (fine sand-sized) Planktonic foraminifera Diatoms Echinoids Glauconite (rare, detrital)
Matrix:	Microsucrosic dolomite Carbonate mud	Microcrystalline dolomite (rare), microsucrosic dolomite (rare), mostly uncemented
Size of Grains:	0.04 to 10mm	0.04mm to 3cm

Table 5. (Cont.) Subfacies Type Descriptions and Microfacies grouped within each subfacies.

Subfacies No.	Subfacies 13.	Subfacies 14.
Sedimentary Structures: (in order of abundance)	Burrows Laminations (rare)	Angular bed (thick) Graded beds Thin bedding Laminations Thin laminations Isolated sand and shell deposits
Occurrence:	Arcadia Formation	Peace River Formation
Thickness of Strata:	1 to 2m	0.5 to 1.5m

with all grains being at least sand-sized. The most common grain types are quartz sand and mollusks. In most cases, the quartz sand component is well-sorted (Figure 13). The overall size of grains ranges up to 2.5 cm, which is the size of some discoid quartz pebbles and mollusk shell fragments.

This subfacies commonly occurs in the lower part of the Peace River Formation, particularly in core W-17115 (Macro Island), where it constitutes about 25% of the section. The thickness of subfacies 2 occurrence ranges from three to 10 m. It rarely occurs in the Arcadia Formation and does not constitute a significant part of that formation.

Subfacies 3

Subfacies 3 is a fine-grained deposit containing a variety of preserved sedimentary structures, including laminations, thin laminations with organic material, intraclasts, lithoclasts associated with a brecciated texture, mud cracks, burrows, and some fenestral pores (Figure 14). Extreme variation in composition cause a very large number of microfacies types to occur within

relatively thin stratigraphic intervals. The predominant grain type is carbonate mud with a variety of minor grain types, including quartz sand, intraclasts, phosphorite nodules, mollusk fragments, and red algae.

This subfacies commonly occurs at, or immediately below, strati-graphic discontinuities. The subfacies is commonly dolomitized, sometimes selectivity between calcitic subfacies. Subfacies 3 occurs in the Peace River Formation (lower section) and is quite common in the lower section of the Arcadia Formation. It constitutes only a few percent of the lower Peace River Formation section and about 5% of the lower Arcadia Formation section. Thickness of occurrence range from 20 cm to three meters.

Subfacies 4

Subfacies 4 is a predominantly siliciclastic deposit containing wide variations in mud content. Bedding is preserved, and is relatively thick (10 to 20 cm). All deposits are burrowed to some degree, even in locations where bedding is preserved (Figure 15). In a few locations, laminations

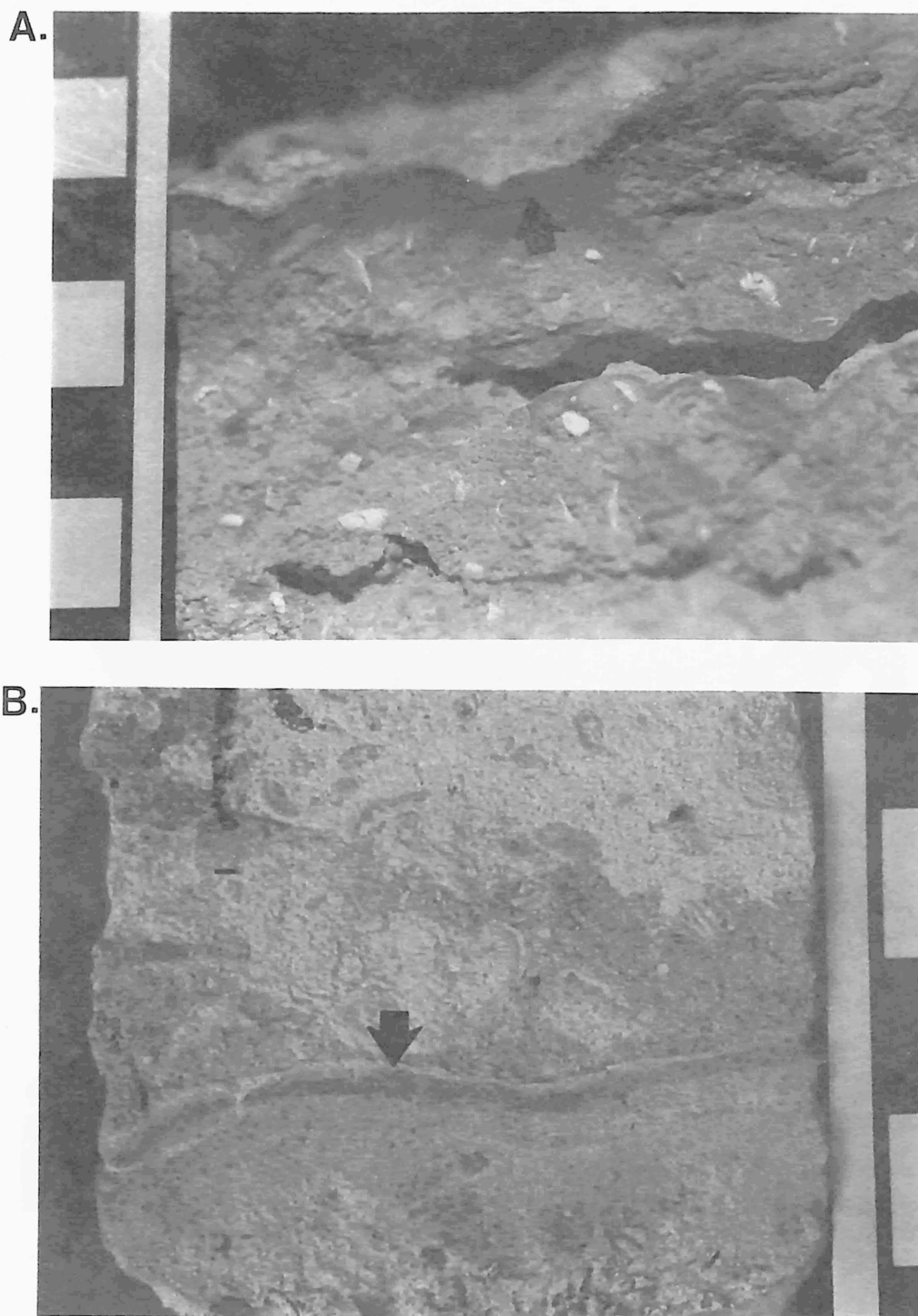


Figure 12. Subfacies 1. Discontinuity deposits within the Hawthorn Group.

A. A duracrust or calcrete deposit in an outcrop of the Late Pleistocene Fort Thompson Formation in Lee County, Florida. Note the thin laminations and the general conformance of the crust to the underlying microtopography. (Scale in centimeters)

B. Laminated crust (arrow) from the Arcadia Formation in core W-17115 at a depth of 257.16 to 257.22 meters (843.7 to 843.9 ft). Note the thin laminations and the conformance of the crust to the underlying microtopography. In this case, the fine-grained crust lies upon a wackestone with a coarser texture. Laminated, dolomitized crusts ranging between 5 and 10 cm in thickness are particularly common in the lower part of the Arcadia Formation in core W-17115. (Scale in centimeters).

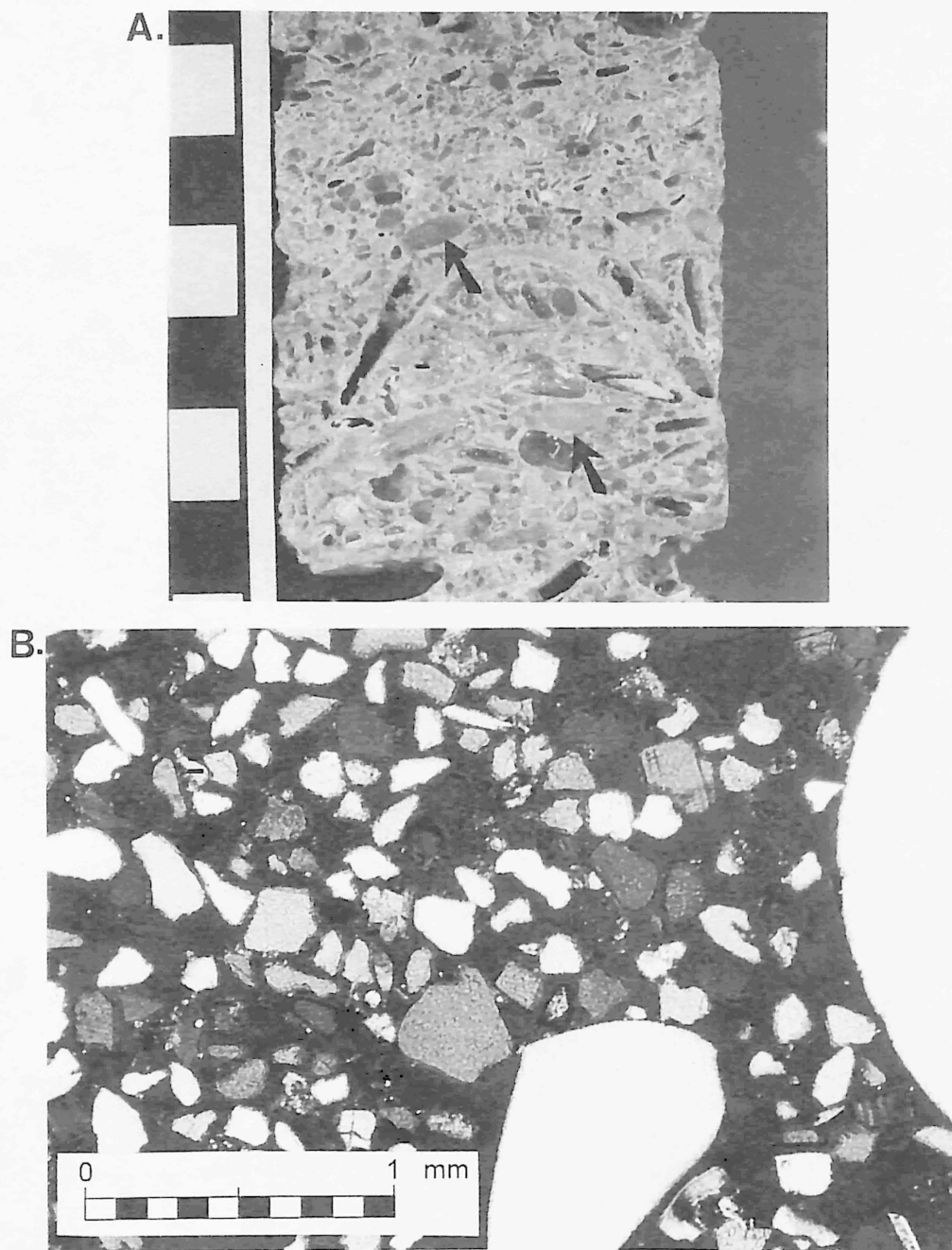


Figure 13. Subfacies 2. Quartz sand and shell deposits in the Peace River Formation in core W-17115

A. Quartz sand and discoïd pebbles with skeletal carbonate fragments from core W-17115 at a depth of 59.22 to 59.34 meters (194.3 to 194.7 ft). The sediment is cemented with sparry calcite. There is no carbonate mud in the rock. Some discoïd pebbles are marked with arrows. The scale at the side is in centimeters.

B. Example of an unlithified quartz sand deposit (grain mount) containing discoïd quartz pebbles from 73.15 to 74.68 meters (240 to 245 ft) in core W-17115. This sand deposit is devoid of mud and skeletal carbonates. The core recovery is poor in this interval because the lack of mud gives the sediment little cohesion, allowing the sediment to wash from the core barrel. The sand is well-sorted and medium to fine-grained.

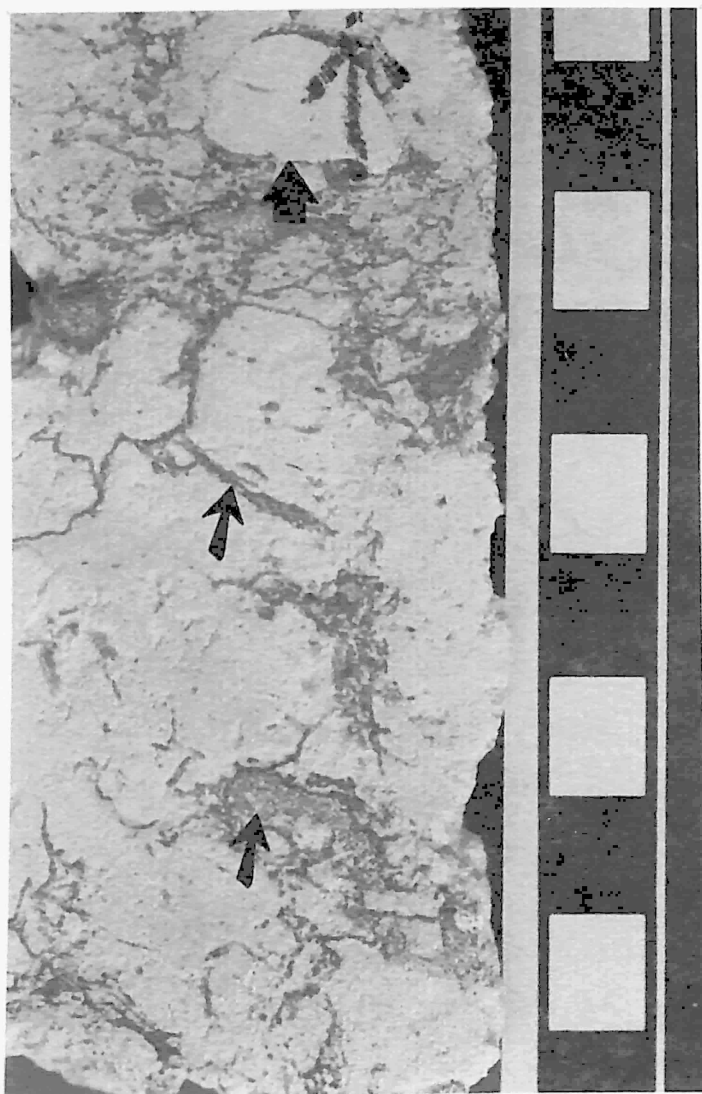


Figure 14. Subfacies 3. Example of brecciated texture in subfacies 3 from core W-17115 at a depth of 236.77 to 236.86 m (776.8 to 777.1 ft). Brecciated textures are common in the subfacies along with some fenestral pores and mudcracks infilled with sparry calcite and some sediment. The sediment is predominantly a fine-grained carbonate mud. In this case, the voids between the brecciated clast are filled with sparry calcite (small arrows). Subrounded clasts (large arrow) are common near the top of brecciated layers. (Scale in centimeters)



Figure 15. Subfacies 4. Intertidal mixed siliciclastic/carbonate deposits from Estero Bay, Florida and an example of subfacies 4 from the Peace River Formation.

A. Holocene mixed siliciclastic/carbonate sand deposit from an intertidal flat area located immediately north of New Pass at Estero Bay on the southwest coast of Florida. Note the thick and thin laminations. Larger-scale bedding is relatively thick at over 10 cm. The deposit is bioturbated, but primary bedding is still preserved to some degree. Dark colored laminations occur within the sand and are organic deposits. A variety of thin-walled mollusks are mixed with the quartz sand. Intraclasts are common in this environment.

B. An example of subfacies 4 from core W-16523 at 36 m (118 ft) below surface in the Peace River Formation. In core W-16523, subfacies 4 shows some preservation of laminations, but most preserved bedding is relatively thick and alternates between clean, fine quartz sand and muddy quartz sand. Also, the muddy sand tends to have few, if any, laminations preserved, because of extensive bioturbation. Some organic staining is present, but is distorted by either bioturbation or perhaps by the coring process. (Scale in centimeters)

are preserved in lithologies lacking mud. Root molds and a variety of course-grained (lag) deposits occur within the subfacies. Subfacies 4 occurs exclusively in the Peace River Formation, most commonly in the lower section. It constitutes up to 15% of the section.

Subfacies 5

Subfacies 5 is a laminated clay occurring exclusively in the upper part of the Arcadia Formation. The predominant grain type is clay with minor occurrences of quartz silt and sand, dolosilt, and sand-sized phosphorite grains. The clay, commonly is very darkly colored, nearly black (Figure 16). It lacks preserved skeletal carbonate grains. In some cases, the laminated clays are burrowed to a minor degree and some apparent root structures are preserved. Subfacies 5 always grades upward into subfacies 6. It constitutes a minor portion of the upper Arcadia Formation (less than 2%) in the northern part of the study area and does not occur in core W-17115.

Subfacies 6

Subfacies 6 is a laminated, microsucrosic dolomitic mudstone/wackestone. Subfacies 6 always occurs associated with subfacies 5, normally stratigraphically above it. The transition between subfacies 5 and 6 is usually gradational, but in some cases the laminated clays of subfacies 5 are brecciated at the contact (Figure 17). These dolomitic mudstones and wackestones are very fine-grained with the predominant particle type being microsucrosic dolomite. A variety of other particle types occur as mostly floating grains that include quartz silt, very fine sand-sized quartz sand and phosphorite, and sand-sized red algae and mollusk shell fragments. Subfacies 6 is commonly laminated with the laminations sometimes disturbed by burrows. The thickness of deposits ranges from one to

three m and this subfacies constitutes only to 2% of the Arcadia Formation.

Subfacies 7

Subfacies 7 is a muddy quartz sand and mollusk deposit or a clayey/sandy molluscan wackestone. Variations in composition are rather extreme, but some sedimentary structures are preserved. Subfacies 7 is similar to subfacies 4 in composition, but it contains significantly more mud, the preserved bedding is thinner, the degree of bioturbation is greater, the occurrence of intraclasts is greater, and the mollusk assemblage is different. Fine quartz sand is the predominant particle type with lime mud and clay being the next most abundant particle types. A variety of other particle types occur within the deposit, including mollusks, intraclasts, sand and gravel-sized phosphorite nodules, and a few red algae grains. The matrix mud is commonly dolomitic or a mix of dolomite and clay. This subfacies occurs in the Tamiami Formation and in the lower Peace River Formation. The thickness of occurrences ranges from 1.5 to six m and constitute up to 10% of the lower Peace River Formation.

Subfacies 8

Subfacies 8 is an unlithified (in most cases) muddy quartz sand with mollusks and other skeletal grains (Figure 18). The predominant characteristics are the lack of preserved bedding, very heavy bioturbation, some percentage of mud throughout the section, and interbedded wackestone and coarse sand and shell containing no mud. The predominant biogenic particle type is mollusks with some red algae and echinoid fragments. Carbonate mud occurs in most of the sediment with some clay also present. Some deposits of coarse shell and quartz sand also occur within subfacies 8. These coarse deposits contain no significant quantity of mud or clay. Detrital grains of glauconite occur, but represent an insignif-

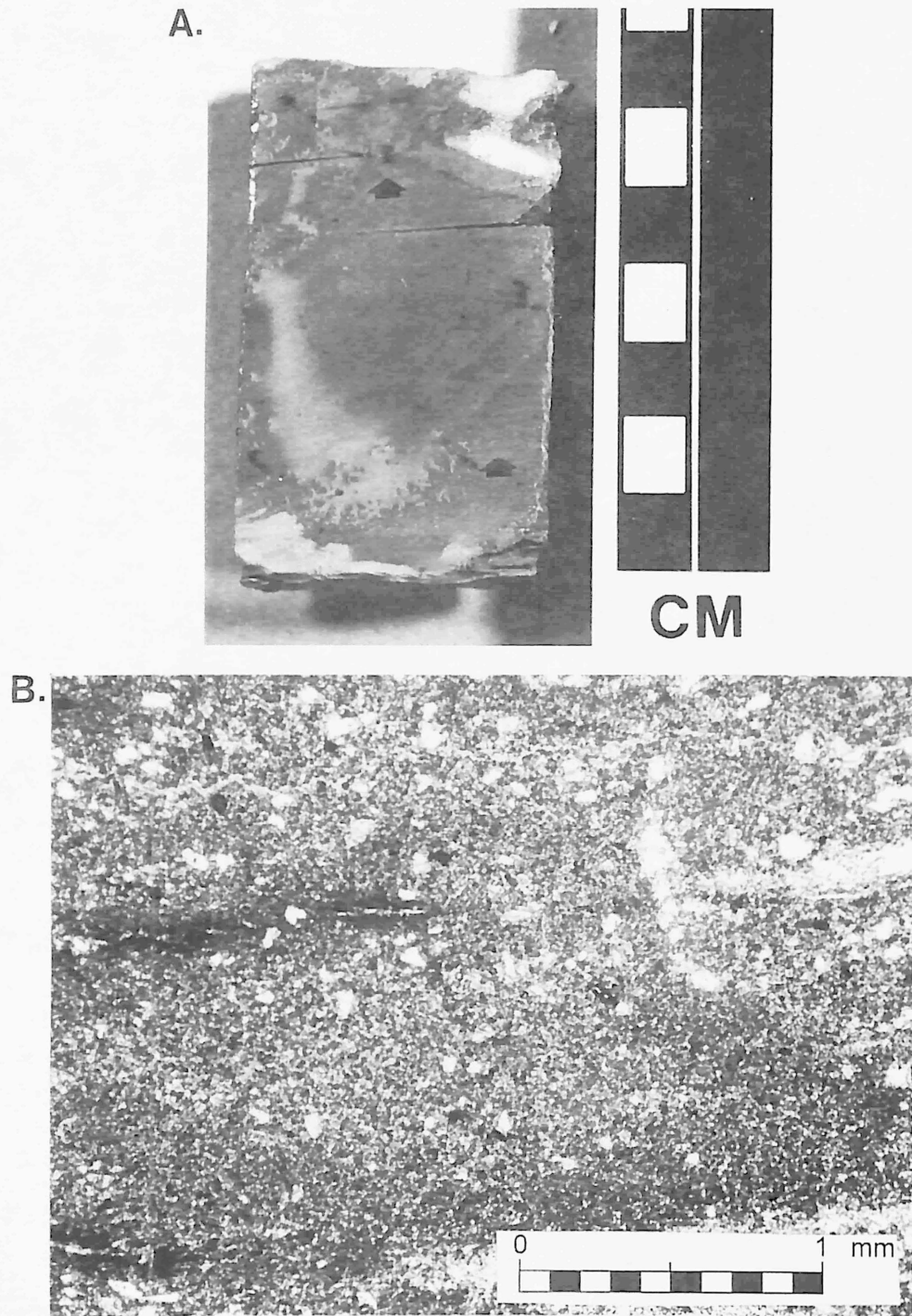


Figure 16. Subfacies 5. Laminated terrigenous clay.

A. Core W-16242 between 133.11 and 133.20 m (436.7 to 437 ft). Some burrows infilled with the overlying carbonate sediment occur at the top of the core. The laminations are 1 and 5 mm in thickness (arrows mark some laminations). The color of the clay is dark green.

B. Thin section from 133.5 m (438 ft) in core W-16242. Note the lack of skeletal carbonate fragments and quartz sand or silt. Some of the clay is very dark in color and appears nearly opaque in the thin section. This dark-colored material is commonly thin and lenticular. It is believed to be organic material or remnant organic staining. The lighted-colored streaks mark the base of some laminations.

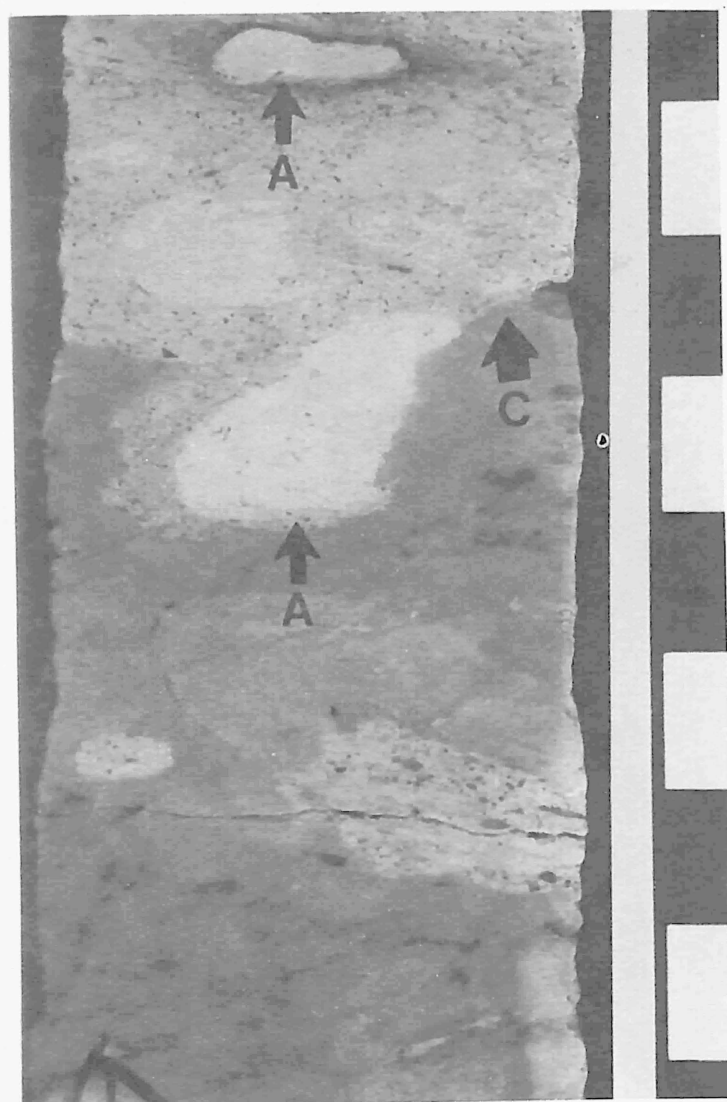


Figure 17. Subfacies 6. Example of subfacies 6 in core W-16242 from a depth of 131 to 133.5 meters. Contact between subfacies 5, a clay deposit, and subfacies 6, a carbonate mud deposit, in core W-16242 is between 131 and 132.0 meters (429.8 to 433 ft). The actual contact occurs at the arrow labelled as "C" and clay is mixed into the overlying carbonate sediment. Within this section, the deposit is laminated. The base of subfacies 6 is burrowed (arrows labelled "A"). Note the very fine-grained texture of the carbonate. (Scale in centimeters).

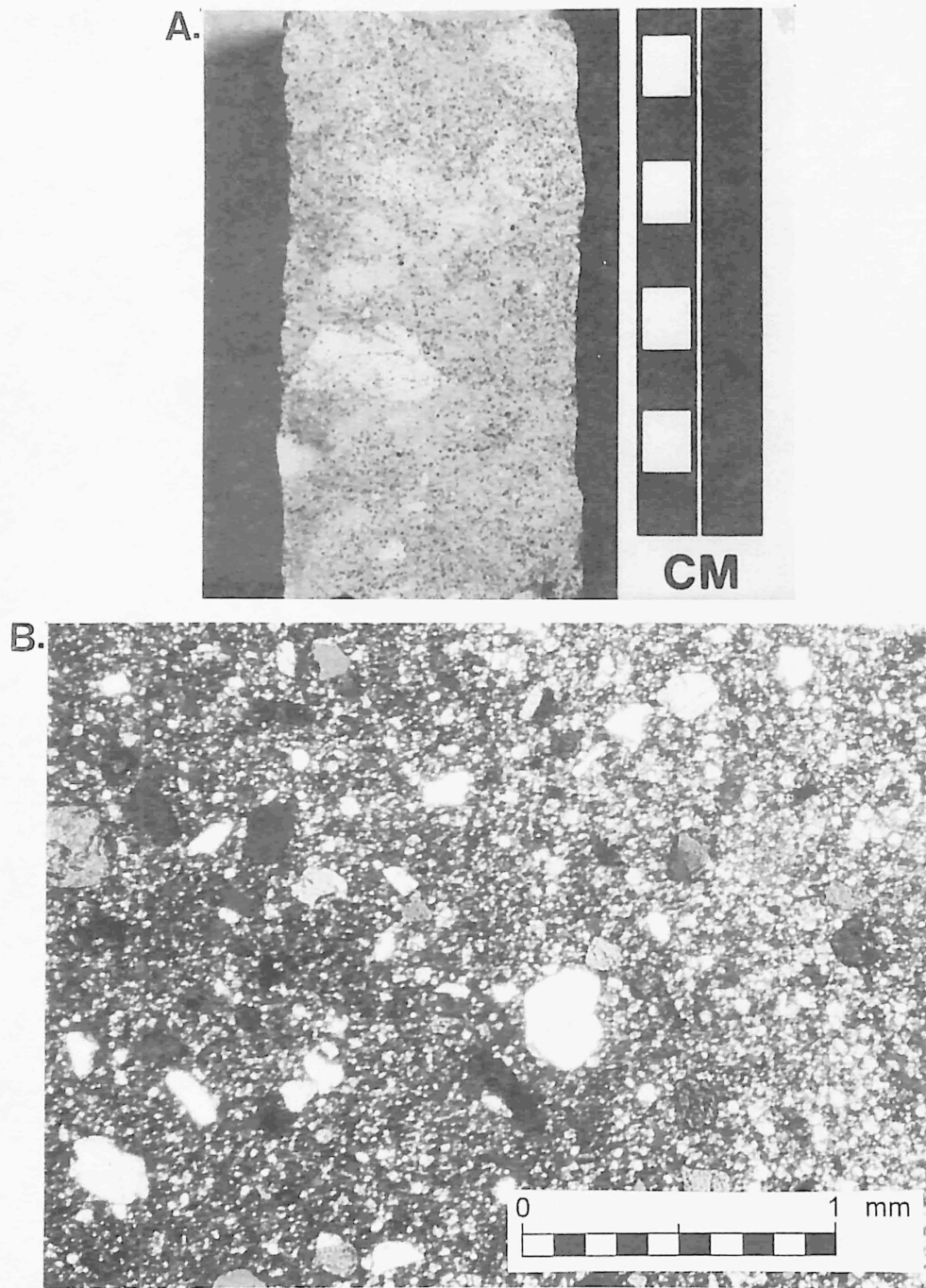


Figure 18. Subfacies 8 in the Arcadia Formation.

A. Segment of core between 160.63 and 160.75 meters (527 to 527.4 ft.). Note the mottled texture and the "salt and pepper" appearance, caused by the mixture of quartz sand and dark-colored phosphorite sand. (Scale in centimeters)

B. Fine to very fine quartz sand and sand-sized phosphate in a matrix of carbonate mud from the Arcadia Formation from 159.87 to 159.96 meters (524.5 to 524.8 ft). Thin section in plain light from 159.87 m (524.5 ft) in core W-16242. Note the relatively abundant percentage of quartz sand and sand-sized phosphate nodules. The large concentration of sand-sized sediment and the relatively large thickness of these deposits (in many cases over 5 meters) is an indication of nearshore sediment transport. The deposit contains significant quantities of carbonate mud. Note that there is no grading and the distribution of grains appears to be random, also an indicator of heavy reworking.

icant percentage of the sediment composition.

Subfacies 8 occurs within the lower Peace River Formation and in the upper part of the Arcadia Formation. It constitutes a significant part of the lower Peace River Formation stratigraphic section, up to 35%. It is also a significant subfacies in the upper part of the Arcadia Formation, particularly in the northern part of the study area (core W-16242), where it constitutes up to 15% of the section.

Subfacies 9

Subfacies 9 consists of a number of microfacies types, but the predominant lithology is sandy molluscan wackestone (Figure 19). The most significant characteristics of subfacies 9 are the high degree of bioturbation, the lack of preserved bedding, the large diversity of biogenic grain types, the presence of quartz sand in significant abundance, and the presence of carbonate mud. The most abundant particle type is carbonate mud, much of which is dolomitized. Quartz sand and phosphorite nodules are dispersed throughout this subfacies. Glauconite and pyrite grains are commonly found in the middle section of the Arcadia Formation. In the lower part of the Arcadia Formation, a wide variety of biogenic components occur, with mollusks and corals being quite common (Figure 19). In this part of the section, the predominant wackestones commonly contain molluscan and coralline packstones and numerous other grain types are common. In the middle and upper part of the Arcadia Formation, the skeletal grain components are predominantly mollusks with occurrences of many other flora and fauna. Although subfacies 9 is heavily bioturbated, there are some rare occurrences of thin bedding. Burrows are commonly infilled with coarser sediment and shell, and sand

beds lacking mud are present. Some phosphatic crusts occur within subfacies 9, commonly at discontinuities. Subfacies 9 occurs throughout the Arcadia Formation and is the most common subfacies, constituting up to 45% of the formation at a given location.

Subfacies 10

Subfacies 10 is a sandy, molluscan, echinoid, bryozoan wackestone. It contains a variety of other microfacies types when viewed on a smaller scale. The subfacies is heavily bioturbated with bedding rarely preserved. The predominant grain type found in the sediment is carbonate mud. In many ways, subfacies 10 is similar to subfacies 9, but there are some significant differences, which are: the abundance of quartz sand is lower, the predominant biogenic grain types are mollusks, echinoids, and bryozoans commonly similar in abundance, the percentage of skeletal grains in the matrix mud is often lower, the range of grain sizes of particles is smaller, and no corals or green algae are found in this subfacies (Figure 20). Skeletal grain deposits lacking mud are not common, but still are present. Although some bedding is preserved, it is rare and is thin or lamination (less than one cm in thickness) in scale. Subfacies 10 occurs predominantly in the upper and middle parts of the Arcadia Formation, where it constitutes up to 30% of the section at a given location.

Subfacies 11

Subfacies 11 is a *Hyotissa* packstone or wackestone. The predominant feature of this subfacies is the abundant occurrence of the genus *Hyotissa*, which is a large, oyster-like mollusk. These mollusks are quite large, ranging up to 30 cm in height and are commonly found in a matrix of carbonate mud or quartz sand (Figure 21). Other molluscan species and bryozoans occur in

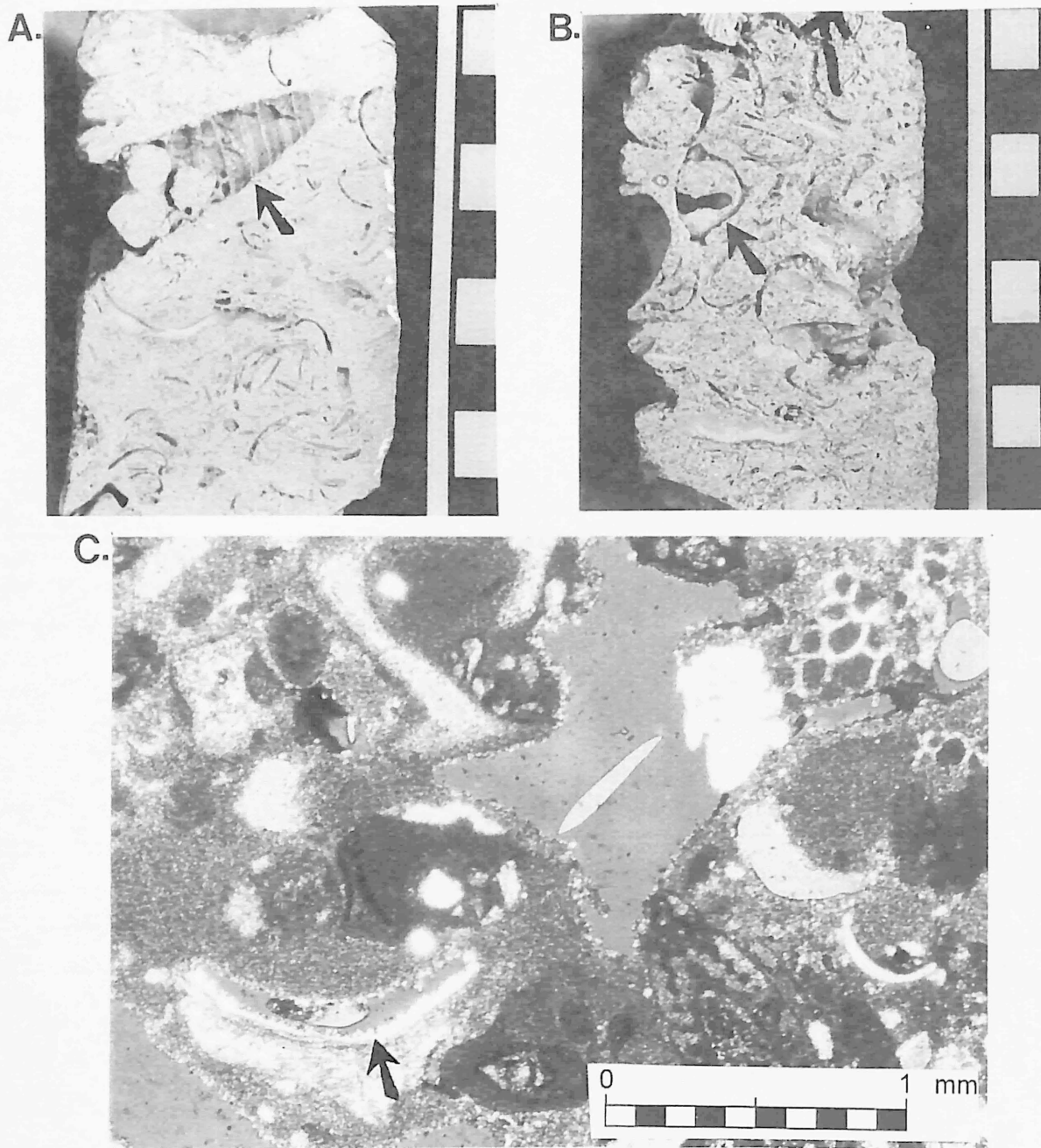


Figure 19. Examples of subfacies 9 in core W-16242.

A. A sandy molluscan wackestone from 191.63 to 191.72 meters showing molds of gastropods and bivalves. The arrow points to a *Turritella* sp., which commonly lives in a shallow, open-marine environment. (Scale in centimeters)

B. A sandy molluscan wackestone/packstone from 190.8 to 190.9 meters. The lower arrow points to a shell fragment from the genus *Yoldia* sp. and the upper arrow to a mold of a *Cyprea* sp. Other common mollusks occurring in subfacies 9 include *Chione* sp. and various different mollusks believed to occupy the shallow, open-marine environment. These mollusks commonly occur in 1 to 10 meters of water in an open shelf environment (Parker, 1956). Arrow at upper edge of core is for up orientation. (Scale in centimeters)

C. Thin section from 186.5 m (611.9 ft.) showing a sandy molluscan packstone/wackestone in plain light. Note the large number of mollusk grains (selectively dissolved - molds remaining). Arrow to dissolved mollusk.

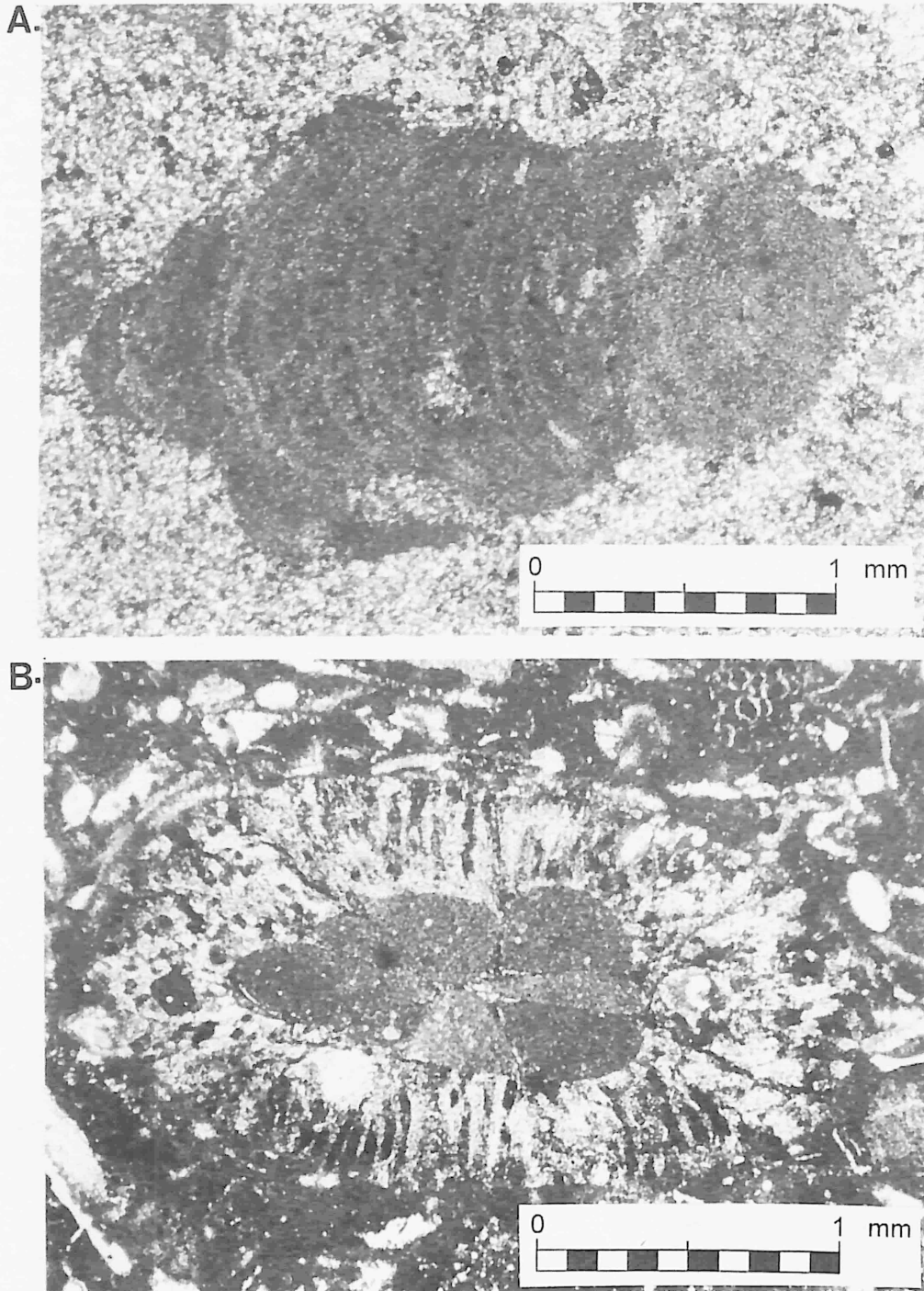


Figure 20. Examples of subfacies 10 from the Arcadia Formation in core W-16242.

A. Thin section from 155.75 meters (511 ft) in polarized light. The lithology is a red algae/bryozoan wackestone. Red algae oncolites occur below a depth of 85 meters or on rocky shoreline (Wilson, 1975). The occurrence of the red algal oncolites in the fine-grained matrix is distinctive evidence for a deep-water environment.

B. Example of the bryozoan *Cyclostomata* from the Arcadia Formation in core W-16242. This genera of bryozoan has good tolerance to water depths of over 100 meters. Although it is common in relatively deep water, it also occurs in some shallow water deposits to near wave base. Therefore, it is not an absolute deep water indicator, but when found in abundance with other features of the sediment, such as no quartz sand and other deep water tolerant mollusks, it is considered to be an auxiliary depth indicator. From 139.08 meters (456.3 ft) in core W-16242 in plain light.

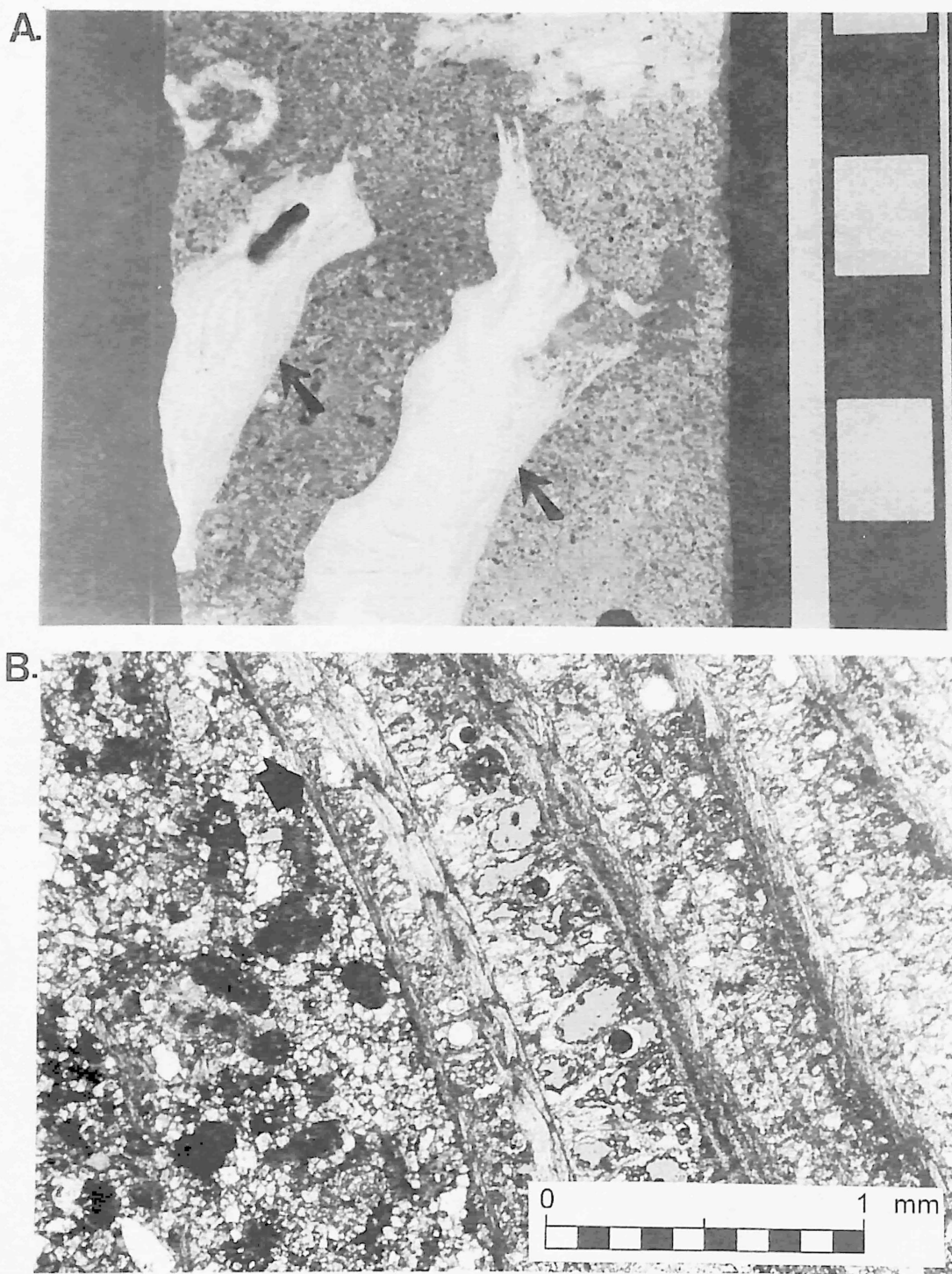


Figure 21. Subfacies 11. Examples of the relatively deep water mollusk *Hyotissa* subfacies from the Arcadia Formation in core W-16242.

A. *Hyotissa* subfacies example from the Arcadia Formation in core W-16242 between 126.7 and 126 meters (415.6 and 416 ft). Note that the *Hyotissa* are in growth position (vertical orientation) in the lower part of the core sample. The sediment between shells is a quartz-rich carbonate mud. *Hyotissa* are marked by arrows. (Scale in centimeters)

B. Thin section from 126.7 meters (415.6 ft) in core W-16242 (field width is 16.20 mm). Note that the *Hyotissa* shell can be porous (arrow) and commonly contains sediment incorporated into it, such as sand-sized phosphorite grains.

the sediments. In many cases, the *Hyotissa* shells are found in living position and are heavily bored by other marine organisms. This subfacies is common in the Tamiami Formation and occurs in the upper and middle part of the Arcadia Formation, where it constitutes a minor part of the stratigraphic section (a few percent).

Subfacies 12

Subfacies 12 is a molluscan wackestone lacking significant concentrations of quartz sand. It occurs predominantly in the southern part of the study area within only the Arcadia Formation (core W-17115). The predominant grain type is carbonate mud with significant quantities of mollusks and some echinoids and bryozoans (Figure 22). Minor quantities of phosphorite, fine quartz sand, and benthic and planktonic foraminifera also occur in the sediment. The sediment is extensively bioturbated, but some laminations are preserved. The concentration of skeletal grains is lower compared to subfacies 9 and the sediment can be described as moderated to lightly packed (relatively lower abundance of skeletal grains) wackestone. Subfacies 12 constitutes only about three to five percent of the Arcadia Formation section and is most significant in the middle of the formation.

Subfacies 13

Subfacies 13 is quite similar to subfacies 12, but the dominant skeletal grain contained in the sediment is bryozoans (Figure 22). This subfacies also occurs only within the Arcadia Formation in the southern part of the study area (core W-17115). The most significant characteristics of this subfacies are a lack of preserved bedding caused by extensive bioturbation, the moderate to slight packing of skeletal grains, and the relatively low abundance of quartz sand. Where quartz sand and phosphorite occur in the sediment, they are fine sand-

sized. Some clay occurs within this subfacies. A few preserved laminations occur, but are truncated by burrows.

Subfacies 14

Subfacies 14 occurs solely within the Peace River Formation. This subfacies is characterized by extremely wide variations in composition, preserved, thick angular beds (Figure 23), graded beds (Figure 24), some preserved thin beds and laminations, and intermittent coarse sand and shell beds lacking mud. The unit is rarely bioturbated. A large number of grain types occur within the formation. The predominant grain types are dolosilt, calcite silt, clay, and quartz silt and sand. The abundance of these constituents varies within the unit as a whole and within beds (see composition section). Within the thick beds, foraminifera and diatoms are commonly abundant with some mollusk and echinoid fragments occurring at the base of beds. Sand-sized phosphorite grains are common throughout the unit and a few grains of glauconite occur. The unit rarely contains any significant quantities of cement. Previous studies showed that the dolosilt grains had sharp edges and showed little pitting (Green, 1994). This unit constitutes all of the upper part of the Peace River Formation in the northern part of the study area, but it pinches out from north to south and does not occur in core W-17115.

INTERPRETATION OF SUBFACIES

Introduction

Sediment composition, sedimentary structures, faunal and floral assemblages and stratigraphic succession were used to interpret the sediment subfacies. The described subfacies are interpreted to be within five general categories. These general groups include: 1) emergent or discontinuity deposits, 2) restricted shallow water, including supratidal, intertidal, and

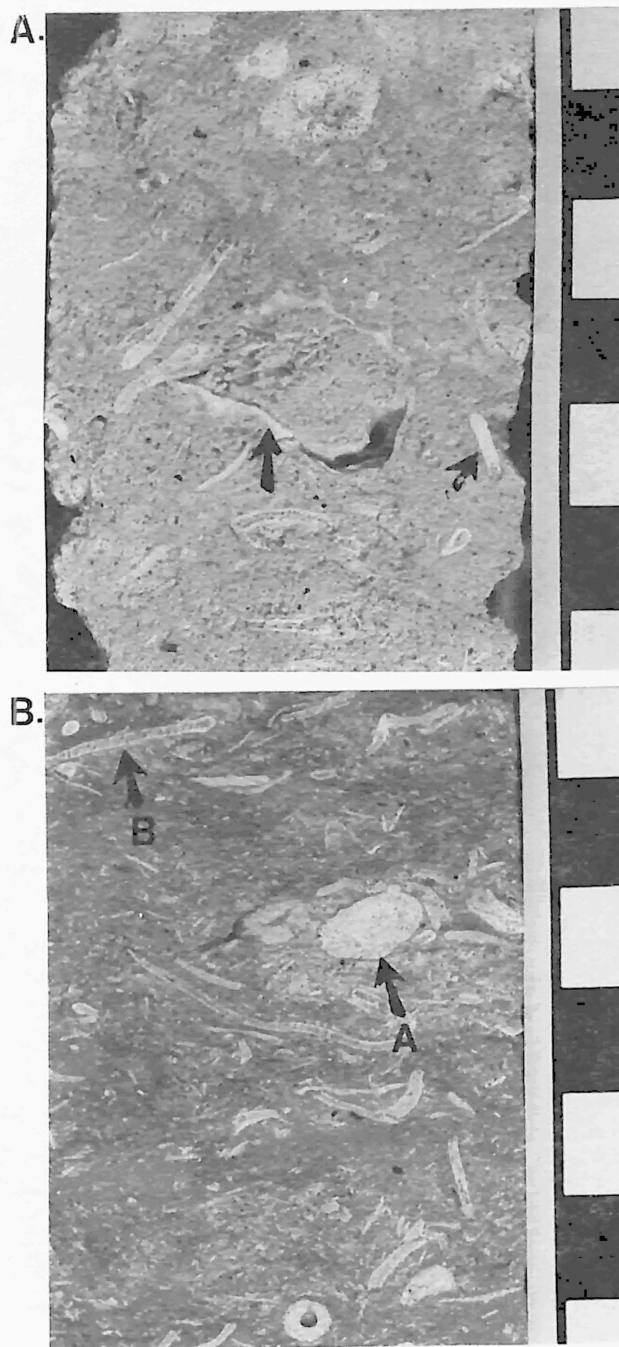


Figure 22. Examples of subfacies 12 and 13 from the Arcadia Formation in core W-17115 (bar scales are 1 cm increments).

A. Example of subfacies 12 from core W-17115 between 195.38 and 195.53 meters (641 and 641.5 ft). This molluscan wackestone contains no significant quantity of quartz and the density of biota within the sediment is quite low. Mollusks are the predominant fauna (marked by arrows). (Scale in centimeters)

B. Example of subfacies 13 from core W-17115 between 197.66 and 197.82 meters (648.5 and 649 ft). The biota in this subfacies are virtually all bryozoa with a few mollusks. The matrix sediment is carbonate mud with no quartz sand and a minimal quantity of phosphorite. The arrow marked "A" points to a stem of a tubular bryozoan. The arrow marked "B" points to a flat, platy branching bryozoan, which is another genus. (Scale in centimeters)

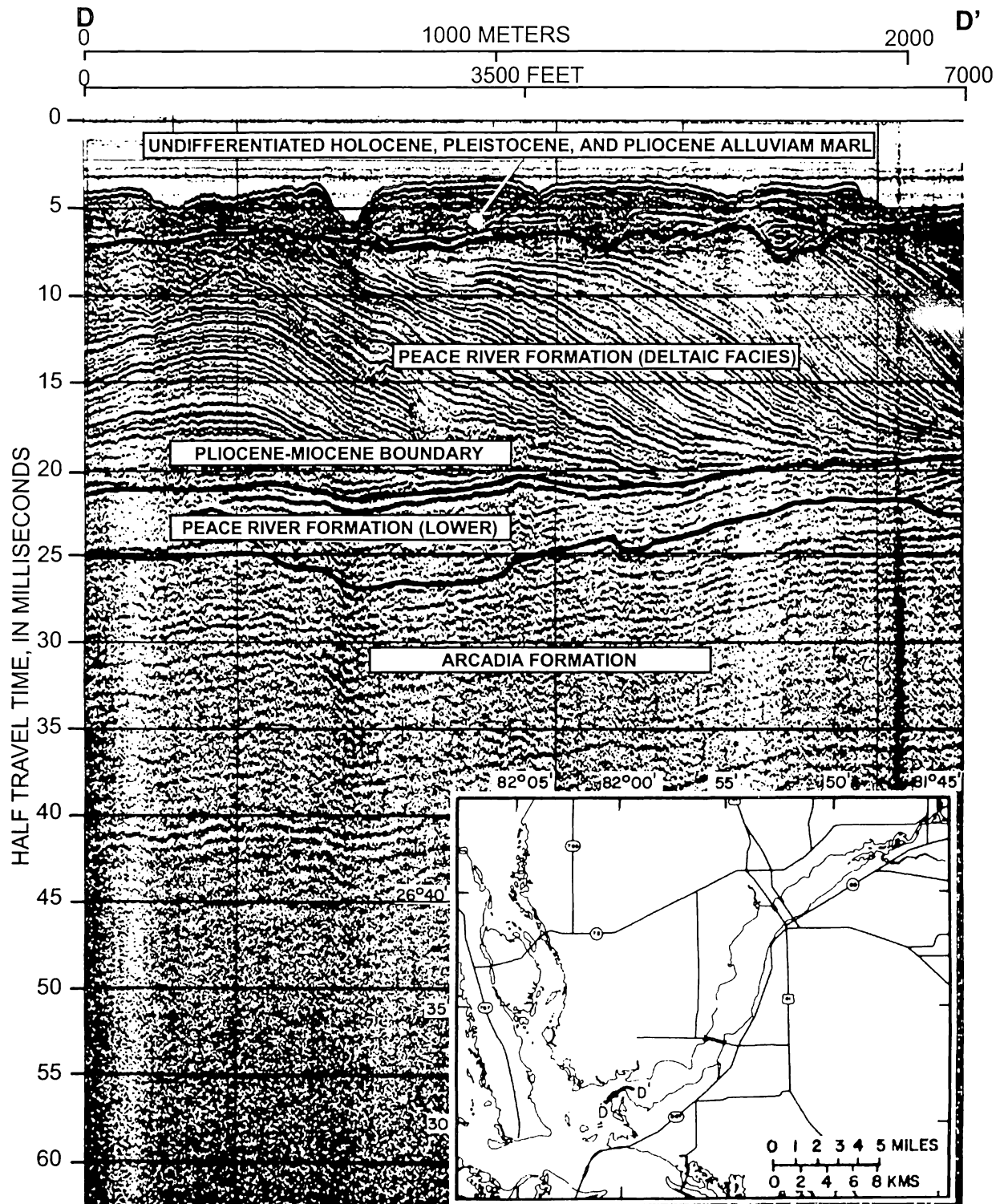


Figure 23. High-resolution seismic reflection profile (modified boomer source) in the Caloosahatchee River illustrating subfacies 14, labelled as Peace River Formation (deltaic facies). Profile modified from Missimer and Gardner (1976). Note the large-scale angular bedding in the upper Peace River Formation. The bedding is flat-lying in the lower Peace River Formation and the disconformity between the Arcadia Formation and Peace River Formation shows some erosion features (truncated reflectors).

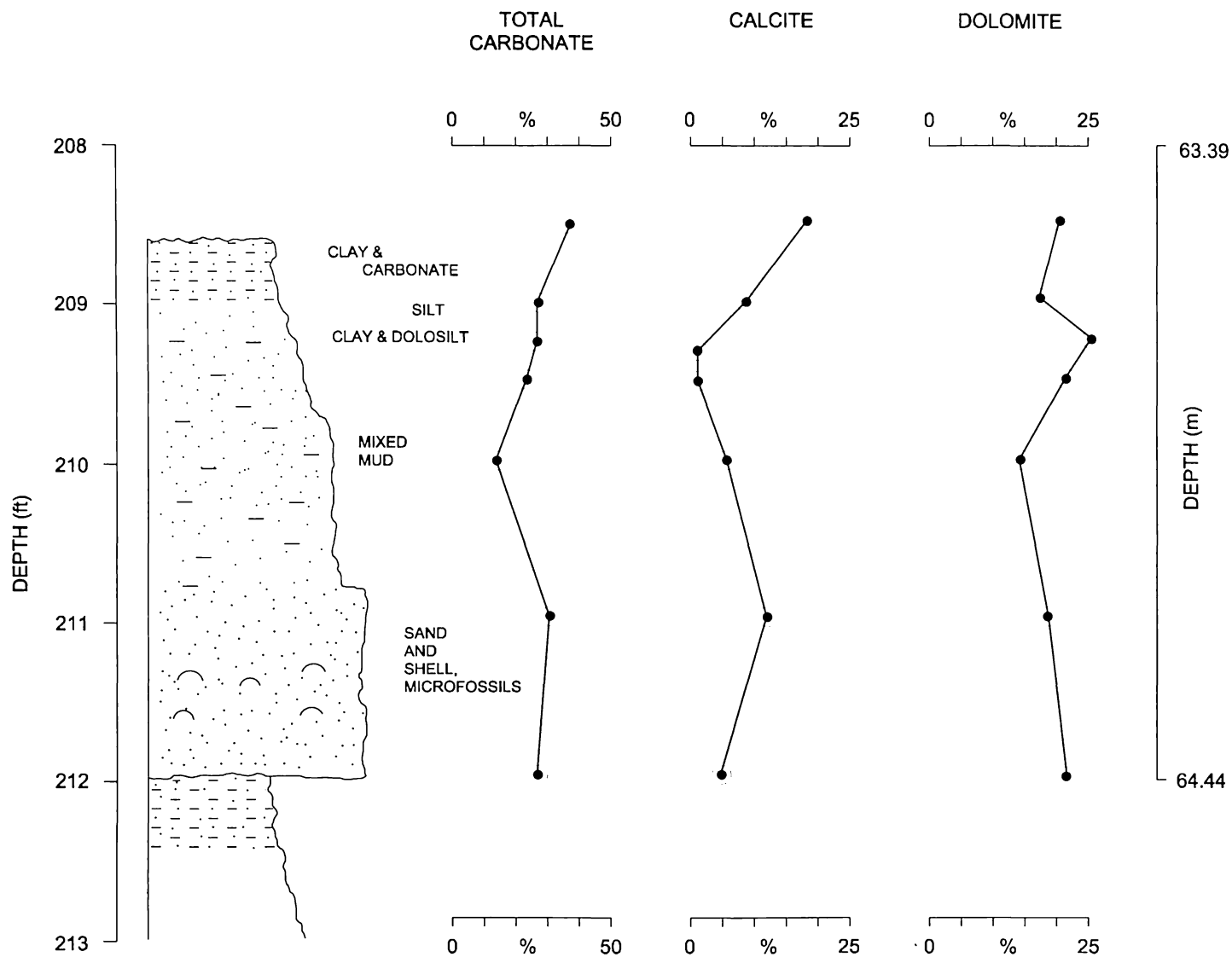


Figure 24. Diagram showing a typical graded bed sequence in the Peace River Formation in core W-16242 from a depth of 208 to 213 feet (63.39 to 64.44 meters). There are many graded beds in subfacies 14, particularly within the upper 5 to 10 meters of section at many localities. Depths are below land surface.

lagoon deposits, 3) beach and nearshore deposits, 4) shallow ramp, including carbonate, siliciclastic, and mixed deposits, and 5) deep ramp, including mixed carbonate and siliciclastic deposits. It is important to note that quartz sand occurs in virtually all depositional environments from shallow to deep with the exception of the laminated clay deposits (subfacies 5) and within sections of a few slightly-packed wackestone subfacies (subfacies 12 and 13). The diagnostic features most important in the interpretation of the subfacies are shown in bold type within Table 5.

Discontinuity Deposits, Subfacies 1

A number of probable discontinuity horizons (described as subfacies 1) are present in the Arcadia Formation and some within the Peace River Formation. These features are noted on Plates 1, 2, and 3 and in the rock data matrices. There are two general types of features that are interpreted to be exposure horizons or discontinuity deposits found within subfacies 1, subfacies 3, and subfacies 6, and one or two additional deposits found in subfacies 9 and 10.

The first type of discontinuity surface is a laminated to thinly laminated crust consisting of quartz sand and carbonate cemented by either micrite or dolomite. These crusts are relatively thin, ranging in thickness from two to 10 cm, and occur only at stratigraphic breaks between two different subfacies, usually atop a shallow-water deposit. The laminated crusts do not have a uniform thickness and laminated sediments sometimes infill apparent karstic features within the underlying sediment. The crusts commonly contain marine mollusk shell fragments and nodular, detrital phosphorite. Based on the characteristics described, these crusts are interpreted to be calcretes, similar to the laminated crusts, termed duracrysts by Goudie (1973), Multer and Hoffmeister (1968), and Robbin and Stipp (1979). The calcretes occur within the lower and upper

parts of the Arcadia Formation.

The second discontinuity interpreted to be an exposure horizon is a nearly pure, microsucrosic dolomite crust, sometimes laminated with angular lithic fragments. The crust is dolomitized along the top of the discontinuity and sometimes contains fine-grained mud within burrows. The crust is usually associated with an underlying, laminated calcitic mud containing few skeletal grains and sometimes fenestral pores. Commonly, the underlying calcitic sediment is brecciated or contains mud cracks. These dolomite crusts stand out because they are bounded by calcitic sediments containing no evidence of dolomitization. The crusts range from five to 20 cm in thickness and are common in the lower part of the Arcadia Formation (five to 10 occurrences in core W-17115). Because of the selective dolomitization of the crusts, their irregular geometry, their brecciated nature, and their stratigraphic position at the contacts between differing subfacies, they are interpreted to be selectively dolomitized levee crests such as those described in the Holocene of Andros Island in the Bahamas (Shinn et al., 1965; Shinn, 1983). Some alternative depositional environment interpretations may also include selectively dolomitized crusts occurring in intertidal settings, such as those in the Florida Keys (Atwood and Bubb, 1970).

Another discontinuity deposit is a cemented to uncemented carbonate, containing lithic fragments, gravel and pebble-sized phosphorite nodules, some quartz sand and gravel with little mud. These deposits commonly mark the top of a subfacies and are important markers in the stratigraphic column. The cements are either microsucrosic dolomite or phosphorite.

Restricted Facies, Subfacies 3, 4, 5, 6 and 7

A number of subfacies are interpreted to be restricted water depositional environ-

ments. These environments are: laminated to non-laminated sandy carbonate deposits (subfacies 3), predominantly siliciclastic with a minimal quantity of mud (subfacies 4), laminated terrigenous clays (subfacies 5), laminated predominantly carbonate supratidal deposits containing some quartz sand (subfacies 6), and mixed muddy quartz sands and carbonate muds with lagoonal mollusks (subfacies 7). A shallow-water restricted environment produced the laminated sandy mudstone/wackestone subfacies (3). This subfacies is separated from subfacies 6, because it has large variations in amount and composition of carbonates and siliciclastics, it can be either dolomitic or calcitic, and it is not absolutely associated with an underlying terrigenous clay facies. Subfacies 3 commonly occurs near or at the top of shallow water subfacies at many different locations within the Arcadia Formation. Laminations are commonly preserved in the deposits, but an increase in disturbance of bedding by bioturbation is noted in the lower part of some sequences. Many sedimentary structures are preserved in subfacies 3 compared to subfacies 6. Brecciation, mud cracks, intraclasts, lithoclasts, and burrows, sometimes containing a higher concentration of skeletal grains, occur within the laminated sandy mudstone/wackestone subfacies. Based on the sedimentary structures, it is interpreted to be a peritidal (supratidal and intertidal) deposit occurring over a wide range of energy conditions from above the mean high tide to about one to two m below sea level to areas located adjacent to tidal channels. There is a corresponding wide range of mixed carbonate and siliciclastic compositions contained within subfacies 6.

Subfacies 4 is a predominantly siliciclastic deposit with a skeletal carbonate and carbonate intraclast component. It is laminated in certain cases and it can be separated from subfacies 2 (beach subfacies) by the occurrence of burrows, root molds, and some mud. It commonly occurs

with an association to subfacies 7. The bedding is commonly relatively thick at 15 to 20 cm. It is interpreted to be a relatively high-energy deposit (due to lack of significant mud deposition), where mud deposition is not common, such as adjacent to tidal channels, in intertidal areas adjacent to deep water, and in areas adjacent to barrier islands. An alternative interpretation is a shallow offshore bar or ebb delta near a tidal inlet or offshore of a sandy beach. The occurrence of intraclasts does suggest restricted rather than offshore deposition. Some Holocene deposits with a similar structure and composition occur in Charlotte Harbor, Estero Bay, and in the Ten Thousand Islands (Huang and Goodell, 1967; Missimer, 1970; Scholl, 1963). Subfacies 4 is considered to be a minor subfacies with limited occurrence in the Peace River Formation.

A laminated terrigenous clay subfacies (5) occurs at several intervals, commonly separating predominantly carbonate composition sediments within the Arcadia Formation. This subfacies is characterized by the occurrence of thin laminations with some minor burrows and infilled features characterized by branching and thinning with depth versus relatively uniform thickness of burrow diameters which are believed to be root structures. The clays are palygorskite (attapulgitite), sepiolite and montmorillonite (smectite), sometimes containing various impurities. Commonly, the clay contains some microcrystalline dolomite rhombs and some very fine sand-sized phosphorite (francolite).

Based on the laminations, the association with the overlying supratidal carbonate, the presence of organic material, and the lack of any open marine microfossils, such as foraminifera, the laminated clay subfacies (5) is interpreted to be a lagoonal deposit in a very restricted water body with little diversity of bottom-dwelling organisms. The dark color, from dark green to nearly black, is indicative of a reducing bottom condition, which may indicate a

lagoonal environment with no significant infauna adapted to the reducing conditions (may be deep lagoon, because of low oxygenation). Also, the clays commonly contain elongate streaks of organic material. An alternative interpretation of the dark-colored, laminated clays would be a freshwater marsh. However, there are some traces of marine fossils that suggest marine deposition is more probable. Dark colored clays, interpreted as anoxic lagoonal deposits, are known to occur in predominantly carbonate sequences within cyclothems in the Upper Pennsylvanian of Kansas and in the Illinois Basin (Evans, 1966; James, 1970).

The laminated carbonates of subfacies 6 lie on top of the laminated clays of subfacies 5. The contacts are abrupt (composition changes in 20 to 30 cm), but some clay is incorporated into the overlying carbonate (Figure 17). There is a compositional grading from nearly no carbonate at the base of subfacies 5 to nearly pure carbonate at the top of subfacies 6.

Subfacies 6 contains a series of diagnostic features that suggest it was deposited in an intermittently exposed environment, such as supratidal or high intertidal. First, it is a fine-grained deposit that required minimal wave activity to allow deposition. Second, laminations and fine laminations are preserved in many examples. Third, it is sometimes capped with a laminated, microsucrosic dolomite crust (subfacies 1) or a laminated carbonate mud containing oblate mud clasts with organic staining. Fourth, the subfacies occurs near or at the top of sediment sequences at a stratigraphic break marked by a change to a different subfacies. The thickness of subfacies ranges from one to three m. The composition and sedimentary structures of subfacies 6 share the characteristics of the Holocene supratidal deposits of the Bahamas and the Persian Gulf (Shinn et al., 1969; Purser and Evans, 1973; Shinn, 1983; Hardie and Shinn, 1988).

A muddy quartz sand with mollusks

and muddy sandy molluscan wackestone (subfacies 7) occurs in association with subfacies 2 in shoaling-upward sequences. The mud component of subfacies 7 is a mix of calcitic mud, dolosilt, and clay. Shallow water mollusks, particularly restricted oysters, pectens, and barnacles, commonly occur in this subfacies. There is a rare occurrence of thin beds, but most of the deposits are bioturbated. Intraclasts of carbonate mud with clay occur within the sediments as well as concentrations of mollusk shell and phosphorite nodules. There is a complete mixing of the siliciclastic and carbonate components within these sediments. Subfacies 7 is interpreted to be a shallow lagoonal deposit based on the presence of restricted water mollusks and the percentage of mud in the sediment. This subfacies occurs within the Tamiami Formation, the lower section of the Peace River Formation (10 to 15% of section), and in several parts of the Arcadia Formation section (two to five percent of section). The stratigraphic position of the subfacies in Holocene sediments is well illustrated at the top of core W-16242 (Plate 1) and was previously described beneath Sanibel Island by Missimer (1973a), in upper Biscayne Bay by Wanless (1969), and in Charlotte Harbor, Florida by Huang and Goodell (1967).

Beach Facies: Laminated Sands, Grainstones and Packstones with Quartz Sand, Subfacies 2

A series of mud-free quartz sands, sands and mollusk shells, and quartz sands with discoid, quartz pebbles and quartz gravel occurs within the Peace River Formation. Some of the deposits are laminated with either horizontal or angular orientations (cross-bedded). Many of the microfacies occurring within this subfacies are composed solely of quartz sand. Some of the quartz sands contain discoid quartz pebbles up to 1.5 cm in diameter (Figure 13). The presence of discoid quartz pebbles

in the stratigraphic section in southern Florida was previously reported by Peck et al. (1979a) and recently in Warzeski et al. (1996). In terms of hydraulic movement, the quartz pebbles are similar to the larger mollusk fragments that occur on modern beaches with the well-sorted, fine quartz sand. The predominantly skeletal deposits are similar in structure and composition to the Holocene deposits of Sanibel Island, Florida (Missimer, 1973a), which contain both thick beds of shell alternating with laminated quartz sands (also in core W-16242, Holocene section). Although subfacies 2 is best illustrated in the Marco Island core, it is a major regional facies. These deposits range in thickness from three to 10 m, which is similar to the thickness of Holocene sand and shell deposits of the Florida West Coast barrier islands (Missimer, 1973). Based on the laminations and cross-laminations, the sorting of the sands (hydraulically well sorted in most cases), the occurrence of discoid quartz pebbles, and the lack of mud, subfacies 2 is interpreted to be a beach deposit or a very shallow ramp deposit adjacent to the shoreline. The Peace River Formation section in core W-17115 contains 15 to 20 percent of this subfacies.

Inner Ramp Facies, Subfacies 8 and 9

Subfacies 8 and 9 are predominantly siliciclastic and carbonate units that share the following diagnostic characteristics: 1) extremely heavy bioturbation and a general lack of preserved bedding, 2) diverse composition with a mix of sediment and faunal and floral types, 3) the presence of corals, mollusks, red algae, some green algal, and other fauna and flora that live in a shallow, open-shelf environment, 4) the presence of some mud, either carbonate or clay, and 5) frequent occurrences of winnowed quartz sand and/or shell beds sandwiched between wackestones or muddy sands.

Subfacies 8 is a group of quartz-rich

microfacies. It is a slightly muddy quartz sand and shell unit containing a nearshore mollusk assemblage with echinoids, some bryozoans, and red algae (Figure 18). The quartz sand ranges from medium to very fine in grain size and the sand component is generally well-sorted. The mud component is a combination of carbonate silt and clay with both calcite and dolomite grains and a small concentration of clay minerals being mostly montmorillonite and palygorskite. Detrital grains of glauconite occur in some of the sands. Thin concentrations of winnowed sand and shell, commonly containing phosphorite sand and gravel, occur in between muddy sediments.

Subfacies 9 is a series of mixed carbonate/siliciclastic microfacies containing a diverse composition. The predominant fauna is mollusks with some echinoids, bryozoans, red algae, green algae, and corals (lower section of Arcadia Formation) (Figure 19). Some detrital phosphorite and glauconite occurs throughout the section and is concentrated at discontinuities. Some "primary" glauconite occurs in the sandy wackestone microfacies in deeper water where there is less quartz sand. Concentrations of winnowed sand, shell, and phosphorite occur frequently within a wackestone matrix. No evidence for well-developed reefs was found and the vertical and horizontal distribution of corals seems to indicate that the corals are solitary, growing on hardgrounds.

Based on the characteristics described, the quartz sand and shell subfacies (subfacies 8) and the sandy molluscan/skeletal subfacies (subfacies 9) are interpreted to be inner ramp deposits. The inner ramp is defined as open marine conditions with water depths from about 1.5 to 20 m. Although wave base in the Gulf of Mexico is considered to be about 10 m, storm wave base is at about 20 m (Bernard et al., 1959; Bernard et al., 1962). Evidence for sediment movement between 10 and 20 m in the Gulf of Mexico includes the observation of coarse sediment accumulations on the

bottom, particularly in small depressions. Some grading of sediment on continental shelves is reported to a depth of 20 m at several other locations around the world, such as the Atlantic Ocean shelf off the United States and the shelf off the Elbe Estuary (Swift, 1970; Reineck and Singh, 1980). In the Gulf of Mexico off of Sanibel Island, from the shoreline to a depth of 20 m, there are storm lag deposits and the soft, sessile organisms are not present on the rock ledges. From a depth of 20 m seaward, there is no visible evidence of shifting sediment.

Subfacies 8 shows similar characteristics to the predominantly siliciclastic Holocene Southwest Florida ramp, where the sands contain some mud and mollusk shell is the predominant skeletal component (Doyle, 1979; Holmes, 1988). Another example of a similar mixed siliciclastic/carbonate ramp is the Holocene inner ramp off Puerto Rico (Pilkey et al., 1988). Subfacies 8 constitutes about 50% of the lower Peace River Formation in core W-17115, about 20% of the lower Peace River Formation in core W-16523, all of the lower Peace River Formation in core W-16242, and about 5% of the Arcadia Formation in core W-16242. Some Holocene inner ramp deposits that share similar characteristics of Subfacies 9 are the Great Pearl Bank in the Arabian Gulf and the inner ramp off extreme South Florida (Tucker and Wright, 1990; Wilson and Jordan, 1983). Storm deposits associated with this type of environment are described by Aigner (1985). These deposits are winnowed sands with variable skeletal components and generally poor sorting, commonly isolated within muddy sediments. Subfacies 9 constitutes about 5% of the lower Peace River Formation in core W-16523, about 7% of the lower Peace River Formation in core W-17115, about 40% of the Arcadia Formation in core W-16242, about 45% of the Arcadia Formation in core W-16523, and about 40% of the Arcadia Formation in core W-17115.

Outer Ramp Facies, Subfacies 10, 11, 12 and 13

Four outer ramp subfacies were defined with one additional subfacies probably deposited on both the inner and outer ramp. The outer ramp is defined by water depth on the open shelf ranging from about 20 to about 120 m or the area between the approximate storm wave base to just landward of the shelf break. The four primary outer shelf subfacies are: 1) the mixed skeletal, sandy molluscan, echinoid, bryozoan packstone/wackestone subfacies (subfacies 10), 2) the *Hyotissa* packstone/wackestone subfacies (subfacies 11), 3) the molluscan wackestone subfacies (no quartz sand) (subfacies 12), and 4) the bryozoan wackestone subfacies (subfacies 13).

The sandy molluscan, echinoid, bryozoan packstone/wackestone subfacies (subfacies 10) is a collection of complex sandy skeletal assemblages with variable amounts of mud. The overall percentage of siliciclastic grains is lower in this subfacies compared to the sandy molluscan skeletal subfacies (subfacies 9). Quartz sand occurring in subfacies 10 is fine to very-fine grained. Nodular phosphorite occurs mostly as sand-sized grains with a few thin concentrated accumulations. Glauconite is present as detrital grains and appears as a primary alteration product in some microfacies, in which the glauconite fills pores and surrounds skeletal and siliciclastic grains. Although packstones are present, the predominant rock types are skeletal wackestones. There are some thin accumulations of skeletal grains along with quartz sand and phosphorite. This subfacies characteristically has mollusks, echinoids, and bryozoans present in nearly all stratigraphic intervals (Figure 20). One indicator of greater water depth is the common occurrence of benthic and planktonic foraminifera and ostracods along with several genera of bryozoans and echinoids that have a deep water depth tolerance. Some

thin bedding (one to 10 cm) occurs in certain sequences, but most of the sediments have been bioturbated to a variable degree. Most of the bryozoans are the flat-branching and encrusting varieties, along with the small round genera, which occur in the order Cyclostomata (Figure 20). Bryozoans and echinoids occur in a wide range of water depths and numerous species have been dredged from up to several hundred meters of water in the Florida Straits (Canu and Bassler, 1928). Most of the living species of Cyclostomata and other bryozoans have depth tolerance up to well over 100 m (Canu and Bassler, 1928; Osburn, 1914; 1940). The exact water depth of bryozoan occurrence for various genera is unknown in the Gulf of Mexico. There are also occurrences of red algal oncoids, which commonly occur below a depth of 85 m (Wilson, 1975; Fig. 20). Based on reduced percentage of quartz sand, the stratigraphic position of this subfacies, the observed sedimentary structures, and the overall faunal composition, subfacies 10 is interpreted to be the innermost of the outer ramp deposits, bordering and overlapping the sandy molluscan skeletal subfacies. A Holocene example of this subfacies occurs in the Arabian Gulf (Purser, 1973) and the infaunal assemblage is similar to that found on part of the Holocene Southwest Florida ramp (Doyle, 1979). In models of carbonate ramps, Irwin (1965) and Heckel (1974) place some similar microfacies in the outer ramp. Hammes (1992) also considered this subfacies type to be an outer ramp facies in the Oligocene Suwannee Limestone. Subfacies 10 is common in the Arcadia Formation where it constitutes 15, 20, and 20% of the section in cores W-16242, W-16523, and W-17115, respectively.

The *Hyotissa* packstone/wackestone subfacies (subfacies 11), has no known Holocene equivalent. The occurrence of *Hyotissa* indicates open marine conditions with associated water depths ranging from one to 110 m (Stenzel, 1971). Living rela-

tives of this genus live in the northern warm temperate and tropical zones described by Harry (1985; 1986). An absolute water depth of between 20 and 40 m is considered to be reasonable by Harry (personal communication). An extensive review of the depositional environment of *Hyotissa* was conducted by Meeder (1987), who concluded that the *Hyotissa* packstone environment occurred on the open ramp more or less straddling the area shallower and deeper than wave base. In the Pliocene occurrences of *Hyotissa* studied by Meeder (1987), the large gryphaeid commonly occurred in thick accumulations with some sand and mud contained in the large interparticle openings between shells. Based strictly on the occurrence of *Hyotissa* in growth position, this subfacies is interpreted to be an outer ramp deposit. In the Arcadia Formation, *Hyotissa* occurs mostly in relatively thin accumulations or as solitary organisms in growth position (Figure 21). This subfacies may actually be considered to be part of the sandy molluscan, echinoid, bryozoan packstone/wackestone subfacies. The *Hyotissa* subfacies occurs in the Arcadia Formation (maximum of 5% of section in the cores) and in the Tamiami Formation.

The molluscan wackestone subfacies (subfacies 12) differs from the inner ramp sandy molluscan skeletal subfacies by the lack of quartz sand and the reduced diversity of species (Figure 22). Among the microfacies grouped under this subfacies, echinoids, bryozoans, and both benthic and planktonic foraminifera are common constituents. The molluscan wackestone subfacies commonly is quite bioturbated, contains only a few percent of very fine quartz sand, and commonly is sparsely packed (ratio of shell to mud is low). This subfacies occurs only in the Marco Island core (W-17115), which lies on the eastern margin of the Arcadia Formation platform. Based on the lack of quartz sand, depth tolerant mollusks, and the stratigraphic position, subfacies 12 is interpreted to be an outer ramp

deposit. A Holocene similar in composition and water depth occurrence lies off the Trucial Coast in the Arabian Gulf (Purser, 1973).

The bryozoan wackestone subfacies (13) commonly contains branching, tubular, and some encrusting bryozoans with a few mollusks. The wackestone is commonly sparsely packed with a very minor percentage of very-fine quartz sand (Figure 22). The matrix mud is mostly carbonate with a minor amount of clay. The matrix is cemented with microcrystalline dolomite, but the skeletal grains are commonly calcitic. Based on the abundance of depth tolerant bryozoans, the lack of shallow-water fauna, the high percentage of mud, the absence of significant quantities of quartz sand, and stratigraphic position, subfacies 13 is interpreted to be an outer ramp deposit. Hammes (1992) described a similar outer ramp facies from the Oligocene Suwannee Formation in Southwest Florida. Her interpretation was based on a ramp model and the stratigraphic position of this subfacies at the base of shoaling-upward sequences. This subfacies occurs only in core W-17115, similar to the molluscan wackestone subfacies, where it constitutes less than two percent of the section. Subfacies 1 and 13, respectively the molluscan and bryozoan wackestones, could be grouped within subfacies 10, but the distinguishing characteristics are the sparse packing with skeletal grains and very low percentage or absence of quartz sand.

Inner and Outer Ramp, Subfacies 14

Subfacies 14 is characterized by a very diverse composition and graded beds, which appear as low-sloping, angular features on seismic reflection records (Figures 23 and 24). Commonly, the graded beds have a base of quartz sand with dolosilt/quartz silt above the sand and are capped with laminated clay/carbonate clay (Figure 24). There are a large number of different grain types with many detrital

grains including quartz sand and silt, phosphorite, calcite silt, and dolosilt. There is a wide diversity of bedding features which indicates deposition over a wide range of water depths. There are sand beds with thicknesses ranging from 0.2 to about one m, which are indicative of shallow inner ramp deposition. Some of the sand beds contain coarse sediment deposits that are probably storm lags. Some of the mud beds contain isolated sand deposits and other sands are associated with the graded beds, caused by hydraulic separation during deposition. There are relatively thick beds of fine-grained sediment containing some internal laminations.

A large percentage of the skeletal grains occurring within this subfacies are benthic foraminifera with some planktonic foraminifera, ostracods, diatoms and mollusks (few). Based on the occurrence of this assemblage, Peck et al. (1979b) concluded that this facies was deposited strictly in shallow water due to the presence of several species of brackish water ostracods and benthic foraminifera. However, the type of bedding shown in the seismic record (Figure 23), the graded bedding, and faunal assemblage indicate a deltaic type of depositional environment with a wide variation in water depths as the deltaic lobes covered a ramp. Therefore, based on the bedding structure, the microfossil assemblage and composition, this subfacies is believed to range from inner to outer ramp in depositional environment.

It is quite difficult to find a Holocene deposit analogous to subfacies 14. The wide range in composition, with carbonates and siliciclastics totally mixed, is perhaps unique to this location because of the input of eroded carbonate from the pre-existing platform and the influx of terrigenous siliciclastics from the north into a semi-tropical environment. Subfacies 14 constitutes all of the upper Peace River Formation in cores W-16242 and W-16523.

Table 6. Subfacies Types, Water Depths, and probable Depositional Environments.

Subfacies No.	Subfacies 1.	Subfacies 2.	Subfacies 3.	Subfacies 4.	Subfacies 5.
	Brecciated and laminated packstones	Laminated sands and sandy packstones	Laminated sandy mudstone/wackestone	Quartz sand/sandy molluscan grainstone/packstone	Laminated clay
Depositional Environment:	Exposure surface, karst, pedogenic, laminated with quartz sand and carbonate cement, intraclasts (angular)	Beach facies, nearshore (a few hundred meters from low tide point), littoral zone, shoreface (foreshore), backshore, dune	Supratidal, intertidal flat	Siliciclastic/mixed intertidal/tidal channels, overwash bars	Supratidal, intertidal, protected lagoon (upper intertidal facies)
Estimated Absolute Water Depth:	Diagenetic facies	0-2m	0-1m	0-1m	0-3m
Relative Water Depth at Deposition: Figure 25 Depth Model	0	0-1	0-1	0-1	0-1
Modern Analog:	Florida peninsula, Holocene	Florida east coast, Florida west coast, New Jersey (Cape May) coast, many passive margin beaches	Andros Island, Bahamas (no sand), Arabian Gulf tidal flats, Ten Thousand Island near Cape Romano	Ten Thousand Islands, Florida, Estero Bay, Florida, Charlotte Harbor, Florida	Gulf of California (upper intratidal facies) Ancient Analog: Upper Pennsylvania of Kansas (?) Illinois Basin
References:	Goudie (1973), Multer and Hoffmeister (1968), Robbin and Stipp (1979)	Davis (1985), Missimer (1973), Hsu (1960), King (1979), Ramsey and Galvin (1971), Watson (1971)	Enos (1977), Shinn (1983), Hardie (1977), Reinick (1967), Shinn, Lloyd, and Ginsburg (1969)	Huang and Goodell (1967), Scholl (1963), Missimer (1970), Thompson (1975)	Thompson (1975), Evans (1966), James (1970)

Table 6. (cont.) Subfacies Types, Water Depths, and probable Depositional Environments.

Subfacies No.	Subfacies 6.	Subfacies 7.	Subfacies 8.	Subfacies 9.	Subfacies 10.
	Laminated microsucrosic dolomite, microsucrosic dolomite mudstone/wackestone	Muddy quartz sand and mollusks, muddy, sandy molluscan wackestone	Quartz sand and mollusks, muddy	Sandy molluscan, skeletal wackestone	Mixed skeletal/ sandy molluscan, echinoid, bryozoan wackestone
Depositional Environment:	Supratidal, intertidal, restricted, sabkka	Intertidal, lagoonal, mixed carbonate-siliciclastic	Nearshore, open-marine	Nearshore, inner ramp/ platform, lag in deeper water, deep lagoonal	Open marine, middle to outer ramp/shelf
Estimated Absolute Water Depth:	0-1m	0-4m	2-20m	4-20m	20-40m
Relative Water Depth at Deposition: Figure 25 Depth Model	0-1	0-2	1-5	2-5	5-7
Modern Analog:	Andros Island, Bahamas Arabian Gulf	Upper Biscayne Bay, Florida, Estero Bay, Florida, Laguna Madre, Texas, Ten Thousand Islands, Florida	West Florida shelf	South Florida, Great Pearl Bank, Persian Gulf	South Florida - West Florida shelf, Trucial Coast
References:	Shinn (1983), Shinn, Lloyd, and Ginsburg (1969), Purser and Evans (1973), Hardie and Shinn (1988)	Wanless (1969), Missimer (1970), Parker (1959)	Doyle (1979), Holmes (1988), Pilkey, Bush and Rodriguez (1988)	Tucker and Wright (1990), Aigner (1985), Wilson and Jordan (1983)	Doyle (1979), Purser (1973), Irwin (1965), Heckel (1974)

Table 6. (cont.) Subfacies Types, Water Depths, and probable Depositional Environments.

Subfacies No.	Subfacies 11.	Subfacies 12.	Subfacies 13.	Subfacies 14.
	<i>Hyotissa</i> packstone/ wackestone	Molluscan wackestone	Bryozoan wackestone	Mixed siliciclastic/ carbonate/clay, graded bed
Depositional Environment:	Open-marine, middle to outer ramp	Open-marine, outer ramp	Open-marine, outer ramp	Open-marine, inner-middle to outer ramp, deltaic
Estimated Absolute Water Depth:	20-40m	40-80m	60-120m	15-120m
Relative Water Depth at Deposition: Figure 25 Depth Model	4-7	7-9	8-10	5-10
Modern Analog:	None	South Florida - West Florida shelf Trucial Coast	South Florida (?)	None similar, Colorado River Delta (?)
References:	Meeder (1987)	Doyle (1979), Purser (1973), Heckel (1974)	Tucker and Wright (1990)	No modern analog

DISCUSSION

Depositional Model for the Hawthorn Group on the South Florida Platform

Based on the interpretations of the depositional environments in which the microfacies of the Hawthorn Group were deposited, the entire stratigraphic unit was deposited on a ramp (Table 6). Homoclinal ramp deposits are characterized by low, rather uniform slopes from shallow water into the basin with a continuous grading of sediment types from nearshore sands to deep-water sands and muds (Reed, 1982). Distinct geometries occur on ramps with predominantly carbonate deposition (Ahr, 1972; Wilson, 1975). The mixed siliciclastic and carbonate sediments of the Hawthorn Group produce a nearly continuous transition of sediment facies from shallow to deep water. The low slope and the deposition of many subfacies above the storm wave base caused an extreme variation in sediment composition, resulting in a large number of microfacies being deposited within short geographic distances. A model relating the subfacies to water depth on the ramp is given in Figure 25 and a sectional diagram is given in Figure 26.

Most described ramp deposits occur where the predominant sediment type is carbonate. Where siliciclastic sediments are present on these carbonate ramps, the siliciclastic sediments are not greatly mixed with the carbonates, but occur in belts, such as the Arabian Gulf and the Holocene beaches of southeastern Florida. The subfacies and microfacies described from the Hawthorn Group contain some rather unique characteristics atypical of other ramp deposits. Commonly, ramp deposits contain a rather abrupt boundary between mud deposits occurring within the restricted environments and well-washed grainstones and packstones occurring at the shoreline and on the inner and outer ramp.

Many described ramp deposits contain little or no mud in the open inner or outer ramp subfacies, such as the eastern Florida ramp, the present day west Florida ramp, and other wave-dominated ramps, such as southern Australia (Boreen and James, 1993; James et al., 1994). Modern ramp deposits bordering restricted water bodies, such as the Arabian Gulf, do contain a belt of muddy open-water inner and outer ramp deposits. Ancient eperic sea ramp deposits also produced wackestone and mudstone deposits in the open shelf area.

During the Early Oligocene, the Suwannee Limestone was deposited on the southern Florida Platform as a ramp (Hammes, 1992). The characteristics of the Suwannee Limestone ramp deposition differ significantly from the ramp deposits of the Hawthorn Group despite the common geographic setting. The Suwannee Limestone contains a nearly identical set of subfacies as the Arcadia Formation, but the sediments contain significantly less mud and the predominant lithologies from the shoreline to the deep shelf are grainstones and packstones with only a minor section of wackestone or muddy carbonates (Figure 27).

The Arcadia Formation is characterized by an abundance of mud deposition on the inner and outer ramp. This difference in deposition on this ramp compared to the underlying Suwannee Limestone and other modern or Tertiary ramps is believed to be the result of deposition in deeper water in a somewhat restricted setting with the Gulf of Mexico providing a lower tidal range. A reasonable comparison is that the Gulf of Mexico is more similar to the Arabian Gulf than it is to the Atlantic Ocean in terms of tidal range. The occurrence of mud deposition on the inner and outer ramp tends to occur in "restricted" seas and also occurs in the Arabian Gulf. Within the uppermost part of the Arcadia Formation and in the lower Peace River Formation, the abundance of open ramp wackestone deposits is

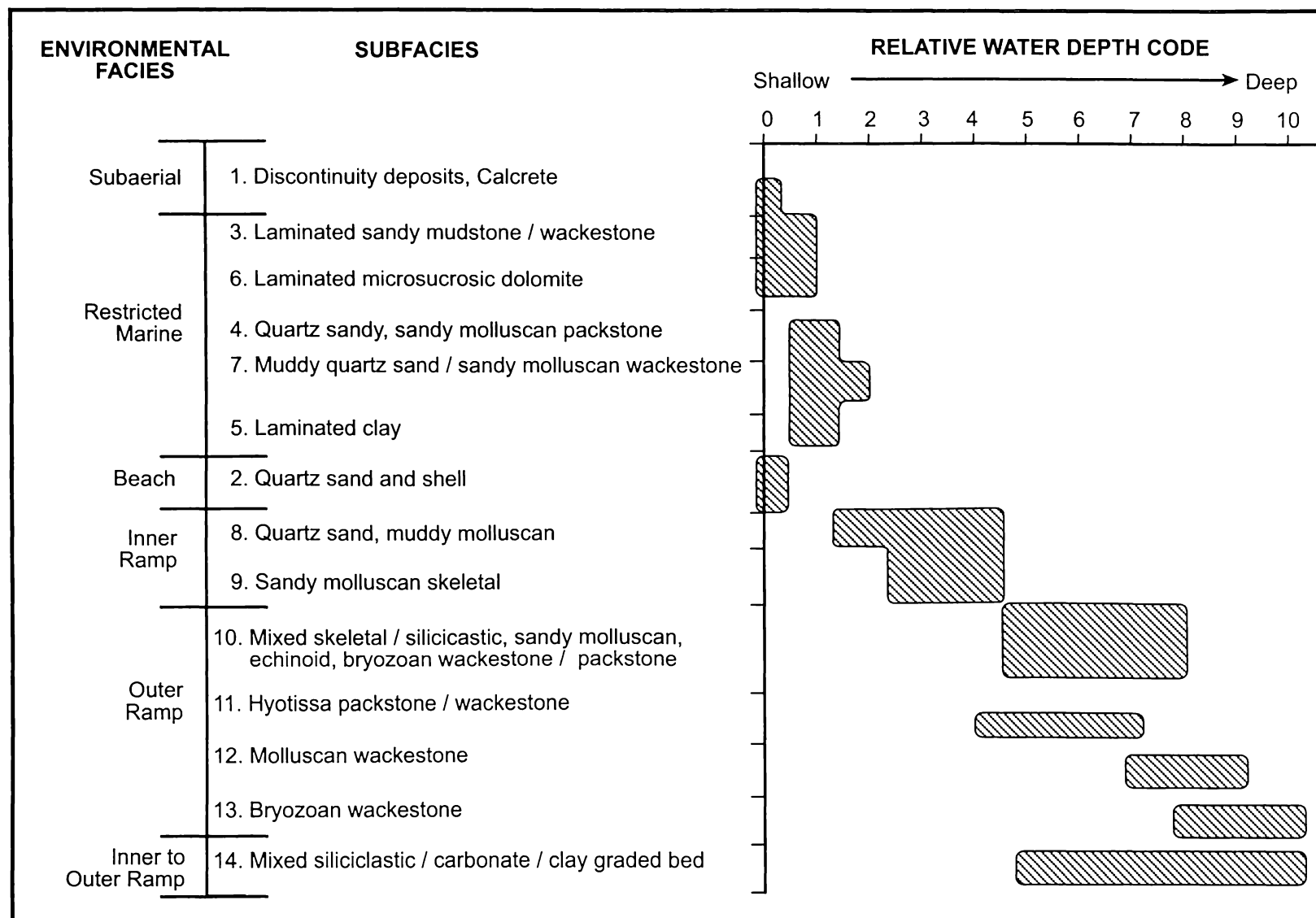


Figure 25. Diagram showing the relative water depths of the 14 primary subfacies described from shallow to deep water. The zone water depth separating the inner and outer range subfacies occur approximately at number 4 on the depth chart. There are no subfacies that occur in the basin or deeper than the shelf break.

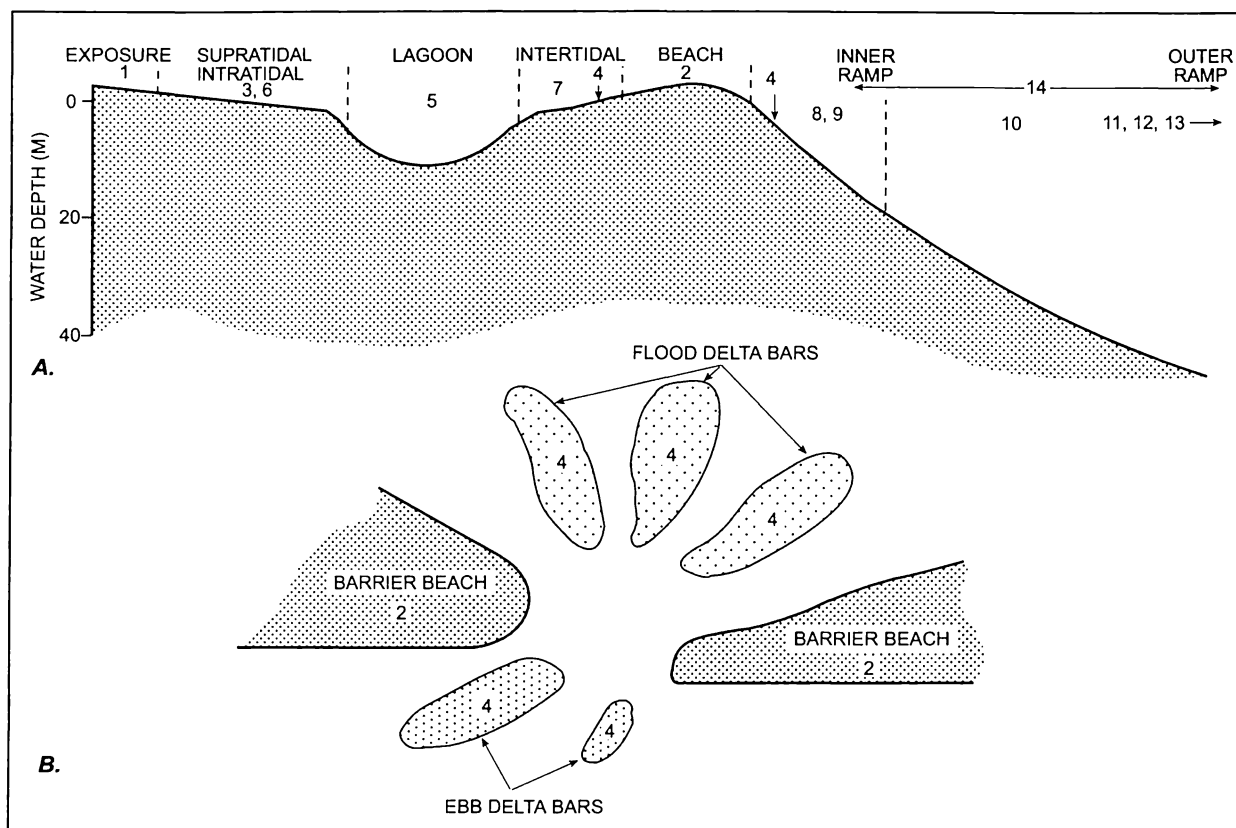


Figure 26. South Florida mixed and carbonate/siliciclastic ramp.

A. Cross-section of a mixed carbonate siliciclastic ramp showing the location of subfacies 1 to 14. Note that subfacies 4 cannot be specifically located on the cross-section.

B. An aerial view of a tidal pass with barrier beaches. Subfacies 4 is believed to occur in intertidal areas adjacent to tidal inlets or tidal delta bars or nearshore bars. Also, it may occur in the channel. Subfacies 2 is normally a beach deposit, but may occur in well-wash channel bars.

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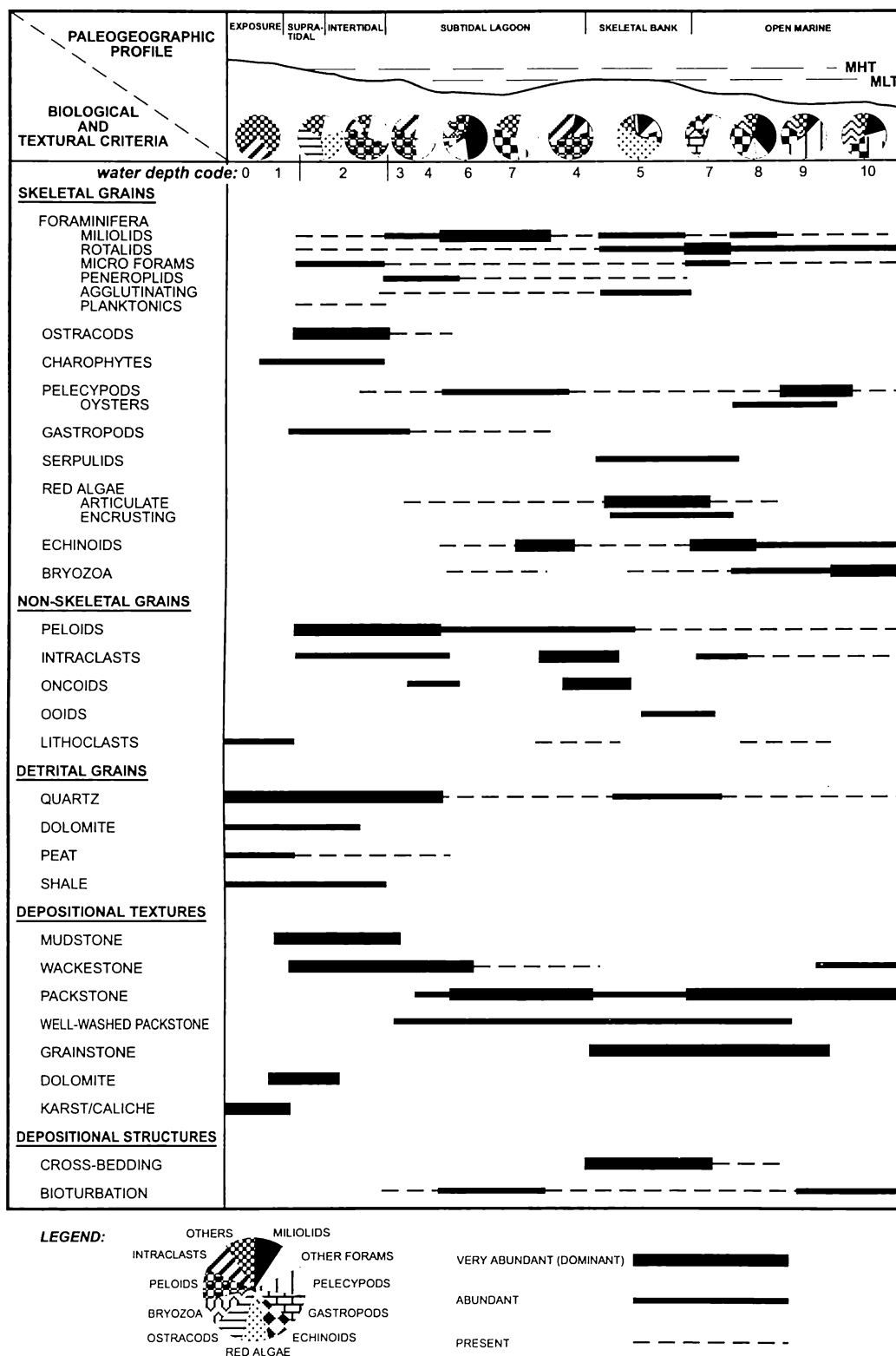


Figure 27. A profile across the Suwannee Limestone shallow-water carbonate ramp displaying the dominant occurrences of major grain types, sedimentary structures, and biological and textural attributes. Each subenvironment is characterized by distinct associations of grain types (from Hammes, 1992). The predominant lithologies in the Suwannee Limestone in southern Florida are packstones and grainstones lacking mud.

diminished, indicating shallower water. The influx of siliciclastic sediments into the predominantly carbonate environment also contributed to a change in the ramp depositional characteristics.

In conclusion, the Hawthorn Group was deposited on a homoclinal ramp in relatively deep water compared to other described ramp deposits. The ramp evolved over time from deposition of predominantly shallow water subfacies near the base of the Arcadia Formation to predominantly deep ramp subfacies in the middle of the formation back to predominantly shallow ramp subfacies in the upper part of the formation. Shallow water ramp deposition was predominant throughout deposition of the lower Peace River Formation. The entire northern part of the ramp was covered by mixed siliciclastic and carbonate sediment in the upper Peace River Formation.

Timing of the Transition from Pure Carbonate to Mixed Carbonate-Siliciclastic Sediment Deposition on the South Florida Platform

Siliciclastic sediments began to enter the South Florida Platform during deposition of the lower part of the Suwannee Limestone, which has an age of Early Oligocene or about 33.7 Ma. Significant accumulations of quartz sand in the Suwannee Limestone were observed in well CO-2318 as well as in a number other wells penetrating this unit in southern Florida. Also, quartz sand is disseminated throughout the Suwannee Limestone in Southwest Florida as observed in thin sections and drill cuttings both in this investigation and by Hammes (1992). The maximum thickness of nearly pure quartz sand observed was about 10 meters. In a few locations, where a series of closely-spaced (less than 1000 m) wells were oriented approximately parallel to the strike of the platform, quartz sand was observed in each well at the same

approximate stratigraphic interval. In closely-spaced (less than 1000 m) wells penetrating the Suwannee Limestone in an east-west direction, perpendicular to the platform strike, the occurrence of quartz sand is not commonly observed in the same stratigraphic position. It is concluded that the quartz sand deposits are narrow belts, likely deposited as shorelines. It is very important to note that the influx of siliciclastic sediment is limited to predominantly quartz sand with little or no terrigenous clay reaching the South Florida Platform.

The largest influx of quartz sand began to occur in the Late Oligocene with the accumulation of the shallow ramp subfacies in the lower part of the Arcadia Formation. The rate of siliciclastic sediment influx increased progressively from the base to the top of the Arcadia Formation and in time from about 26.6 to 12.4 Ma. Some siliciclastic muds accompanied the deposition of the quartz sands. Some of the fine-grained muds were deposited in shallow lagoonal deposits on the platform and in deeper water deposits to the east. It is probable that the influx of muddy sediments along the eastern platform margin was responsible for the partial drowning of that margin (Missimer and Scott, 1995).

After the Middle Miocene sea-level event, which caused the extensive erosion of the Arcadia Formation, subsequent siliciclastic sediment influx in the Peace River Formation, particularly along the eastern margin of the Arcadia Platform, was nearly a "river of sand," producing a sequence of beach deposits. It is probable that some deep water, mixed siliciclastic/carbonate deposits were deposited to the east of the study area (Missimer and Scott, 1995). The carbonate subfacies produced during this time period were limited to mostly beach deposits containing a large percentage of skeletal grains, but siliciclastic sediment deposition was predominant.

In the northern part of the study area, the upper part of the Peace River

Formation is a deltaic deposit consisting of a variety of mixed carbonate and siliciclastic sediments. This deposit is very muddy and completely terminated carbonate sedimentation. The deltaic, fine-grained deposit helped infill the eastern margin of the platform that was part of the platform drowned during Arcadia Formation time (Missimer and Scott, 1995).

Siliciclastic and Carbonate Sediment Mixes and the Process of Sediment Mixing

The transition of the South Florida Platform from primarily carbonate sedimentation to mixed carbonate/siliciclastic sedimentation occurred gradually, beginning with a series of quartz sand influxes. Despite the fact that the siliciclastic sediment influxes were rather rapid pulses, and that the volume of siliciclastic sediment increased with time, the sediments show nearly every composition from nearly pure carbonate to pure siliciclastic on a bed scale, but the sediments were thoroughly mixed throughout the section. Despite the inferred process of siliciclastic sediment transport, and siliciclastic sediment belts along the margins of the platform, the sediments did mix with interior platform carbonate sediments.

Based on the observed characteristics of the sediments, the processes of mixing included: storms, wind, and bioturbation. Throughout the entire Arcadia Formation, the sediments are heavily bioturbated, particularly in all of the inner and outer ramp deposits. The distribution of siliciclastic sediments within each of the ramp subfacies is quite irregular with quartz sand infilling carbonates and fine-grained carbonates infilling predominantly siliciclastic sediments. Many lag deposits occur throughout the entire Hawthorn Group section. In the restricted water deposits within the Arcadia Formation, some very fine to fine-grained, well-sorted, angular quartz sands are present. These sands were likely

transported by eolian processes.

The South Florida Platform was a region of predominantly carbonate sedimentation to the end of Eocene time (Schmidt, 1984). The Gulf Trough or Apalachicola Embayment separated sources of siliciclastic sediments to the north from the pristine carbonate depositional environments to the south (Schmidt, 1984). During the deposition of the Suwannee Limestone in the Early Oligocene, a significant volume of quartz sand bypassed the Apalachicola Embayment, probably during minor low sea-level stands. The first pulses of quartz sand reached the South Florida Platform in the Early Oligocene as prograding belts of sand forming along the platform margins. This depositional model is based on the same pattern observed in the Florida Holocene, where margin quartz sand deposits intrude into the carbonates of Biscayne Bay on the east and the carbonate sediments of Florida Bay to the west.

During deposition of the Suwannee Limestone and some of the lower part of the Arcadia Formation, minor eustatic sea-level changes and storms tended to transport the quartz sands from the shoreline to areas near the interior of the platform. Organisms living in the sediments mixed the quartz sands by burrowing and reworking the predominantly carbonate sediments. The mixing of quartz sands with the carbonates had little initial effect on carbonate sedimentation, because a significant volume of terrigenous mud was not present. The quartz sand was inert and did not affect water turbidity or biological productivity. As the volume of siliciclastic sediment influx onto the South Florida Platform increased, the diversity of depositional environments in the central part of the platform increased with some terrigenous mud being deposited in restricted environments. Storms, bioturbation and wind aided in the mixing of siliciclastic sediments into the carbonate environments of the central part of the platform.

Carbonate sedimentation was interrupted over a large area of the eastern part of the margin by the influx of the siliciclastic sediment and possibly by water clarity changes caused by the major influx of nutrients related to the movement of nutrient-laden water from the Gulf of Mexico over the southern part of the platform (formation of phosphatic limestone in the central part of the platform). The reduction in carbonate sedimentation on the eastern margin caused this margin to migrate west from its approximate current position about 100 km (Missimer and Scott, 1995).

After the Middle Miocene, the central part of the South Florida Platform ceased to grow upward with predominantly carbonate sediments. In the late Miocene, predominantly siliciclastic sediments were added, again as southward prograding beach deposits. After the Messinian, a major change in the sedimentation pattern occurred with a prograding deltaic unit burying the mixed siliciclastic and carbonate sediments. The deltaic sediments penetrated the southern platform only to a location near the Lee-Collier county line (central platform). A large portion of the drowned part of the eastern platform was infilled by predominantly mixed muddy siliciclastic and carbonate sediments during the late Miocene and early Pliocene.

In conclusion, the hypothesis of Mount (1984) that most carbonate/ siliciclastic sediment mixes show minimal internal mixing within small scale facies is not supported by the sediment transition on the South Florida Platform. Beginning with the Lower Oligocene Suwannee Limestone and continuing with all of the Neogene formations lying above it, all of the stratigraphic section contains mixes of both carbonate and siliciclastic sediments. The extreme variations in sediment composition and the diversity of associated flora and fauna within the Hawthorn Group, show that mixed siliciclastic and carbonate

systems can produce rather continuous sedimentation without the siliciclastic sediment totally eliminating carbonate sediment production. Carbonate deposition on a shallow ramp will persist until there is sufficient siliciclastic mud deposition to terminate carbonate sediment production and cause either a change in the geometry of platform growth (migration of eastern platform margin) or complete succession of deposition from carbonate to siliciclastic (deltaic burial). Completely mixed carbonate/siliciclastic sediment sequences are probably quite common in the geologic record based on observations made on the Hawthorn Group and younger deposits found on the Florida Platform.

LATE PALEOGENE AND NEOGENE CHRONOSTRATIGRAPHY OF THE CENTRAL PART OF THE SOUTH FLORIDA PLATFORM

INTRODUCTION

Ages of the upper Paleogene and Neogene sediments on the South Florida Platform have been subject to debate for many years. Previous stratigraphic investigations have assigned ages to many of the formations based on paleontological data correlated to areas outside of the Florida Platform (Cooke, 1936; Mansfield, 1937, 1938; Cooke, 1939; MacNeil, 1944; Parker and Cooke, 1944; Cooke, 1945; Parker et al., 1955; Akers, 1972; Riggs, 1979b; Miller, 1986; COSUNA, 1988; Scott, 1988). The currently accepted ages of many reference sections used for correlation to the Florida Platform have changed, but little effort has been given to revising the chronostratigraphy of the Florida Platform until relatively recent investigations. Beginning in 1972, a series of stratigraphic investigations were conducted that yielded a large quantity of new age data based on planktonic foraminifera (Akers, 1972; Peck, 1976; Peck et al., 1976; Slater, 1978; Peck et al., 1979a;

Peck et al., 1979b; Armstrong, 1980; Peacock, 1981; Peacock and Wise, 1981, 1982; Jones et al., 1991), calcareous nannoplankton (Peck, 1976; Covington, 1992), diatoms (Klinzing, 1980, 1987), helium-uranium dating (Bender, 1973), vertebrate fossil stratigraphy (Jones et al., 1991), strontium isotope stratigraphy (Jones et al., 1991; Hammes, 1992; Compton et al., 1993; Mallinson and Compton, 1993; Weedman et al., 1993; Brewster-Wingard et al., 1997), and magnetostratigraphy (Jones et al., 1991).

It is the purpose of this section to present new data refining the age ranges in the central part of the South Florida Platform of the Suwannee Limestone, the Arcadia and Peace River Formations of the Hawthorn Group, the Tamiami Formation, and the Caloosahatchee Formation (Figure 3). A series of three continuous core borings were used in this investigation (Nos. W-16242, W-16523, and W-17115 in Figure 2). The new data were obtained using strontium-isotope age dating and magnetostratigraphic analyses with a comparison to and correlation with existing planktonic foraminifera, calcareous nannoplankton, and other paleontological data including diatoms and vertebrates. Stable oxygen and carbon isotope data were also collected for comparison to isotopic data in marine sediment of known age to assess distinctive changes in isotopic composition related to global climatic events. All age determinations made in this paper utilize the geologic time scale of Berggren et al. (1995b).

METHODS

Strontium and Stable Isotope Sample Preparation

Samples of unaltered calcitic mollusk shell and a few phosphorite nodules were collected from cores W-16242, W-16523, and W-17115 for the purpose of measuring the strontium-isotope ratios to make age

determinations. A total of 62 samples were chosen for analysis from all samples collected based on the location of the samples within the stratigraphic section and the quality of the shell material. A large percentage of the samples were collected and analyzed from core W-16242 (34 samples), because of the abundant quantity of unaltered shell, the high percentage of core recovery, and the designation of this core for magnetostratigraphic analysis. All samples were carefully washed in distilled water, then placed in an ultrasonic bath to remove additional contaminants. Each sample was further cleaned using dilute hydrochloric acid. Most samples were then cut to expose a fresh surface. Powdered shell was collected by either drilling out the shell interior with a clean dental drill or a clean cube of shell was extracted from the middle of the sample and crushed into a powder. A sufficient quantity of clean powdered shell was collected to perform both strontium-isotope analyses and carbon and oxygen-isotope analyses.

All strontium isotope measurements were made at the University of Florida. The analytical procedure used is described in detail in McKenzie et al. (1988) and Hodell et al. (1990). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured in the triple-collector dynamic mode on a VG354 thermal ionization mass spectrometer. All strontium ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and to Standard Reference Material (SRM) 987 = 0.710235. An evaluation of the analytical precision indicated that the average within-run precision was $\pm 1 \times 10^{-5}$ (two standard error of the mean). When all errors associated with the analytical procedure were summed, a range of ± 22 to 24×10^{-6} was determined for the period in which the data were collected. The strontium isotope variation with time in the world ocean, as presented in the model of Hodell et al. (1991), was used to estimate ages. The

error in conversion to estimated ages cannot be determined, because the model used must be assumed to be correct (P. Mueller, personal communication). The Hodell ages were then corrected to the Berggren et al. (1995b) age model.

All carbon and oxygen isotope data were analyzed at the stable Isotope Laboratory, University of Miami. The isotopic ratios were measured on a mass spectrometer using the standard laboratory procedures (Swart et al., 1991).

Paleomagnetic Measurements

Detailed paleomagnetic data were collected from core W-16242. Up-down oriented samples were collected from 291 stratigraphic intervals. Since the core was collected with a drilling rig, the only orientation of the samples that could be determined was the stratigraphic up direction. Core orientation was checked using geopels wherever observed. Therefore, only inclination data were used to determine the prevalent polarity during or shortly after deposition. All magnetic measurements were made at the University of Miami, Rosenstiel School of Marine and Atmospheric Science. The paleomagnetic measurements were made using a 2G Enterprises 755 superconducting magnetometer contained within a shielded room. All rock magnetic analyses were conducted at the California Institute of Technology using a 2G Enterprises 760 magnetometer. A combination of alternating field and thermal demagnetization methods were utilized to obtain inclination data and to determine polarity.

FORAMINIFERA

Introduction

Studies of the foraminifera in the Neogene and late Paleogene sediments in Southwest Florida were presented in a

series of theses and resultant publications (Peck, 1976; Peck et al., 1976; Peck et al., 1977; Peck et al., 1979a; Peck et al., 1979b; Slater, 1978; Peacock, 1981; Peacock and Wise, 1981; Peacock and Wise, 1982). Since detailed analyses of foraminifera were previously performed on nearby wells having very direct and reliable lithostratigraphic correlation to the cores in this study, projected planktonic foraminifera ages are used. The stratigraphic correlation between the cores studied and the planktonic faunal information collected from nearby wells was accomplished by tracing continuous seismic reflection lines between the wells and core W-16242 on the north (20 km) and by direct correlation of the stratigraphic units into core W-16523 on the south (eight km).

The entire Neogene and Late Paleogene stratigraphic section was not studied in the foraminifera research, but the work was concentrated on the "Tamiami Formation," which was defined at that time as all sediments lying between the disconformity marking the top of the Arcadia Formation and the disconformity marking the base of the Caloosahatchee Formation. Since the definitions of the stratigraphic units have been changed to produce a more consistent framework (Scott, 1988), the foraminiferal investigations were performed on both the Tamiami and Peace River Formations. The only age diagnostic data, however, were obtained from the Peace River Formation. The work performed by Peacock (1981) was mostly limited to the foraminiferal occurrences in the lower part of the Arcadia Formation.

Age of the Arcadia Formation Based on Foraminifera

Work on foraminifera near the base of the Arcadia Formation was conducted by Peacock (1981). He noted the occurrence of *Miogypsina hawkinsi* and *Archaias floridanus* in the lower part of the Hawthorn Group. Cole (1938) believed that all species

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of *Miogypsina* were restricted to the Late Oligocene. Cole (1941) used the occurrence of *Archaias floridanus* as an indicator of the Tampa Formation in southern Florida. Both *Archaias* and *Miogypsina* were observed near the base of the Arcadia Formation in each of the cores studied. The implied Late Oligocene age of these foraminifera matches well with the other age dating methods for this part of the stratigraphic section.

Age of the Peace River Formation Based on Foraminifera

Analysis of the foraminifera occurrence in a series of six wells in Lee County and several additional wells in Hendry County were made by Peck et al. (1979a; 1979b).

They defined a series of stratigraphic units based on several type wells. Well L-1849 lies adjacent to the Caloosahatchee River only about one km south of the seismic reflection line made in the river channel (Figure 28). Based on the correlations and the unit terminology given in Peck et al. (1979a) and Peck et al. (1979b), their unit 2 is equivalent to the upper part of the Peace River Formation and their units 3 to 8 are equivalent to the lower Peace River Formation. The lower Peace River Formation in core W-16242 from 88.54 to 91.74 m is equivalent to unit 8 in well L-1849. The upper Peace River Formation from 57.91 to 88.54 m in core W-16242 is equivalent to units 2A-B in well L-1849. Additional planktonic foraminifera data

WELL L - 1849	UNIT (Peck, et. al.)	DEPTH (Feet below surface)	CALCAREOUS NANNOFOSSILS										PLANKTONIC FORAMINIFERA									
			<i>Discoaster brouweri</i>	<i>D. berggrenii</i>	<i>D. quinqueramus</i>	<i>D. variabilis</i>	<i>Coccolithus pelagicus</i>	<i>Cyclcoccolithus leptoporus</i>	<i>Helicopontosphaera kampfneri</i>	<i>Reticulofenestra pseudumbilica</i>	<i>Globigerina bulloides apertura</i>	<i>G. bulloides bulloides</i>	<i>G. druryi decoraperta</i>	<i>G. nepenthes</i>	<i>Globigerinoides obliquus extremus</i>	<i>G. obliquus obliquus</i>	<i>G. quadrilobatus quadrilobatus</i>	<i>G. ruber</i>	<i>Globorotalia acostaensis humerosa</i>	<i>Hastigerina (H.) siphonifera</i>	<i>Sphaeroidinellopsis seminulina seminulina</i>	<i>S. subdehiscens subdehiscens</i>
PLIOCENE & PLEISTOCENE LOWER TO MIDDLE PIOCENE <i>Dyocibicides biserialis</i> zone ↑ Valvulineria floridana zone ↑ Lenticulina americana zone ↑ UPPER MIOCENE	POST MIOCENE	0 - 20																				
		20 - 35						●	●	●		●										
		35 - 55						●	●	●		●					●			●		
	2A - B	55 - 75	●		●		●	●	●	●		●					●			●		●
		75 - 95			●	●	●	●	●	●		●	●		●	●	●	●		●	●	●
		95 - 115									●	●			●	●	●	●	●		●	
	8	115 - 135	●		●		●	●		●	●	●				●	●	●				
		135 - 145	●		●		●	●		●					●							

Figure 28. Distribution of planktonic foraminifers and calcareous nannofossils in well L-1849 adjacent to seismic line connecting to core W-16242 (from Peck et al., 1979b). The current age ranges for these fossils are given in the summary chronostratigraphy for core W-16242.

WELL L - 1984	UNIT (Peck, et. al.)	DEPTH (Feet below surface)	CALCAREOUS NANNOFOSSILS										PLANKTONIC FORAMINIFERA									
			<i>Discoaster brouweri</i>	<i>D. berggrenii</i>	<i>D. quinqueramus</i>	<i>D. variabilis</i>	<i>Coccolithus pelagicus</i>	<i>Cyclococcolithus leptoporus</i>	<i>Helicopontosphaera kamptneri</i>	<i>Reticulofenestra pseudumbilica</i>	<i>Globigerina bulloides apertura</i>	<i>G. bulloides bulloides</i>	<i>G. dranyi decoraperta</i>	<i>G. nepenthes</i>	<i>Globigerinoides obliquus extremus</i>	<i>G. obliquus obliquus</i>	<i>G. quadrilobatus quadrilobatus</i>	<i>G. ruber</i>	<i>Globorotalia acostaensis humerosa</i>	<i>Hastigerina (H.) siphonifera</i>	<i>Sphaeroidinellopsis seminulina seminulina</i>	<i>S. subdehiscens subdehiscens</i>
LOWER TO MIDDLE PLIOCENE <i>Dyocibicides biserialis</i> zone	U	25 - 45																				
	I	45 - 165					•	•		•												
UPPER MIOCENE	2A - B	165 - 185					•	•		•												
		185 - 206		•	•	•																
		206 - 226			•					•												
		226 - 246		•	•	•	•	•		•												
	3A	246 - 266					•															
		266 - 286																				
		286 - 306																				
		306 - 326	•			•				•												
	4	326 - 346					•			•						•		•				
	6	346 - 366														•		•				
		366 - 386					•						•	•						•		
	8	386 - 406									•	•										

Figure 29. Distribution of planktonic foraminifers and calcareous nannofossils in well L-1984 near core W-16523. This information was taken from Peck et al. (1979). Well L-1984 is located close to core W-16523 (see Figure 34). The age range of the planktonic foraminifers and calcareous nannoplankton from this analysis is discussed in the chronology of core W-16523.

were obtained from well L-1984 (Figure 29). Well L-1984 lies eight km west of core W-16523 and is directly correlated to the core by a published geologic section (Boggess et al., 1981). The correlation of units 1 to 8 in well L-1984 to core W-16523 are shown in Figure 30.

Based on the occurrence of age diagnostic foraminiferal forms including *Sphaeroidinellopsis subdehiscens subdehiscens*, *S. seminulina seminulina*, *Globigerina nepenthes*, and *G. bulloides*

apertura along with the occurrences of the calcareous nannofossils *Discoaster quinqueramus*, *D. berggrenii*, *D. brouweri*, *Reticulofenestra pseudumbilica* and other calcareous nannofossils, Peck et al. (1979a, b) assigned units 2B to 8 to the Late Miocene *Discoaster quinqueramus* Zone of Gartner (1969). This zone was considered to be equivalent to planktonic foraminiferal zones N17 to N18 by Gartner (1969), but Berggren (1973) correlated it to only the latest Miocene zone N17. The distribution

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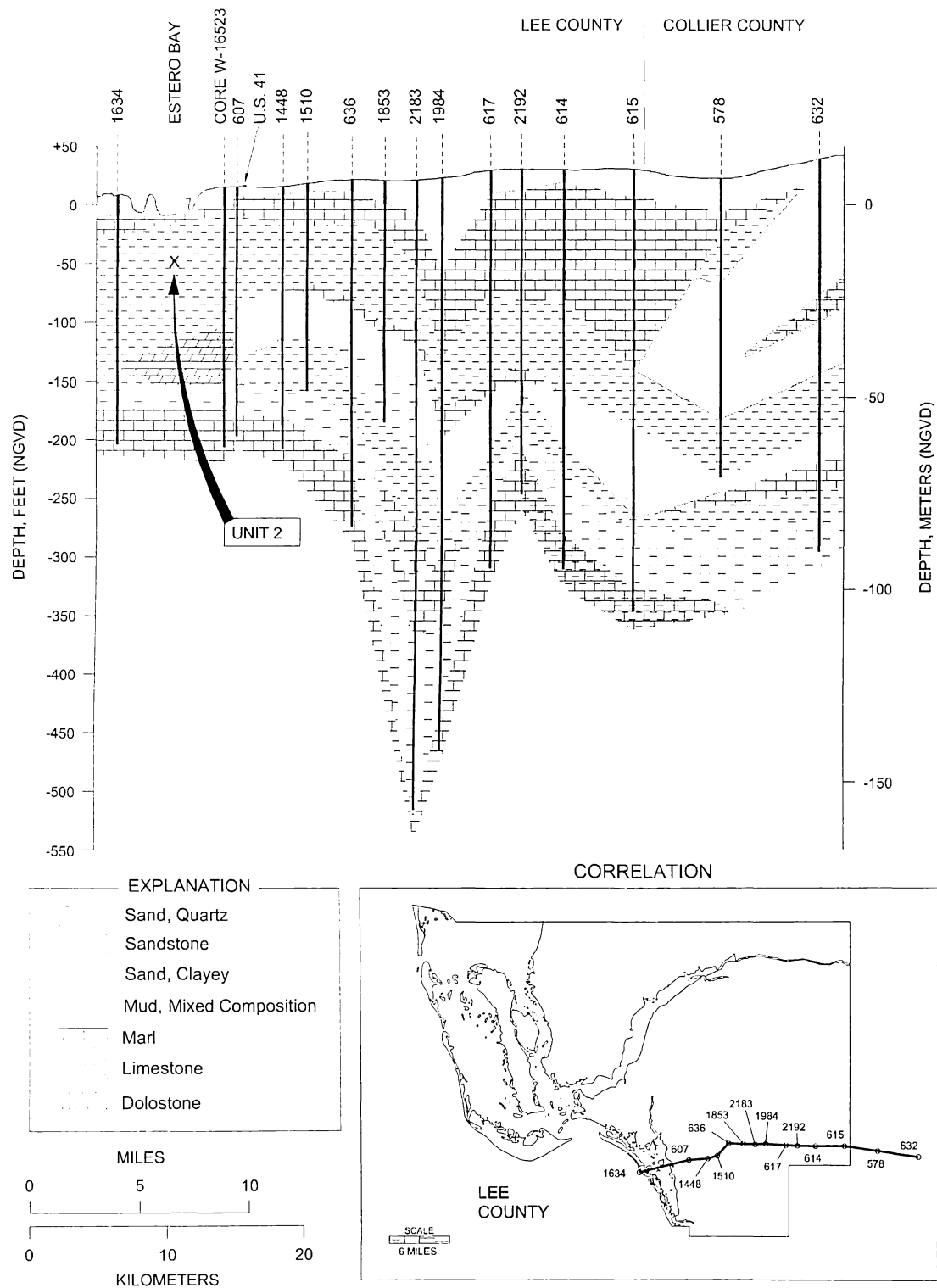


Figure 30. Correlation of well L-1984 to core W-16523 along section D-D' from Boggess et al. (1981). The first clay unit in core W-16523 is equivalent to the combined thickness of units 2A and 2B in Peck et al. (1979b). Unit 2A is equivalent to sediment package P-7 in Plate 2. Unit 2B is equivalent to sediment package P-6 in Plate 2.

of planktonic foraminifera and calcareous nannofossils for well L-1984 is given in Figure 28.

The age designation developed using foraminifera for the Peace River Formation is generally concordant with the chronologies developed using the other methods. There is agreement that the lower part of the Peace River Formation has a Late Miocene age and the uppermost part of the Peace River Formation has an Early Pliocene age (Peck et al., 1979b, division between 2A and 2B). However, the placement of the Miocene-Pliocene boundary between units 2A and 2B is somewhat problematical. There is no major discontinuity within the stratigraphic section at this location. When the seismic reflection record is reviewed along with the core data, a regional discontinuity does exist at the boundary between Units 2 and 3 at every location. In core W-16242, the equivalent of unit 2A rests disconformably upon unit 8. Also, a more recent analysis of the age implications of the calcareous nannofossils place the Miocene-Pliocene boundary at the boundary between Units 2 and 3 (Covington, 1992).

CALCAREOUS NANNOFOSSILS

Introduction

Samples were collected throughout cores W-16242 and W-16523 for calcareous nannofossil analysis. This work was conducted as a research project at the Florida Geological Survey by J. Mitchner Covington. The results of the calcareous nannofossil analyses of these cores was reported by Covington (1992).

Calcareous Nannofossil Stratigraphy of Core W-16242

Calcareous nannofossils were found in core W-16242 only above the contact with

the Arcadia Formation or in the Peace River Formation and younger Neogene units. Also, the samples for calcareous nannofossils were not collected from the lowermost part of the Peace River Formation. Heavy alteration of the carbonate sediments probably caused the destruction of any calcareous nannofossils that may have occurred in the Arcadia Formation. A selected species range chart for core W-16242 is presented in Figure 31. The investigation conducted by Covington (1992; unpublished Florida Geological Survey data) showed that samples from core W-16242 contain varying abundance and diversity of calcareous nannofossils. The age ranges of the calcareous nannofossils are plotted with the other age data on the unified chronostratigraphy of core W-16242 (Plate 4).

The observed assemblage included common to abundant *Sphenolithus abies* and *Reticulofenestra pseudumbilica*, which collectively yield an Early Pliocene age estimate. Discoasters were also present in this interval for the first time, suggesting that the paleoenvironment was more favorable for the deposition of these forms at that time. No calcareous nannofossils were found in the core below a depth of 88.4 m, or just above the contact between the upper and lower part of the Peace River Formation.

Abundant calcareous nannofossils occurred between 73.2 and 88.4 m. Nannofossil abundance began to decrease at a depth of 67.1 m and samples collected from the interval between 48.4 and 64.6 m contained no preserved calcareous nannofossils.

The rare species, *Sphenolithus abies* was observed at the 27.4 m depth. The extinction of *S. abies* occurs in the NN15/CN11b interval and approximates the boundary between the Early and Late Pliocene. This depth interval occurs within the Pinecrest Member of the Tamiami Formation. A barren interval between 21.2 and 22 m was observed.

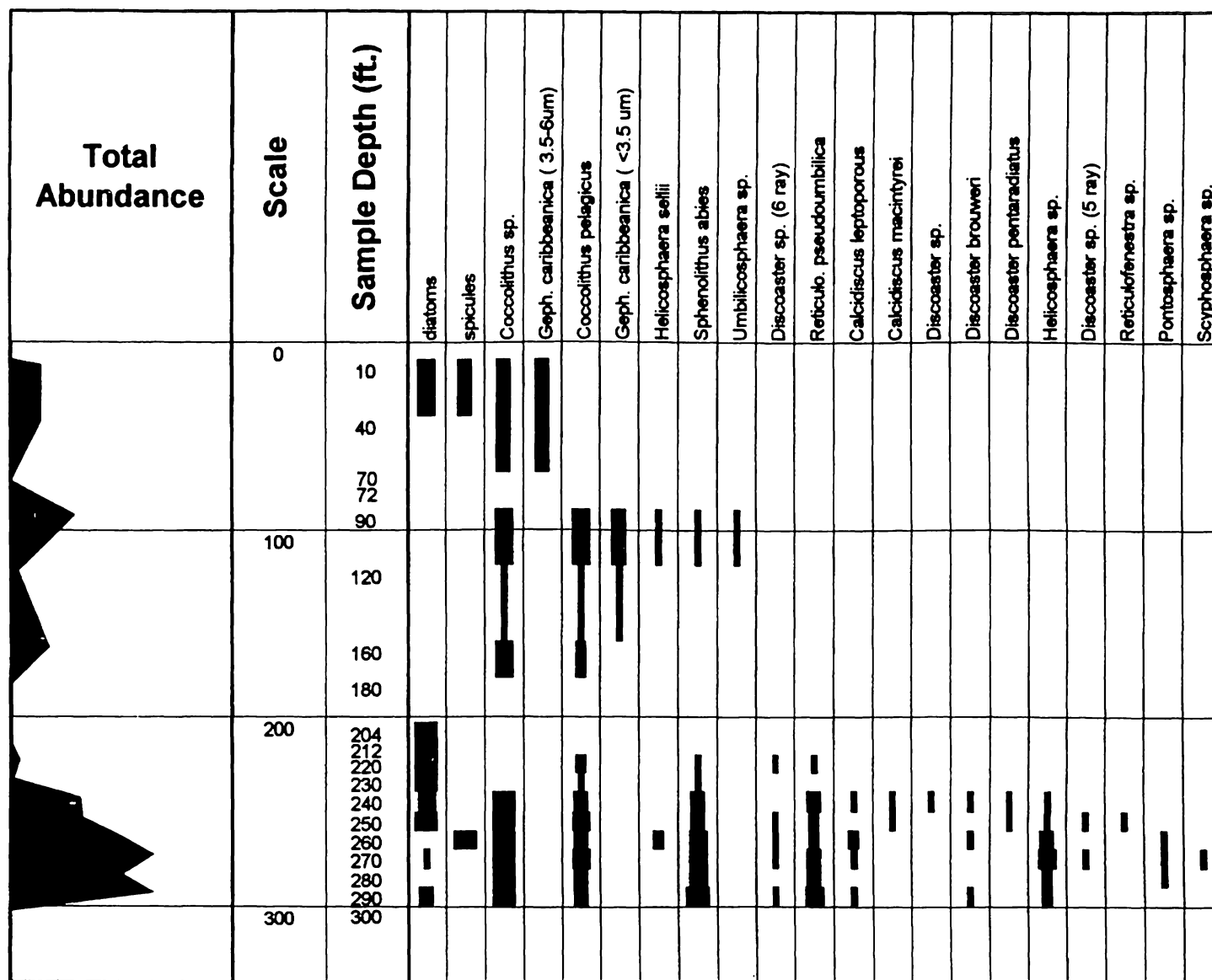


Figure 31. Calcareous nannofossil selected species range chart for core W-16242 (personal correspondence from M. Covington).

In the uppermost samples collected from three to 12.2 m, a few *Gephyrocapsa caribbeanica* were found and no *Pseudoemiliania lacunosa* were observed. This interval is probably within nannofossil zone NN20/CN14b of Martini (1971) and Okada and Burky (1980). Diversity is quite low in this interval and the absence of *P. lacunosa* may be a function of paleoenvironment rather than age. Therefore, the inferred age may be older than indicated. The general age of these sediments is interpreted to be late Pliocene or Pleistocene.

Calcareous Nannofossil Stratigraphy of Core W-16523

Calcareous nannofossils were found in core W-16523 from the mid-section of the Arcadia Formation to the top of the core. They were not found in every stratigraphic interval, but the general state of fossil preservation was better in core W-16523 compared to core W-16242. A selected species range chart is presented for core W-16523 in Figure 32.

The occurrence of *Cyclicargolithus floridanus* was noted at 177.4 m. This species may be indicative of the uppermost Oligocene. A noteworthy occurrence includes that of *Helicosphaera ampliaperta* at 153.6 m below surface. This species indicates an age between CN3/NN4 and CN1/NN2 or Early Miocene.

Discussion of Formation Ages from the Calcareous Nannofossil Data

There was no clear indication of the Miocene/Pliocene boundary in cores W-16242 or W-16523. However, the work of Peck et al. (1979b) in well L-1984, located immediately east of the cores, shows that the Miocene/Pliocene boundary lies at the boundary of the upper and lower part of the Peace River Formation, which is at 25.3 m in core W-16523. The deltaic subfacies of the Peace River Formation is Early Pliocene in age. The boundary between the

Tamiami Formation and the Peace River Formation appears to correspond to the Early-Late Pliocene boundary at 3.55 Ma, but refinements to this interpretation are given with the other age data.

Based on the calcareous nannofossil analysis of Covington (Figures 31 and 32), the possible Late Oligocene age at 177.4 m in core W-16523 lies slightly above the most probable boundary between the Early Miocene and the Late Oligocene based on the occurrence of the foraminifera *Archaias floridanus* and the other age data. The Early Miocene age of the Arcadia Formation at a depth of 153.6 m below surface corresponds well with the strontium ages and the most probable time lines between cores.

Sphenolithus abies (combined with *S. neoabies*) was noted at 18 m, indicating an age at least as old as CN11b/NN15. This is the traditional boundary between the Early and Late Pliocene. The extinction of this species occurs in zone CN12c/NN17, but the diversity of species immediately above this datum may indicate the true extinction point to be higher in the section. *Discoaster asymmetricus* was first observed at 17.7 m below surface and *Helicosphaera sellii* at 12.8 m. The extinction of this species is in CN13b/NN19 according to the calcareous nannofossil zones of Okada and Burky (1980) and Martini (1971), respectively. *Calcidiscus macintyre* was noted at 14.3 m. While the sequence of these marker species is correct, caution should be used in assuming that these species are the true extinction points, as these samples are relatively near the surface and below a barren interval.

Diatoms

Diatoms were found in various zones within the Peace River Formation. The diatom stratigraphy of this section was studied by Klinzing (1987) and the diatom occurrences were noted in the Peck et al. (1979). Klinzing (1987) described an

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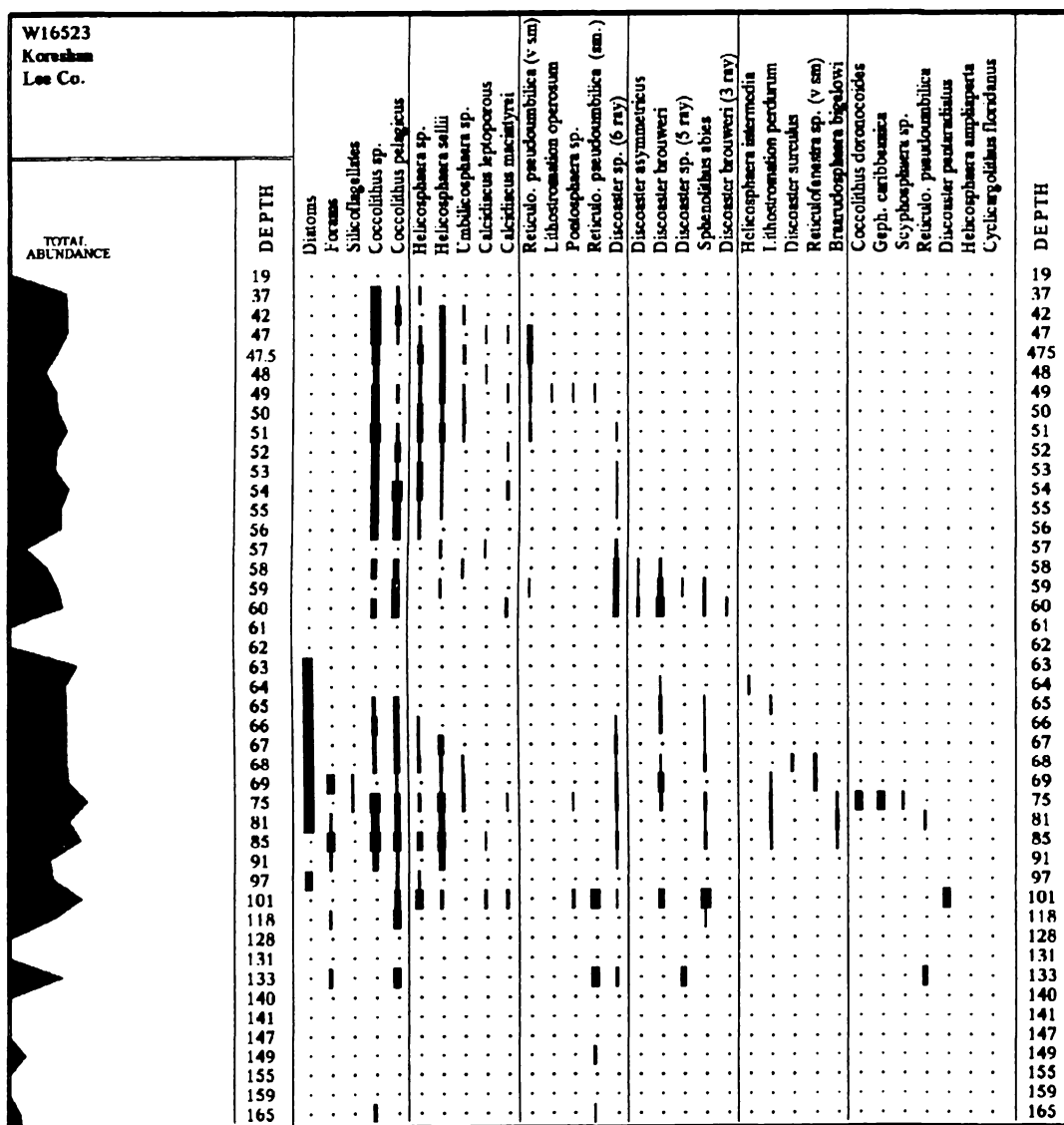


Figure 32. Calcareous nannofossil selected species range chart for core W-16523 (from M. Covington).

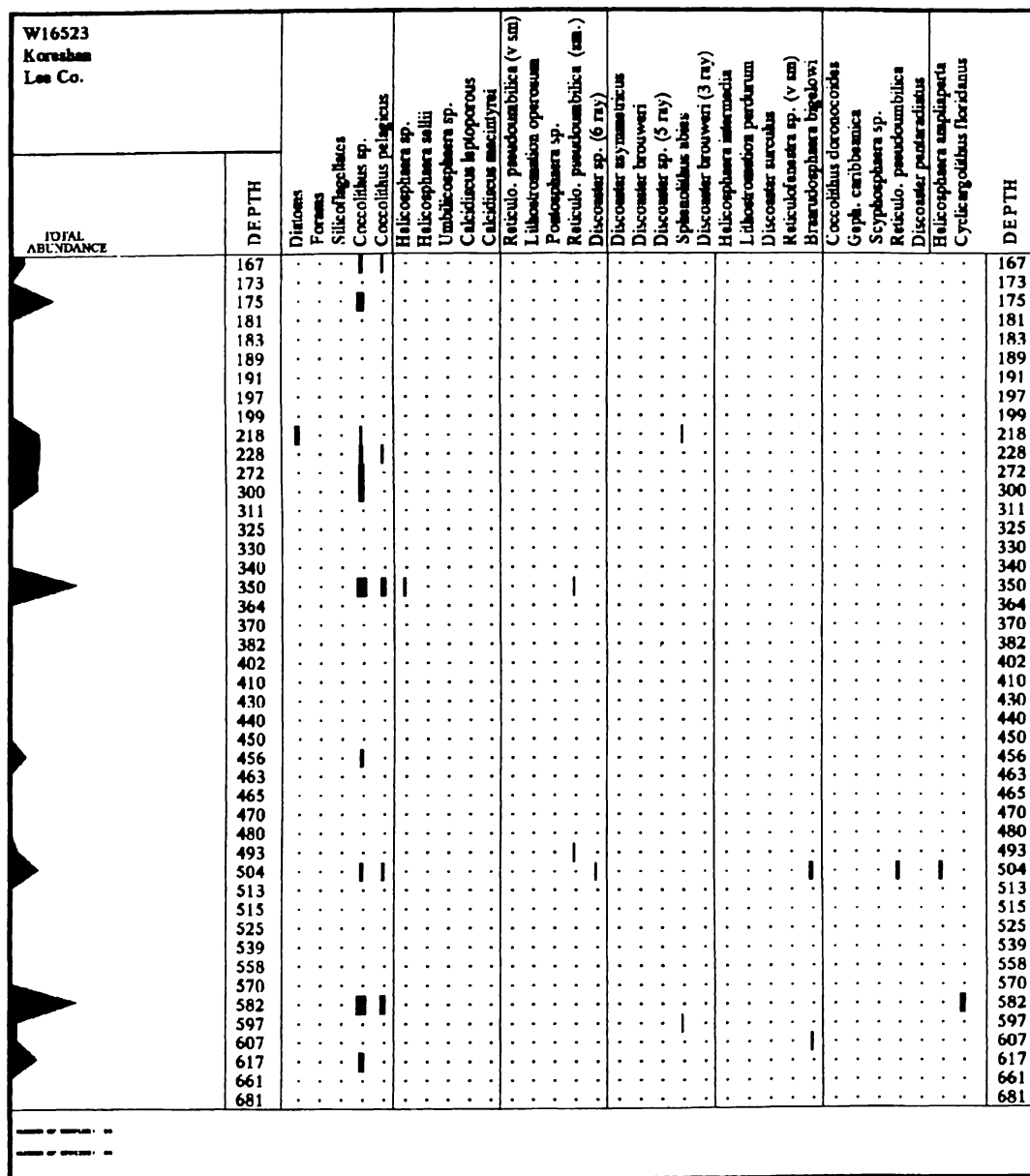


Figure 32 (Cont.). Calcareous nannofossil selected species range chart for core W-16523.

assemblage of diatoms in core W-14072, which is located about seven km to the east of core W-16523. Peck et al. (1979b) noted the occurrence of the diatoms in unit 2B and stated that only two of the diatoms were age diagnostic. The species *Actinoptycus bismarkii* and *Diploneis eximta* were reported to occur exclusively in the Late Miocene. Klinzing (1987) concluded that the Peace River Formation was Pliocene in age based on the occurrence of two species, *Thalassiosira oestrupii* and *Cussia tatsunokuchiensis*, which were believed to occur exclusively in the Pliocene. The work of Klinzing (1987) may indicate that the primary diatom bed, which occurs near the base of the upper Peace River Formation is Pliocene in age. However, the absence of detailed range data for each diatom species raises questions with regard to the actual stratigraphic occurrence of the marker species. Based on the diatom data obtained on the Peace River Formation, it is concluded that no diagnostic age designation can be made.

STRONTIUM-ISOTOPE STRATIGRAPHY

Introduction

The ratio of $^{87}\text{Sr}/^{86}\text{Sr}$ in seawater has varied significantly during Phanerozoic time (Wickman, 1948; Brass, 1976; Burke et al., 1982; Koepnick et al., 1985; Hess et al., 1986; Miller et al., 1988; Smalley et al., 1994). In the Tertiary, the ratio has increased, but at a variable rate (Hodell et al., 1989; Hodell et al., 1990; Hodell et al., 1991). The origin of the strontium isotope variation is not fully understood, but the long-term changes are related to tectonic processes, which caused changes in the exposure of the earth's crust and rock types exposed at surface to weathering. Short time-scale climatic changes influencing continental weathering, such as glaciation, may be responsible for exposing old shield

rocks, leading to accelerated erosion rates of rocks with higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Armstrong, 1971).

If equilibrium between the isotopic ratios of strontium in seawater and living, shell-producing organisms is assumed, the time dependant change of the strontium-isotope ratios in seawater is reflected in unaltered shell tests and can be used to date the material (Hodell et al., 1991). Therefore, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in unaltered calcareous marine fossils has been used successfully to determine the age of marine sediments (McKenzie et al., 1988). Both marine microfossils (benthic foraminifera) and mollusk shells have been dated using the $^{87}\text{Sr}/^{86}\text{Sr}$ technique (Hodell et al., 1991; Jones et al., 1991; Bryant et al., 1992; Compton et al., 1993). Compton et al. (1993) also demonstrated that phosphorite nodule strontium-isotope dates can be used to estimate the age of marine sediments when reworking is not significant.

Results

Strontium-isotope ratios were measured on 62 samples collected from cores W-16242, W-16523, and W-17115 (Table 7). Age determinations were made using the regression curves developed by Hodell et al. (1991) with an extrapolation to the Late Oligocene and comparison to the curve developed by Oslick et al. (1994). The measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to the appropriate NBS-987 value before age determinations were made. A total of 34 samples were analyzed from core W-16242, 17 from core W-16523, and 11 from core W-17115. In core W-16242, the material used for strontium-isotope analysis was mostly unaltered calcitic mollusk shell with the exception of samples M-5, M-6, and M-7 (aragonitic mollusks), sample M-36 (phosphorite nodule), sample M-37 (phosphorite crust), sample M-40 (recrystallized coral), and sample M-42 (foraminifera extracted from whole rock). In cores W-16523 and W-

Table 7 - $^{87}\text{Sr}/^{86}\text{Sr}$ Measurements and calculated ages of samples from cores W-16242, W-16523, and W-17115.

Sample No.	Description	Depth (m)	$^{87}\text{Sr}/^{86}\text{Sr}$ Raw	Regression $^{87}\text{Sr}/^{86}\text{Sr}$	Age ¹ (Ma)	Age ² (Ma)	Age Range ³ (Ma)
Core W-16242							
M-5	<u>Chione cancellata</u> (bivalve)	21.03	0.709086	0.709077	1.81		2.37-1.25
M-6	<u>Turritella</u> sp.	23.77	0.709048	0.709039	2.45		3.01-1.89
M-7	Pecten	28.04	0.709041	0.709032	2.45		3.01-1.89
M-8	<u>Chlamys eboreous</u>	29.95	0.709022	0.709013	2.91		3.47-2.35
M-9	<u>Chlamys eboreous</u>	31.70	0.709049	0.70904	---**		4.92-2.61
M-10	<u>Belanus</u> sp.	33.04	0.709015	0.709006	---**		4.92-2.61
M-11	Pecten	35.36	0.709064	0.709055	---**		4.92-2.61
M-12	Pecten	36.91	0.709025	0.709016	---**		4.92-2.61
M-13	<u>Hyotissa</u>	43.98	0.708874	0.708865	10.49*		11.85-9.13
M-14	<u>Hyotissa</u>	44.58	0.708907	0.708898	9.23*		10.59-7.87
M-15	<u>Hyotissa</u>	47.24	0.708905	0.708894	9.38*		10.74-8.02
M-16	Pecten	49.12	0.709032	0.709023	---**		4.92-2.61
M-17	Pecten	50.29	0.709065	0.709056	---**		4.92-2.61
M-19	Oyster	57.04	0.709031	0.709022	---**		4.92-2.61
M-29	Pecten	74.07	0.709050	0.709041	---**		4.92-2.61
M-30	Pecten	78.09	0.709010	0.709001	---**		4.92-2.61
M-31	Pecten	88	0.709030	0.709021	---**		4.92-2.61
M-20	Oyster	88.7	0.708626	0.708617	17.5*	17.98	18.24-16.76
M-32	Oyster	89.21	0.708860	0.708851	10.9		12.26-9.54
M-33	Oyster	106.22	0.708780	0.708771	13.8	15.7	15.16-12.44

¹ Age from Hoddell, et al. (1991), corrected to time scale of Berggren, et al. (1995b); ² Age from Oslick, et al. (1994), corrected to time scale of Berggren, et al. (1995b); * Not plotted, obvious stratigraphic error; ** On flat part of Hoddell curve.

Table 7 (cont.)- $^{87}\text{Sr}/^{86}\text{Sr}$ Measurements and calculated ages of samples from cores W-16242, W-16523, and W-17115.

M-33	Oyster	106.22	0.708780	0.708771	13.8	15.7	15.16-12.44
M-21	Oyster	113.33	0.708768	0.708759	14.3	17.5	15.66-12.94
M-22	Oyster	113.69	0.708746	0.708737	15.1	17.2	16.46-13.74
M-25	Oyster	118.57	0.708643	0.708634	17.3	21.7	18.04-16.56
M-27	Oyster	121.46	0.708752	0.708743	15.3	16.9	16.66-13.94
M-28	Oyster	126.49	0.708742	0.708733	15.3	16.9	16.66-13.94
M-34	Oyster	137.89	0.708640	0.708631	17.3	17.79	18.04-16.56
M-35	Pecten	162.92	0.70849	0.708481	19.8	19.95	20.54-19.06
M-36	Phosphorite nodule	166.42	0.708550	0.708541	18.8	19.12	19.54-18.06
M-37	Phosphorite crust	173.13	0.708460	0.708451	20.3	20.3	21.04-19.56
M-38	Mollusk	176.48	0.708340	0.708331	22.5	22.2	23.24-21.76
M-39	Pecten	190.23	0.708130	0.708121	25.2	25.7	25.94-24.46
M-40	Coral (altered)	192.02	0.708130	0.708121	25.2	25.7	25.94-24.46
M-41	Bivalve	202.69	0.708070	0.708061	26	26.7	26.74-25.26
M-42	Whole rock (forams)	207.87	0.708010	0.708001		28.3	29.61-26.99
W-16523							
K18	Oyster	5.49	0.709080	0.709071	1.89		2.45-1.33
K55	Oyster (thin walled)	16.76	0.708930	0.708921	---		4.92-2.61
K71.6	Anomia (bivalve)	21.82	0.709000	0.708991	---		4.92-2.61
K105.5	Oyster	32.16	0.708680	0.708671	16.6	17.2	17.34-15.86
K148.5	Pecten	45.26	0.70884	0.708831	11.7	13.3	13.06-10.34
K193	Oyster	58.83	0.70885	0.708841	11.3	13.0	12.66-9.94

Table 7 (cont.)- $^{87}\text{Sr}/^{86}\text{Sr}$ Measurements and calculated ages of samples from cores W-16242, W-16523, and W-17115.

Sample No.	Description	Depth (m)	$^{87}\text{Sr}/^{86}\text{Sr}$ Raw	Regression $^{87}\text{Sr}/^{86}\text{Sr}$	Age ¹ (Ma)	Age ² (Ma)	Age Range ³ (Ma)
K252.1	Oyster	76.84	0.70857	0.708561	18.5	18.4	19.24-17.76
K301.9	Oyster	92.01	0.70850	0.708491	19.6	19.8	20.34-18.86
K397	Oyster	121.01	0.70856	0.708551	18.6	18.9	19.34-17.86
K443.2	Pecten	135.09	0.70859	0.708581	18.9	18.5	19.64-18.16
K492.1	Plicula (bivalve)	149.99	0.70844	0.708431	20.5	20.5	21.24-19.76
K553	Pecten	168.55	0.70828	0.708271	23.7	23.9	24.44-22.96
K585.3	Pecten	178.4	0.70873	0.708721	15.9	17.9	16.64-15.16
K623.6	Hytissa	190.07	0.70813	0.708121	25.2	25.7	25.94-24.46
K664.5	Pecten	202.54	0.70812	0.708111	25.4	25.8	26.14-24.66
K708.2	Pecten	215.86	0.70805	0.708041	26.2	27.0	26.94-25.46
W-17115							
MI47.5	Hytissa	14.48	0.70903	0.709021	---	---	4.92-2.61
MI75.5	Oyster-thin wall	23.01	0.70903	0.709021	---	---	4.92-2.61
MI111.1	Oyster thin-wall	33.86	0.70904	0.709031	---	---	4.92-2.61
MI144.5	Pecten	43.89	0.70902	0.709011	---	---	4.92-2.61
MI192	Bivalve	58.52	0.70889	0.708881	9.94	---	11.30-8.58
MI340	Oyster	103.63	0.70873	0.708721	15.7	16.5	17.06-14.34
MI389.3	Oyster	118.66	0.70871	0.708701	16.3	16.8	17.04-15.56
MI447	Bivalve	136.25	0.70872	0.708711	16.1	16.7	16.84-15.36
MI474.4	Oyster-thin wall	144.6	0.70857	0.708561	18.5	18.8	19.24-17.76
MI571	Pecten	174.04	0.70863	0.708621	17.5	17.9	18.24-16.76
MI623.3	Hytissa	189.98	0.70852	0.708511	19.4	19.5	20.14-18.66

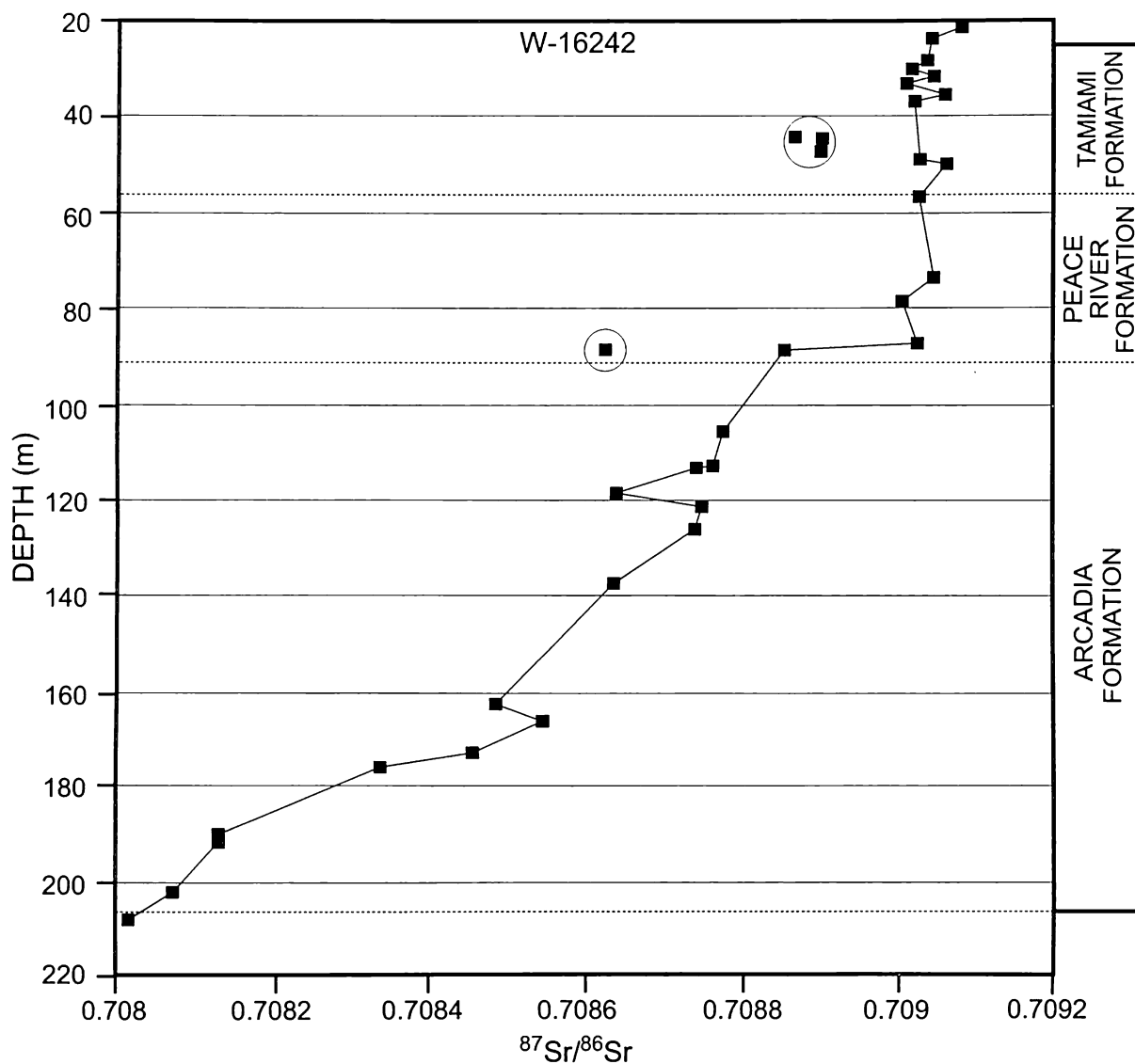


Figure 33. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with depth in core W-16242 showing a general reduction with age. This trend is consistent with the models of $^{87}\text{Sr}/^{86}\text{Sr}$ variation in seawater with time (Hoddell et al., 1991; Oslick et al., 1994). Four of the measured ratios were not in stratigraphic order and were eliminated from the age analysis, because of sample contamination or reworking of the shell from which the samples were collected. Depths are below land surface.

17115, all material analyzed for strontium isotopes was calcitic mollusk shell.

The reduction in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio with depth was relatively consistent in core W-16242 (Figure 33) with the exception of three samples within the Tamiami Formation section (numbers M-13, M-14, and M-15) and one sample in the lower part of the Peace River section (number M-20). The four samples with lower than expected strontium-isotope ratios were shell samples, from the genus *Hyotissa*. Petrographic examination of thin sections containing *Hyotissa* showed that, in some cases, very fine sand-sized phosphorite grains were trapped within the shell structure of the mollusk. Since phosphorite is reworked throughout the younger part of the stratigraphic section above the Arcadia Formation, it is likely that any phosphorite incorporated in younger mollusk shells would be much older and would be a significant factor in causing a lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. It is also possible, although less likely, that these samples were reworked. There is consistency in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio above and below the suspect samples, which strengthens the case to dismiss the validity of these samples. A similar case can be made for sample M-20, which yielded a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio much lower than anticipated. In this case, it is likely that this shell material was reworked, because of its stratigraphic position near a major discontinuity. Based on the variation in the data within the stratigraphic framework, it can be concluded that this set of data appears to yield a relatively consistent pattern and that it is necessary to have a fairly large number of analyses in order to rely strictly on strontium-isotope data for age determination.

Strontium-isotope data collected from core W-16523 showed considerable scatter, but the overall trend for the stratigraphic units was similar to core W-16242 (Figure

34). Sample K105.5 showed a very low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, which is the probable result of phosphorite contamination as previously described or the shell may be reworked. Sample K585.3 showed a very high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, which cannot be explained, but may be the result of sample contamination.

The strontium-isotope data from core W-17115 also show a relatively consistent stratigraphic pattern similar to the other cores (Figure 35). There is some scatter in the data in the lower part of the core with sample MI571 showing a higher than expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. The lower stratigraphic section of core W-17115 was not extensively sampled because of a lack of acceptable material for strontium-isotope analysis.

STRONTIUM-ISOTOPE AGE CONSTRAINTS ON STRATIGRAPHIC UNITS

Introduction

Age determinations were made by comparing the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to the variation in $^{87}\text{Sr}/^{86}\text{Sr}$ in the ocean through time as determined by Hodell, et al. (1991) and for the Oligocene to Middle Miocene sediments the ages were also determined using Oslick et al. (1994). Age determinations made using both models were corrected to the time scale of Berggren et al. (1995b). A series of regression curves were developed by Hodell et al. (1991) to allow age approximation in various time increments during the Neogene. Because of a change in the laboratory technique at the University of Florida, in order to use the regression curves for age approximation, it was necessary to subtract 9×10^{-6} from the measured ratio before using the equations because of a change in the MBS 987 value (P. Mueller, personal communication). The Hodell et al. (1991) age model was used, because of inconsistent results of the middle Miocene age determinations obtained

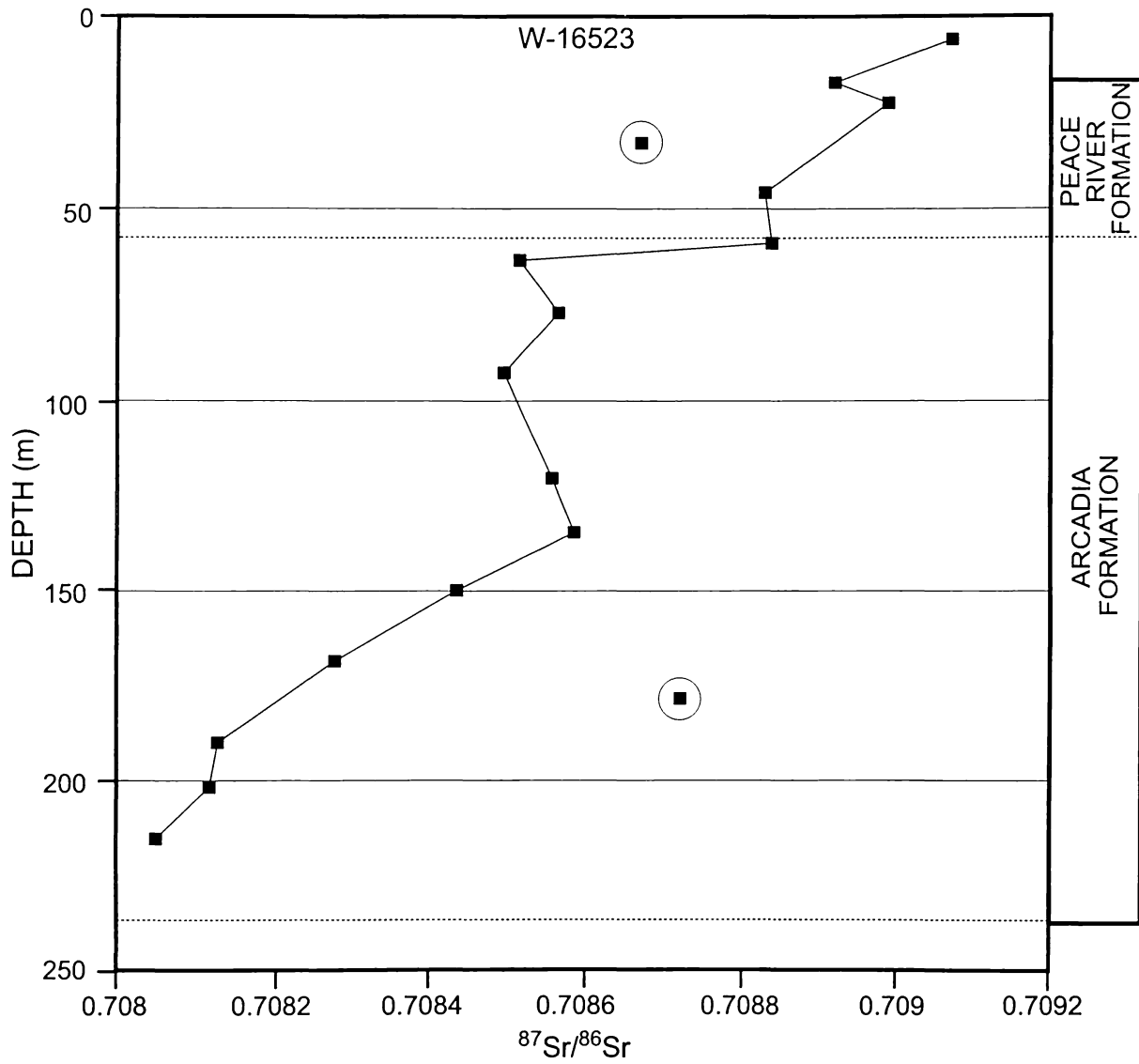


Figure 34. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with depth in core W-16523. The ratio generally declines with age, but the reduction is not regular, suggesting some reworking and/or contamination of samples. Depths are below land surface.

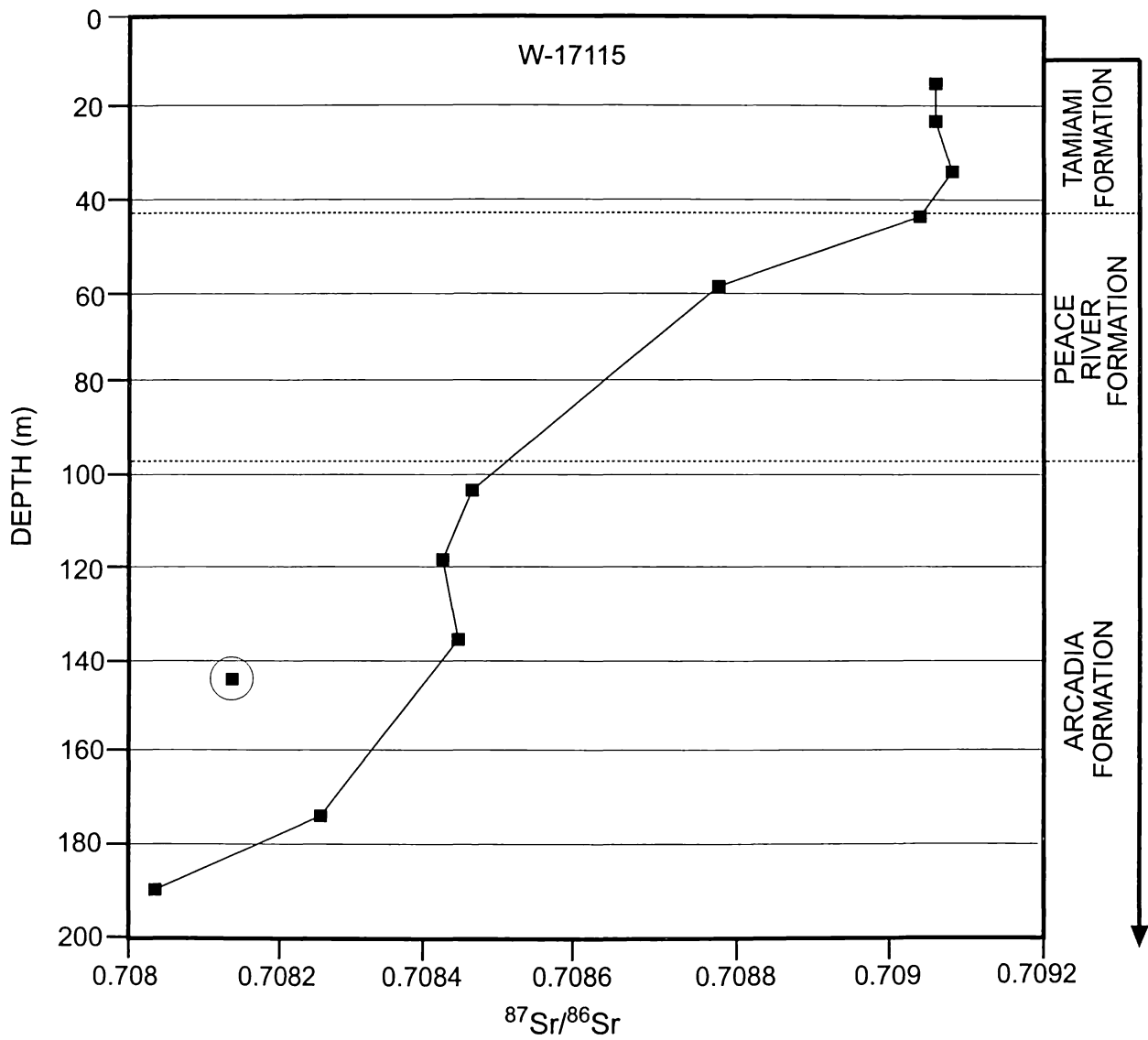


Figure 35. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with depth in core W-17115. The reduction in the strontium isotope ratio is relatively consistent with the exception of sample MI571 at MI474 (at 144 meters). Depths are below land surface.

using the Oslick et al. (1994) model. During some specific time increments, 4.5 to 2.5 Ma and 8.0 to 5.5 Ma, the slope of the strontium-isotope curve is flat, which does not allow an accurate age to be determined within that interval. However, it does provide some significant constraints on the range in age.

Based on the regression age determination, plots of age versus depth for each of the three cores were constructed in Figures 36, 37, and 38. Within core W-16242 there are quite significant gaps in the time stratigraphic record at depths of about 24, 30, 88, 92, and 175 m (Figure 36). Gaps in the time stratigraphic record in core W-16523 occur at about 10, 23, 56, and 155 m (Figure 37). Although few strontium-isotope values were collected from core W-17115, gaps occur at 44 and 100 m (Figure 38). All stratigraphic data for each core are plotted with the strontium-age determinations in Plates 1 to 3.

Age of the Suwannee Limestone Based on Strontium Isotopes

Only one sample was collected from the Suwannee Limestone for age determination in core W-16242. Based on the regression curve of Oslick et al. (1994), the estimated age of the sample from core W-16242 is 29.6 to 26.8 Ma.

Age of the Arcadia Formation Based on Strontium Isotopes

The Arcadia Formation lies disconformably between the underlying Suwannee Limestone and the overlying Peace River Formation (Plates 1, 2, and 3). There are a numerous sediment sequence types within the Arcadia Formation as well as both regional disconformities and minor discontinuities (Sections 2 and 4). Comparisons of strontium-isotope age estimates for the Arcadia Formation in cores W-16242, W-16523, and W-17115 are given

in Table 7.

A relatively large number of samples were collected from the Arcadia Formation in each core because of the lack of information on the age of this unit and the general abundance of unaltered mollusk shell acceptable for strontium-isotope analysis. In core W-16242, 14 strontium-isotope samples were collected and analyzed. Estimated ages ranged from 26.7 to 12.4 Ma. The estimated ages were concordant with the stratigraphic position in the core with the exception of sample M-20, which was likely reworked. This sample was collected from an oyster, which sometimes yield anomalous $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, as discussed earlier (Dr. P. Mueller, University of Florida, personal communication). The youngest age estimate of 12.9 Ma shows that a gap of one to three million years, based on age error ranges, occurs between the top of the Arcadia Formation and the base of the Peace River Formation in this core. Another gap in the stratigraphic record occurs at approximately 177 m below surface. The age estimate for the lowest sample collected in the section, at a depth only about five m above the Suwannee/Arcadia Formation contact, is 25.3 to 26.7 Ma.

Estimated ages from $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured in core W-16523 are not as consistent with stratigraphic position as observed in core W-16242. The age range of the 11 samples collected from the core are from 26.9 to 9.94 Ma. The estimated age range is similar to that found in core W-16242 with the exception of the 9.94 Ma age determined for the uppermost sample, which overlaps in age with the lower part of the Peace River Formation in all other cores. The error range on the youngest strontium-isotope age suggests that sedimentation at this location may have occurred in late Miocene time, after 11.3 Ma, but this is considered unlikely based on the carbon and oxygen isotope data.

Only six samples were collected from core W-17115 for strontium-isotope analy-

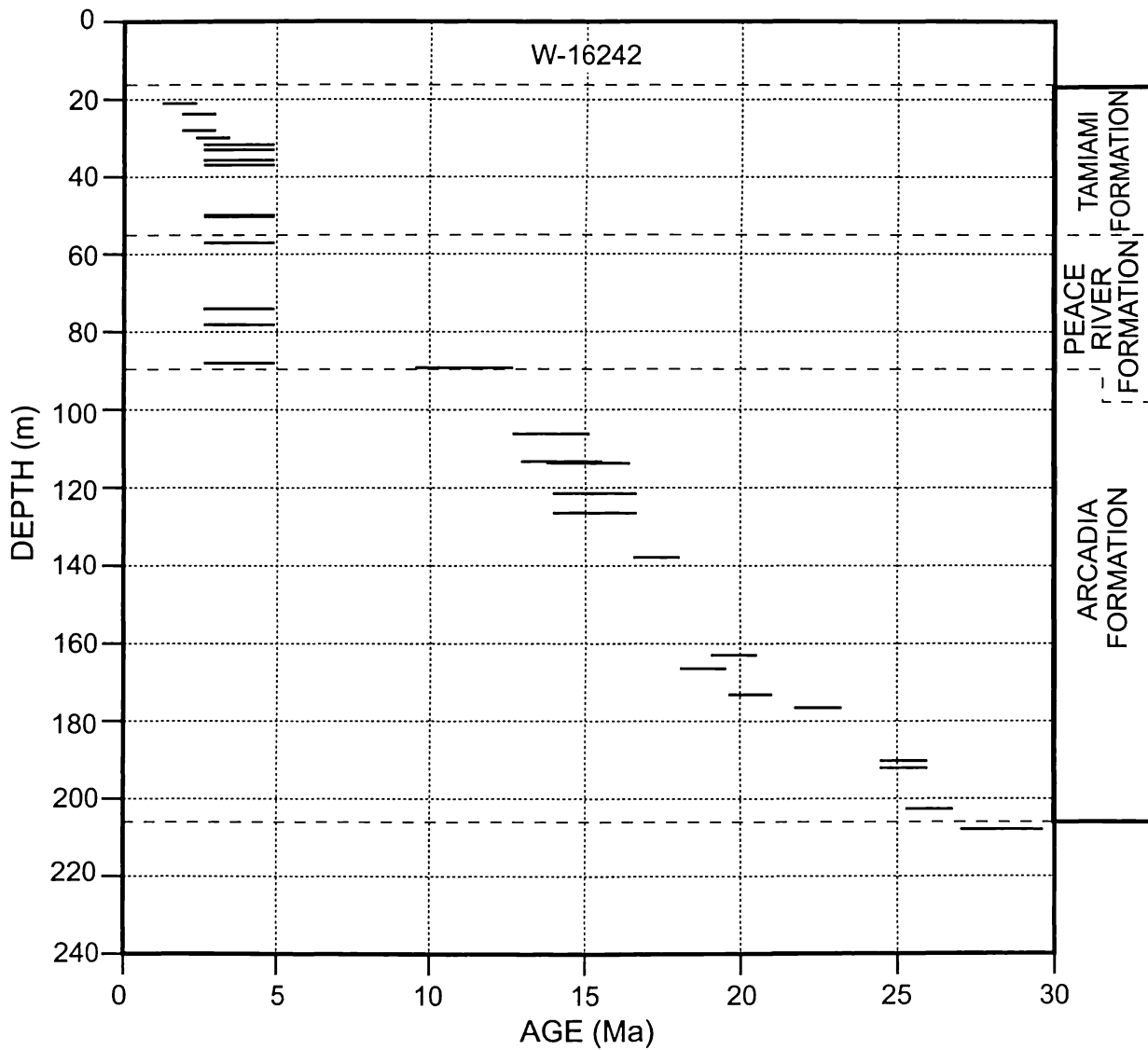


Figure 36. Age ranges of strontium-isotope samples with depth in core W-16242. The model of Hoddell et al. (1991) was used to determine the ages for all samples except the lowermost sample. The lowermost sample age was determined using the model of Oslick et al. (1994). All ages were corrected to the time scale of Berggren et al. (1995b). The bars represent the age error range. Depths are below land surface.

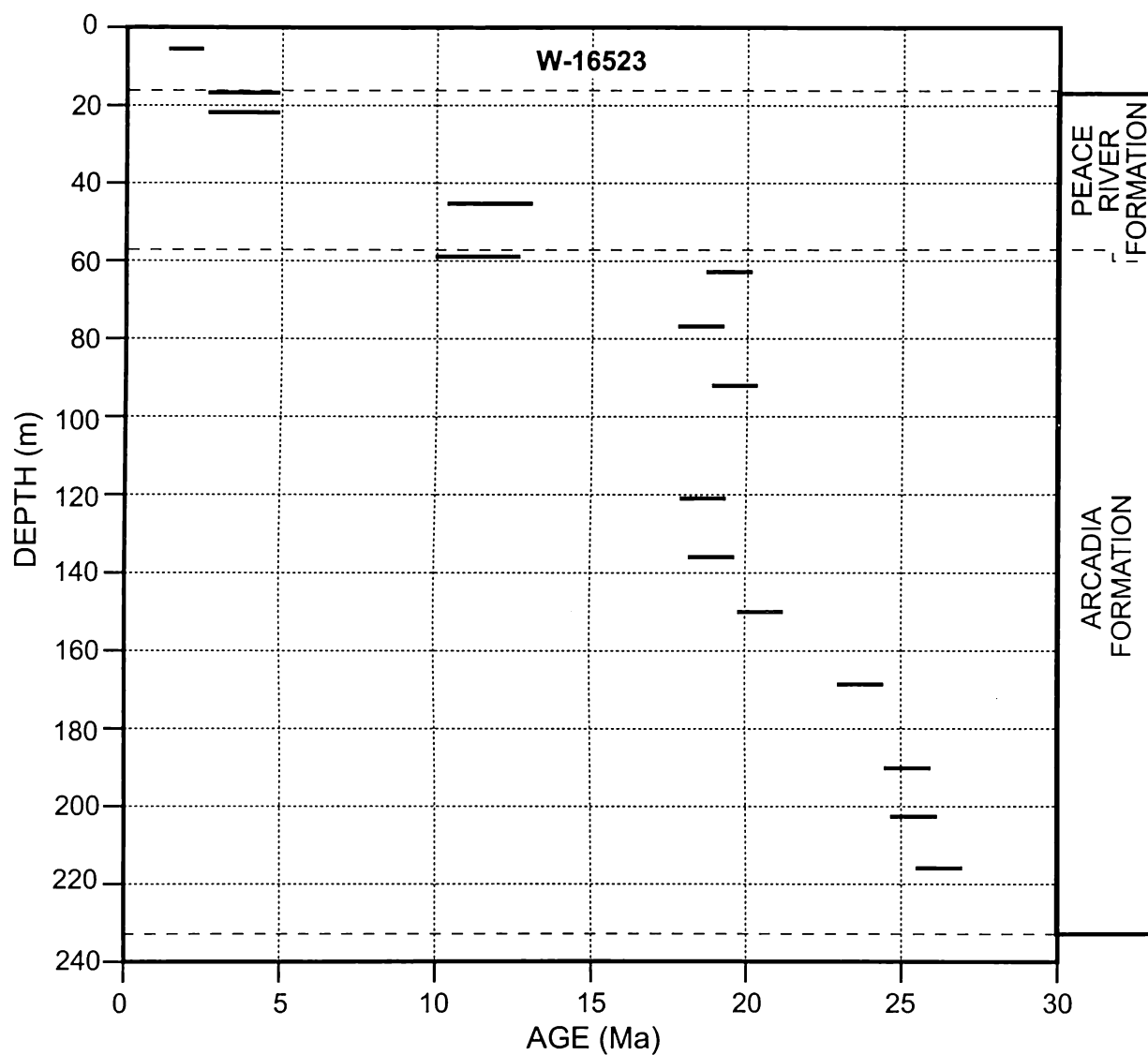


Figure 37. Age ranges of strontium-isotope samples with depth in core W-16523. The model of Hoddell et al. (1991) was used to determine the ages for all samples. All ages were corrected to the time scale of Berggren et al. (1995b). The bars represent the age error range. Depths are below land surface.

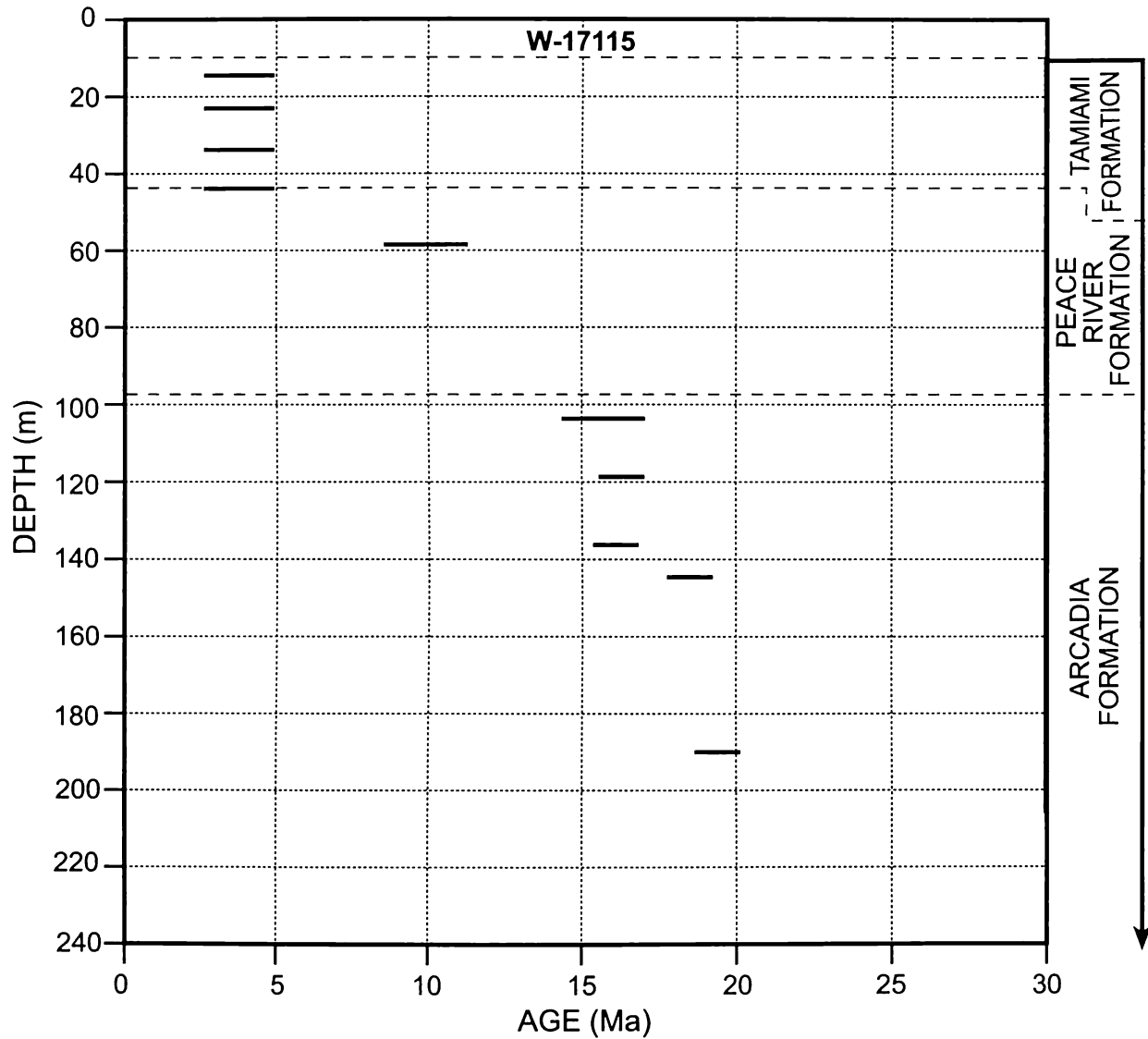


Figure 38. Age ranges of strontium-isotope samples with depth in core W-17115. The model of Hoddell et al. (1991) was used to determine the ages for all samples. All ages were corrected to the time scale of Berggren et al. (1995b). The bars represent the age error range. Depths are below land surface.

sis. Estimated ages ranged from 20.1 to 14.3 Ma based on these few samples. Because of the locations and number of age estimates, it is not reasonable to draw significant conclusions from this data set. These data are useful in assessing down-dip time lines. No datable material could be found in the lower or oldest part of the core.

Based on the strontium-isotope ratios measured in cores W-16242, W-16523, and W-17115, the most reasonable age range for the deposition of the Arcadia Formation is from about 27 to 12 Ma. This means that deposition began within Late Oligocene, Chattian Age and continued into the Middle Miocene, Serravallian Age. Significant hiatuses appear to occur both at the Miocene-Oligocene and the Early Miocene-Middle Miocene boundaries based on the strontium-isotope ages. This estimated time gap appears to be between two and three million years, which will be refined based on magnetostratigraphic data.

Age of the Peace River Formation Based on Strontium Isotopes

There are two distinctive facies within the Peace River Formation. A series of predominantly siliciclastic nearshore ramp, beach, and lagoonal deposits lie in the lower part of the formation capped by a distinct disconformity. The upper unit is a mixed siliciclastic-carbonate unit containing deltaic characteristics, such as graded beds and angular bedding (Figure 23). Stratigraphic comparisons of the strontium-isotope age estimates for cores W-16242, W-16523, and W-17115 are given in Table 7.

A disconformity occurs between the siliciclastic marine facies and the overlying deltaic facies. The lower facies within the Peace River Formation is very thin in core W-16242 (3.5 m) and thickens generally to the south, especially in core W-17115 (55 m).

A single sample was collected from this unit in each core. The sample from core W-16242 yielded an age estimate of 12.3 to 9.54 Ma and the age estimates of the samples from cores W-16523 and W-17115 were 13.06 to 9.94 and 11.3 to 8.58 Ma, respectively. A similar age for this unit in core W-10671 was estimated from strontium-isotope data by Compton et al. (1993).

It was difficult to find good quality shell material for strontium-isotope analysis in the deltaic facies of this formation. Therefore, a relatively small number of samples was collected from cores W-16242 and W-16523. In core W-17115, only the lower siliciclastic unit was present and the deltaic sequence was missing (Plate 3). Three samples were collected from the deltaic sequence in core W-16242. All three samples produced strontium-isotope ratios lying on the flat part of the curve (Figure 39). Therefore, the age ranges are 4.92 to 2.61 Ma. A single sample collected from core W-16523 also yielded an age range of 4.92 to 2.61 Ma. These strontium-isotope age estimates are the same as the age estimates for the lower part of the Tamiami Formation and suggest relatively continuous sedimentation beginning with the deltaic sequence in the Peace River Formation and ending with the sand facies of the Tamiami Formation. Similar strontium isotope age estimates for this stratigraphic unit in core W-10761 to the north (Charlotte County) were reported by Compton et al. (1993).

Based on the age estimates of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, the age of the Peace River Formation ranges from about 13.1 to 2.61 Ma. However, a disconformity separates the two major facies within the unit and a considerable amount of the stratigraphic record is missing based on nannofossil data. The basal, predominantly siliciclastic unit ranges in age from 13.1 to 9.54 Ma and is considered Late Miocene or predomi-

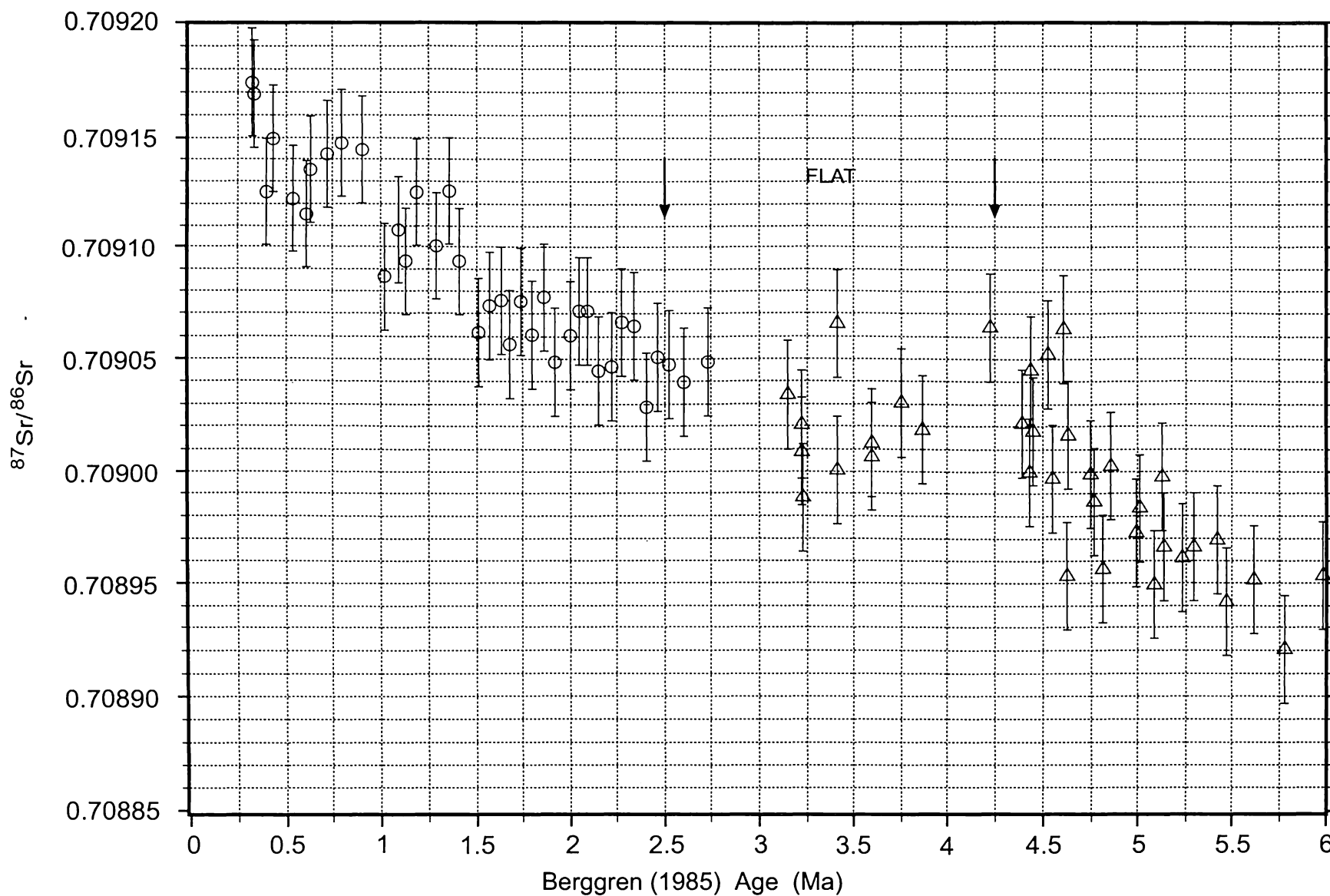


Figure 39. Strontium-isotope ratios versus age range using the Berggren (1985) time scale (from Hodell et al. 1991 data). Note the area of flat curve (marked with arrows), which does not allow an accurate age determination.

nantly Tortonian in age. Although the error range of the strontium-isotope ages suggests that some of the sediments may be Middle Miocene (greater than 11.2 Ma) in age, this is unlikely based on the nannofossil and carbon and oxygen isotope data. The deltaic sequence in the upper part of the formation ranges from 4.92 to 2.61 Ma in age, but in consideration of the measurement errors and age constraint placed on the unit by the overlying section, the actual age probably ranges from about 5.2 to 4.2 Ma.

Age of the Tamiami Formation Based on Strontium Isotopes

Two distinct stratigraphic units were dated within the Tamiami Formation. In core W-16242, the Tamiami Formation is divided into the Sand Facies at the bottom of the section with the Pinecrest Member overlying it, following the terminology used in Missimer (1992b). Samples were collected from each of the three cores within the lower part of the Tamiami Formation for strontium-isotope analysis. In core W-16242, age determinations were made on ten analyses (numbers M-9 to M-19 in Table 7). Three of the ten samples (M-13, M-14, and M-15) are not considered in this discussion because they are invalid as previously discussed. The seven samples showed $^{87}\text{Sr}/^{86}\text{Sr}$ ratios occurring on the flat part of the strontium-isotope curve (see Figure 38). Based on the range of occurrence, the samples age range is somewhere between 4.92 and 2.61 Ma based on the Berggren et al. (1995b) time scale. Two samples were collected from the Tamiami Formation in core W-16523 (numbers K18 and K55 in Table 7). The uppermost sample yielded an estimated age of 1.89 $\pm$ 0.50 Ma, which is suggestive that the uppermost part of the limestone has an age similar to the Pinecrest Member rather than the underlying Sand Facies. The second sample yielded an isotopic ratio, which

placed it on the flat part of the strontium-isotope curve, which yields an age range of 4.92 to 2.61 Ma. The four strontium-isotope age determinations made from core W-17115 (numbers MI 47.5 to MI 144.5) all fall on the flat part of the curve and also yielded an age range from 4.92 to 2.61 Ma.

Three samples were collected from the Pinecrest Member of the Tamiami Formation and had age determinations ranging from 2.91 to 2.45 Ma and with the full stratigraphic error from 3.41 to 1.95 Ma. Similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured from the classical Pinecrest Member beds in Sarasota County (Jones et al., 1991).

Based on the strontium-isotope age estimates, the Tamiami Formation has an age range of 4.95 to 1.95 Ma based on the error range. However, it is quite likely that the age of the Tamiami Formation is actually in the middle range of the values measured, because of the age constraints placed on the unit by the ages of both the underlying Peace River Formation and overlying Caloosahatchee Formation. There is a disconformity occurring within the Tamiami Formation separating the Sand Facies from the overlying Pinecrest Member, with a few hundred thousand years of time missing. Based on the data collected, it appears that the Sand Facies of the Tamiami Formation was deposited rather rapidly in perhaps a time period of only a million years most likely between 4.2 and 3.2 Ma.

MAGNETOSTRATIGRAPHY

Introduction

Determination of magnetic polarity changes within sediment sequences is an accepted method of approximating the age of the sediments (Cande and Kent, 1992; Berggren et al., 1995a). However, the use of the magnetostratigraphy is not an independent method to determine age, especially when a stratigraphic section is divided by one or more disconformities. In this

study, a number of biostratigraphic and chronostratigraphic methods were applied to assist magnetostratigraphic correlation to the GPTS of Berggren et al. (1995b).

Measurement of depositional remnant magnetization or early post-depositional remanent magnetization in carbonate sediments has been recently utilized to determine polarity changes (Kirschvink, 1983; McNeill et al., 1988; McNeill, 1989). The Neogene sediments of the South Florida Platform present some interesting problems, because they contain both weakly magnetized carbonate sediments and detrital siliciclastic sediments containing a significantly stronger magnetic carrier.

Laboratory Methods

Analytical procedures utilized in this investigation closely follow those described by McNeill et al. (1988).

Rock Magnetic Analysis

A series of 12 samples representing all of the general rock types found in the stratigraphic section of core W-16242 were selected for rock magnetic analysis. The purposes of the rock magnetic analysis was to identify and assess the carrier of magnetic remanence. The measurement sequence involved: measurement of the sample natural remanent magnetization (NRM), sample demagnetization at 100 mT, anhysteretic remanent magnetization (ARM) acquisition at 100 mT with field bias of 0, 0.5, 1.0, 1.5, and 2.0 mT, alternating field (AF) demagnetization (21 steps) of isothermal remanent magnetization (IRM), and IRM saturation (31 steps).

Coercivity spectral analysis plots and ARM acquisition plots were constructed from the magnetic measurements. From these data it was possible to perform a modified Lowrie-Fuller test to aid in assessing if the NRM was carried by single-domain/pseudo single-domain magnetite or a coarser multidomain component (Lowrie

and Fuller, 1971).

Since the carrier was suspected to be single-domain magnetite in the predominantly carbonate sediments and multi-domain or pseudo single-domain magnetite associated with the siliciclastics, an ARM analysis was performed on each sample on which the coercivity spectral analysis was performed. A plot of the ARM data at each bias field step vs. the ratio of ARM to saturation IRM value was made for each sample. ARM plots, calibrated for freeze-dried, non-interacting single-domain bacterial magnetite vs. highly interacting, single-domain, chiton magnetite (upper and lower open circles in plot, respectively), are indicators of the magnetic interacting status of single-domain grains within the natural rock matrix (Cisowski, 1981).

Paleomagnetic Methodology and Sample Classification

Oriented samples collected from core W-16242 were measured using a 2G Enterprises cryogenic (superconducting) magnetometer located within a magnetically shielded room. Samples were collected from the core by drilling plugs where the rock was well lithified, pressing plastic cubes into the core where it was unlithified, or hand carving small blocks where the core could not be drilled, but was too hard to use the plastic cubes. The collected samples were about six cm³ in size with some variation in the hand carved samples. The magnetic susceptibility of each weighted sample was measured by use of a Bartington susceptibility meter to help assess variation in the magnetization in the core. Next, the NRM of each sample was measured and then the samples were systematically demagnetized at progressively higher AF in steps ranging between five and 10 mT. The samples contained in the plastic cubes were demagnetized using AF up to 100 mT. All other samples were demagnetized to 50 mT using AF and then thermal demagnetization. The thermal demagnetization pro-

cedure involved heating each sample for a period of 1 hour in a furnace and the samples were then cooled in a Mu-metal shield before the paleomagnetic measurements were made. The thermal demagnetization steps began at 100°C and proceeded at 50°C steps to 400°C. The thermal increment was reduced at this temperature to 25°C steps. Samples were demagnetized until the J value was consistently below about 3×10^{-8} emu or when the sample became magnetically unstable (non-reproducible measurements). Upon completion of the demagnetization, the magnetic susceptibility of each sample was remeasured.

A least-squares analysis of paleomagnetic data was used to calculate the inclination angle and the maximum angular deviation (MAD) of the sample (Kirschvink, 1980). The paleomagnetic data were reviewed to assess the consistency of the inclination angle and declination at each demagnetization step to judge the validity of the calculated final inclination angle.

The samples were classified into four general groups for analysis. Class A samples usually showed a uniform decay of the vector component, MAD angles of 100 or less, at least 12 data points were measured, and a steady decline in the J/Jo ratios during demagnetization and the inclination was determined with considerable certainty. Class B samples often showed two vector components one of which was removed during AF and low thermal demagnetization, usually had MAD angles less than 150 or less for the stable component and at least 10 data points were measured. The stable component showed a steady decline in the J/Jo ratio with demagnetization. The inclination angle determinations (using the stable component) for this group are viewed as still being reliable. Class C samples showed an initial steady decline in the J/Jo values, but in the thermal demagnetization stages, the J value began to rise, indicating a mineralogic transformation. A

determination of the inclination angle could be determined from the AF data and the lower temperature demagnetization steps in most of these samples. MAD values were usually less than 200 for the stable samples, and at least five points were measured. However, in several samples a consistent inclination value could not be accurately determined and the results had to be discarded or left in question. Class D samples showed either very weak, unstable magnetization and/or a very irregular change in the J/Jo ratio during demagnetization. The data from these samples were not useable for polarity and inclination determinations. A series of samples are listed as Class E. Class E samples have a higher MAD than normally acceptable (greater than 20°). However, all parts of the demagnetization curve yield a consistent polarity result and the error angle is close to the Class C standard. These samples, following AF and thermal demagnetization, were judged reliable to determine polarity.

Results

Magnetic Remanence Intensity

There is a general relationship between the strength of sediment magnetization and the percentage of the siliciclastic component within the sediment. Beginning at the base of the core, there is a distinct increase in the magnetic susceptibility at about 201 m, which correlates closely to the stratigraphic boundary between the Suwannee Limestone and the Hawthorn Group. There is a general increase in the siliciclastic component of the sediment up-section in the Arcadia Formation. Extreme variation in magnetic susceptibility occurs in the upper part of the Arcadia Formation and it correlates quite well to the presence of a higher percentage of siliciclastic sediment, particularly with regard to clay mineral occurrence. Magnetic susceptibility is generally high throughout the Peace River

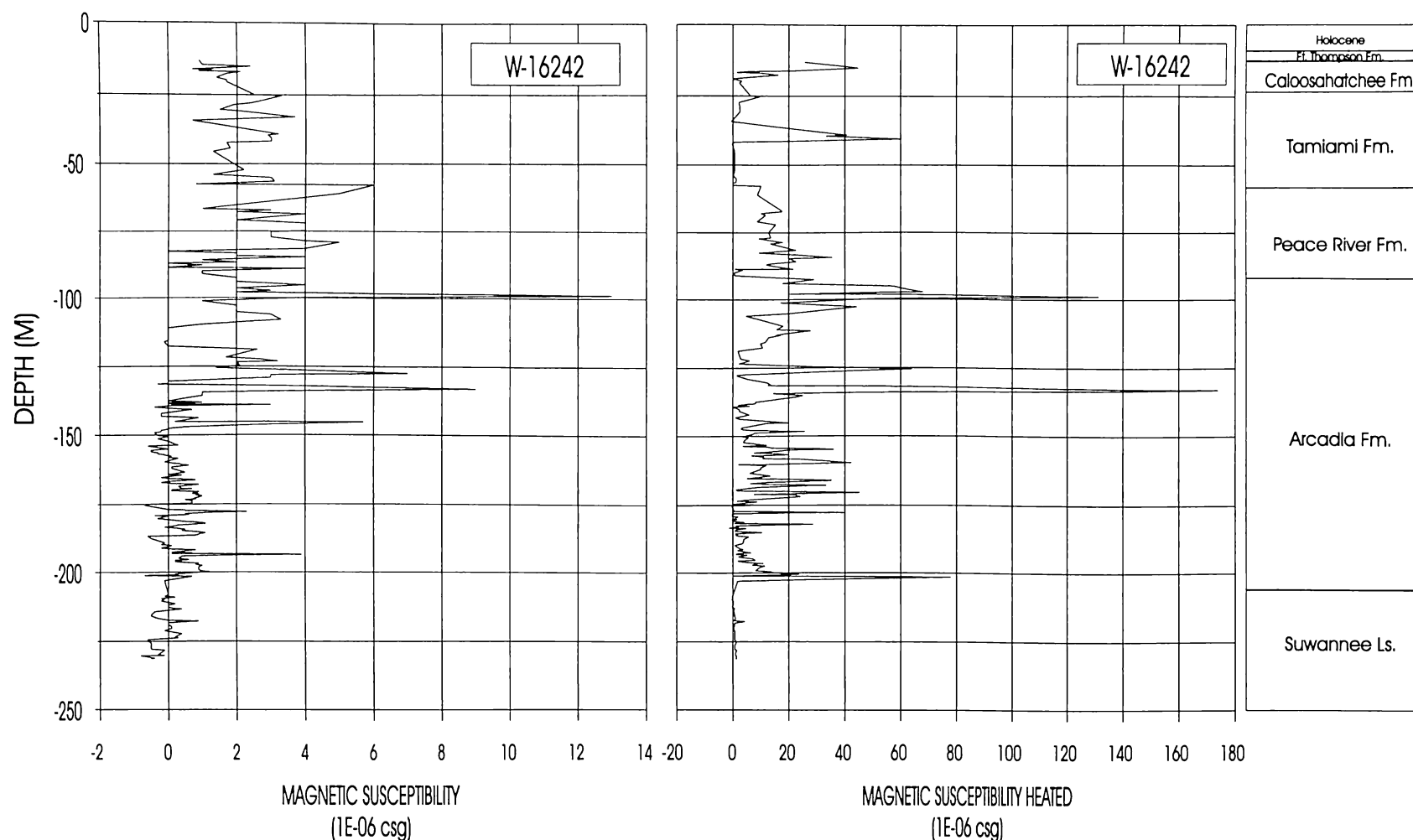


Figure 40. Magnetic susceptibility with depth in core W-16242. On the left, the measured magnetic susceptibility increases from the predominantly carbonate sediments of the Suwannee Limestone upward into the mixed carbonates and siliciclastics of the upper Arcadia Formation and Peace River Formation. A re-measurement of the magnetic susceptibility after thermal demagnetization (on right) shows a substantial susceptibility increase in samples collected from the Arcadia and Peace River Formations. This increase was caused by mineral transformation, probably pyrite to hematite. These data aided in determining the reliability of demagnetization steps and correlated well with increases in intensity during progressive heating. Depths are below land surface.

Formation, but is lower toward the base of the deltaic sequence, which is more carbonate-rich (see Plate 1). The magnetic susceptibility shows considerable variation, but is generally lower in the upper Neogene section, from 0 to 57.61 m in core W-16242 (Figure 40), compared to the upper Peace River Formation, which begins at about 58 m. A comparison between the stratigraphic variation in the initial magnetic susceptibility and the susceptibility of post-thermal demagnetization shows that throughout the Hawthorn Group, there was a general increase in magnetic intensity (Figure 40). This indicates some change in the mineral composition of the sediment occurred during the heating and cooling process. Pyrite was observed in the sediments showing the increase in magnetic susceptibility and there was a distinct odor of sulfur during the heating process, possibly indicating a transformation of pyrite to hematite. Glauconite was also observed in the sediment within the Arcadia Formation and may have had an impact on the magnetic susceptibility increase. It should be noted that the sediments within the overlying Tamiami Formation and in the underlying Suwannee Limestone showed no significant increase in post-thermal magnetic susceptibility.

The NRM intensities tend to follow the same general trends as the magnetic susceptibility data with generally higher intensities within the Hawthorn Group compared to the bounding formations (Figure 41). Many of the highest magnetic intensity rocks tend to be those of predominantly siliciclastic composition and some carbonate rocks containing a significant concentration of magnetic glauconite (Odin and Fullager, 1988).

Many of the samples responded to the demagnetization with a relatively uniform, regular decay in magnetic intensity (Figure 42). Samples with particularly high initial J values (mostly group A), in the range of 1×10^{-4} to 1×10^{-5} Am²/kg, showed a generally more uniform decline in magnetic inten-

sity. As previously discussed, the samples were grouped by their pattern of magnetic intensity decline during demagnetization. A uniform decay in magnetic intensity occurs in many samples containing a significant component of siliciclastic sediment or several of the dolomite units containing glauconite. Examples of a relatively uniform to somewhat irregular decline in the J/J_0 ratio with demagnetization, Group B type samples (26%), are given in Figure 43. Most of the samples showed some degree of irregularity, Class C samples (29%), in the J/J_0 values with demagnetization (Figure 44), but reliable inclination values could be obtained from most of these samples prior to mineralogic alteration. In about 50% of samples collected from the Arcadia Formation, magnetic intensity increased instead of decreasing during at least part of the thermal demagnetization. In most cases, the increase in magnetization did not occur until the 300°C step (Figure 41). The largest increases in magnetic intensity occurred during the 450° to 500°C steps. This increase in the magnetic intensity is the result of thermal alteration of sample mineralogy, with a probable transformation of pyrite or some other iron-rich mineral to hematite. This transformation and remagnetization probably would not have occurred if the samples were cooled in an oxygen-free environment. Additional research will be required in order to determine the exact nature of the mineralogic change. Although these samples did show irregular variation in the J/J_0 ratio with demagnetization, in most cases the data were sufficient to determine an inclination value with a reasonable degree of certainty. Some of the samples showed very low NRM values and became unstable during the initial steps of demagnetization or showed extreme variations, group D samples (13%), in the J/J_0 ratios during the overall demagnetization process (Figure 45). No reason-

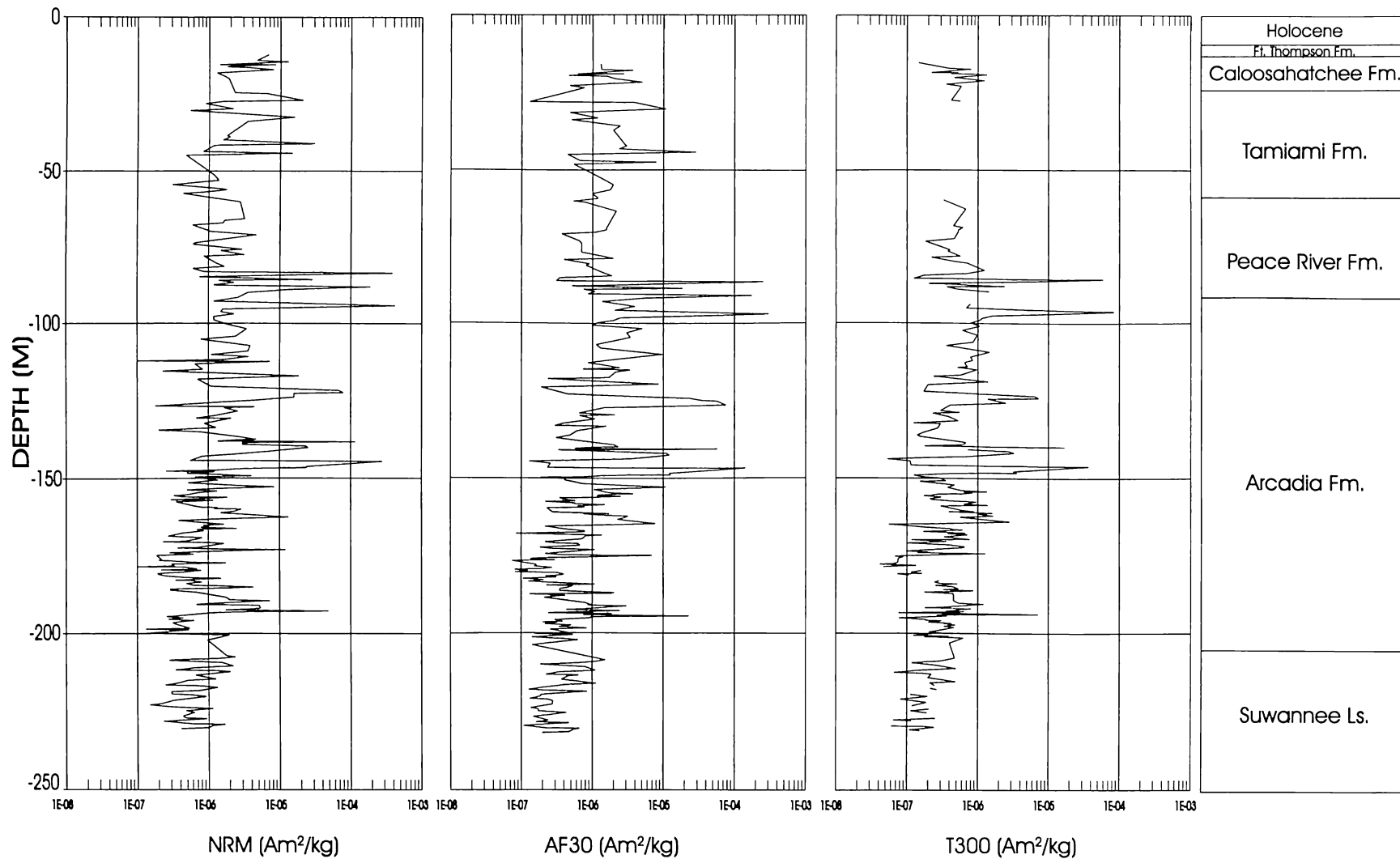


Figure 41. Natural remanent magnetization, magnetization after exposure of samples to a 30 mT alternating field, and magnetization after thermal treatment of samples to 300°C with depth in core W-16242. Depths are below land surface.

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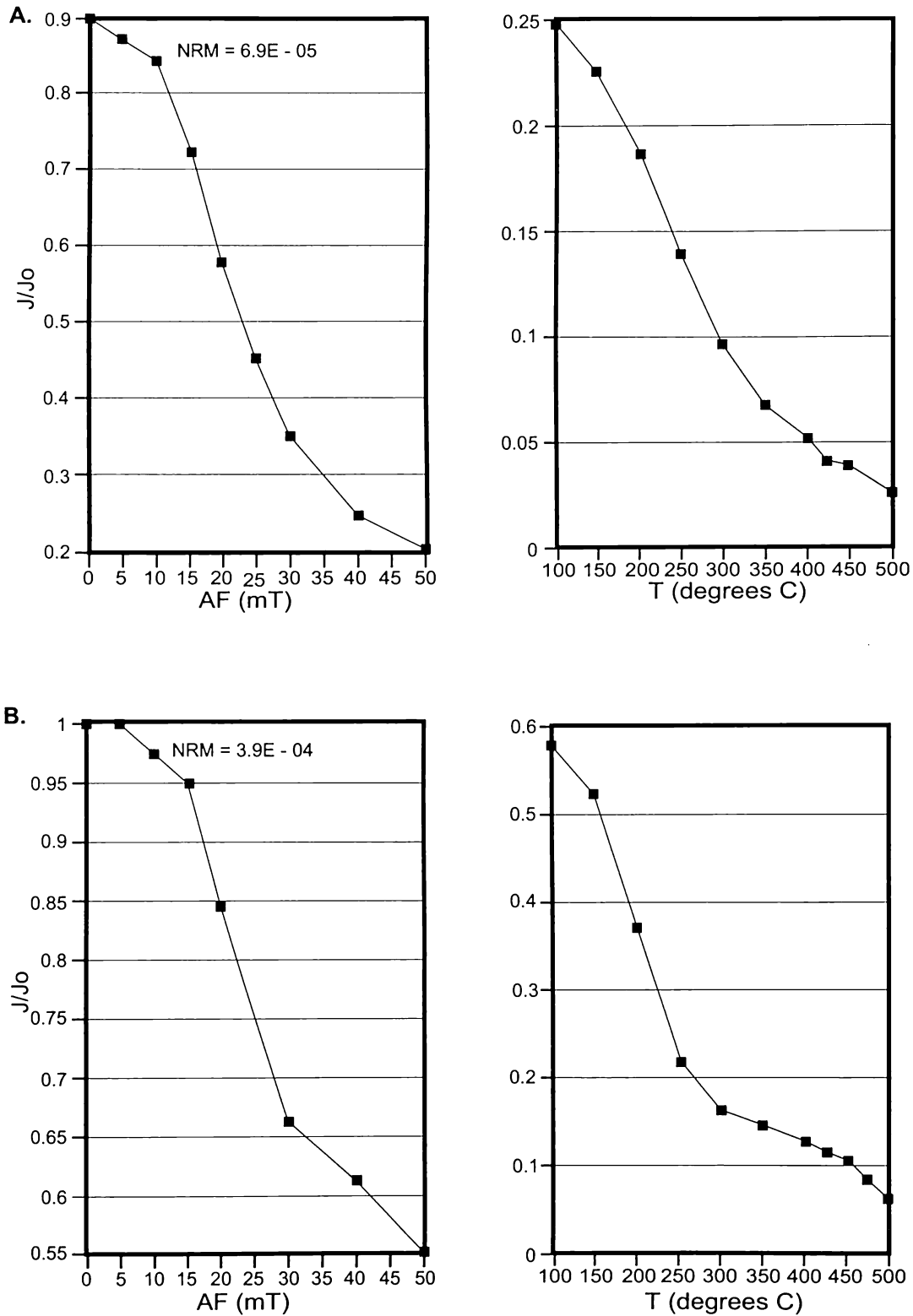


Figure 42. J/J_o plots for class A samples from core W-16242. Class A samples show a generally consistent decline in magnetic field intensity (J) with each step of alternating field (left) or thermal (right) demagnetization. Example A is the J/J_o plot for sample 93 and example B is the J/J_o plot for sample 58.

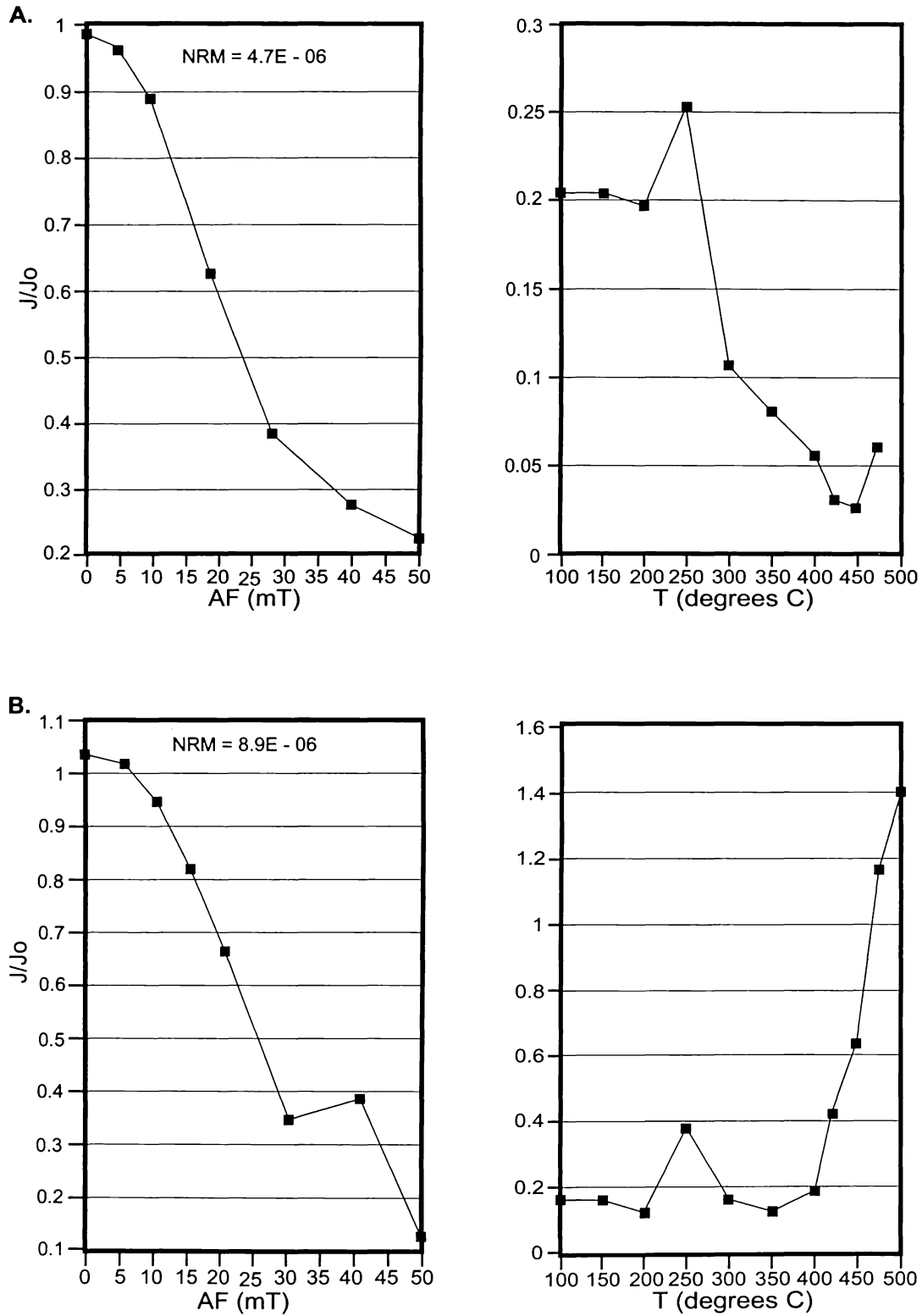


Figure 43. J/J_o plots for class B samples from core W-16242. Class B samples generally show a consistent decline in magnetic intensity after alternating field (left) and the lower temperature during thermal treatment (right). Some increase in magnetic intensity occurs after 350°C, because of mineral transformation. Example A is the J/J_o plot for sample 47 and B is for sample 57.

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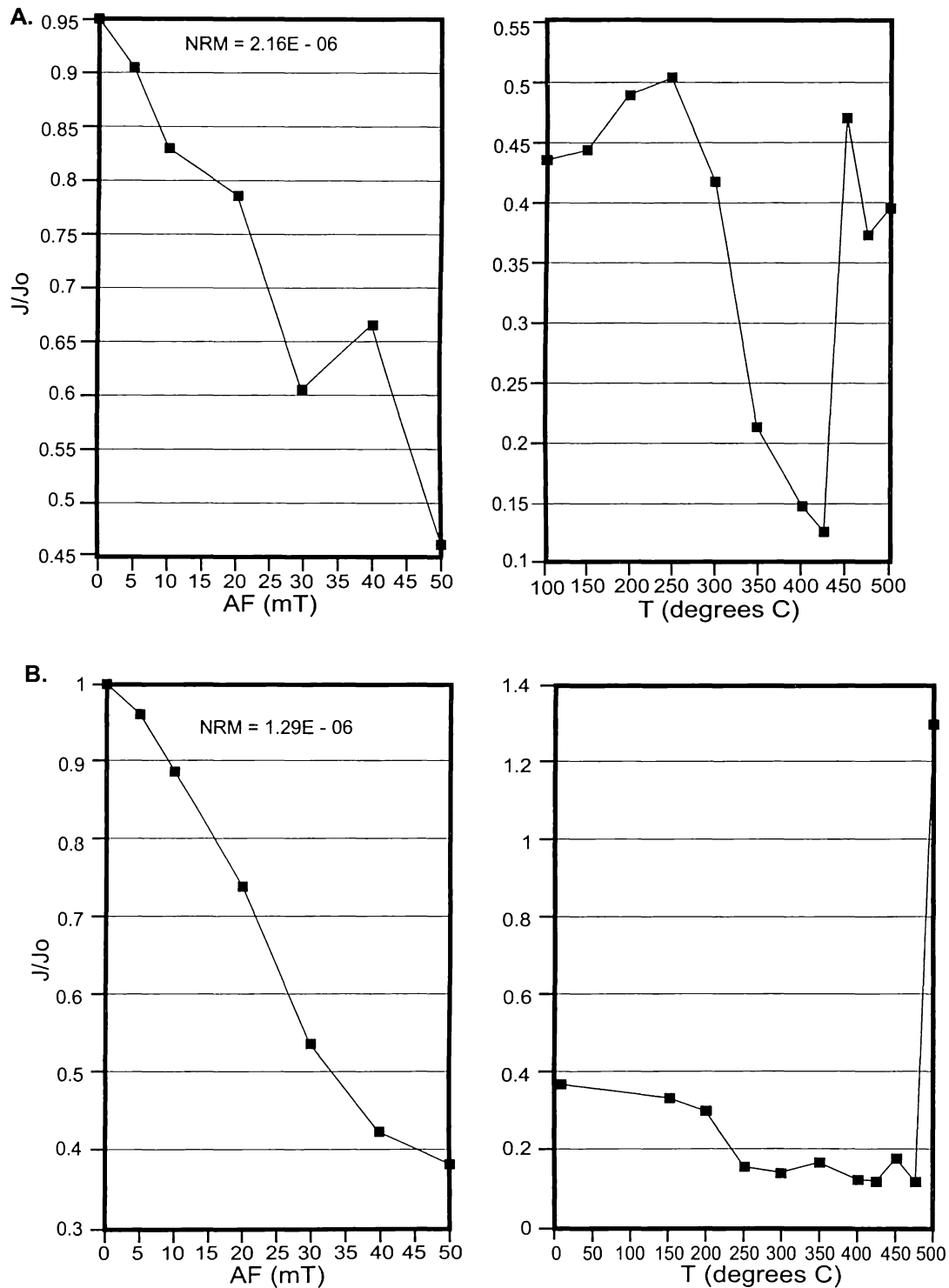


Figure 44. J/J_o plots for class C samples from core W-16242. Class C samples show some inconsistency in decline of the magnetic intensity either/or both alternating field (left) and thermal demagnetization. Example A is the J/J_o plot for sample 140. There is some irregularity in both the alternating field and thermal demagnetization steps. Example B is the J/J_o plot for sample 129, which shows a consistent demagnetization during alternating field, but magnetic intensity varies during thermal treatment. In both cases, the magnetic intensity increases in the later steps of thermal demagnetization as a result of minimal transformation.

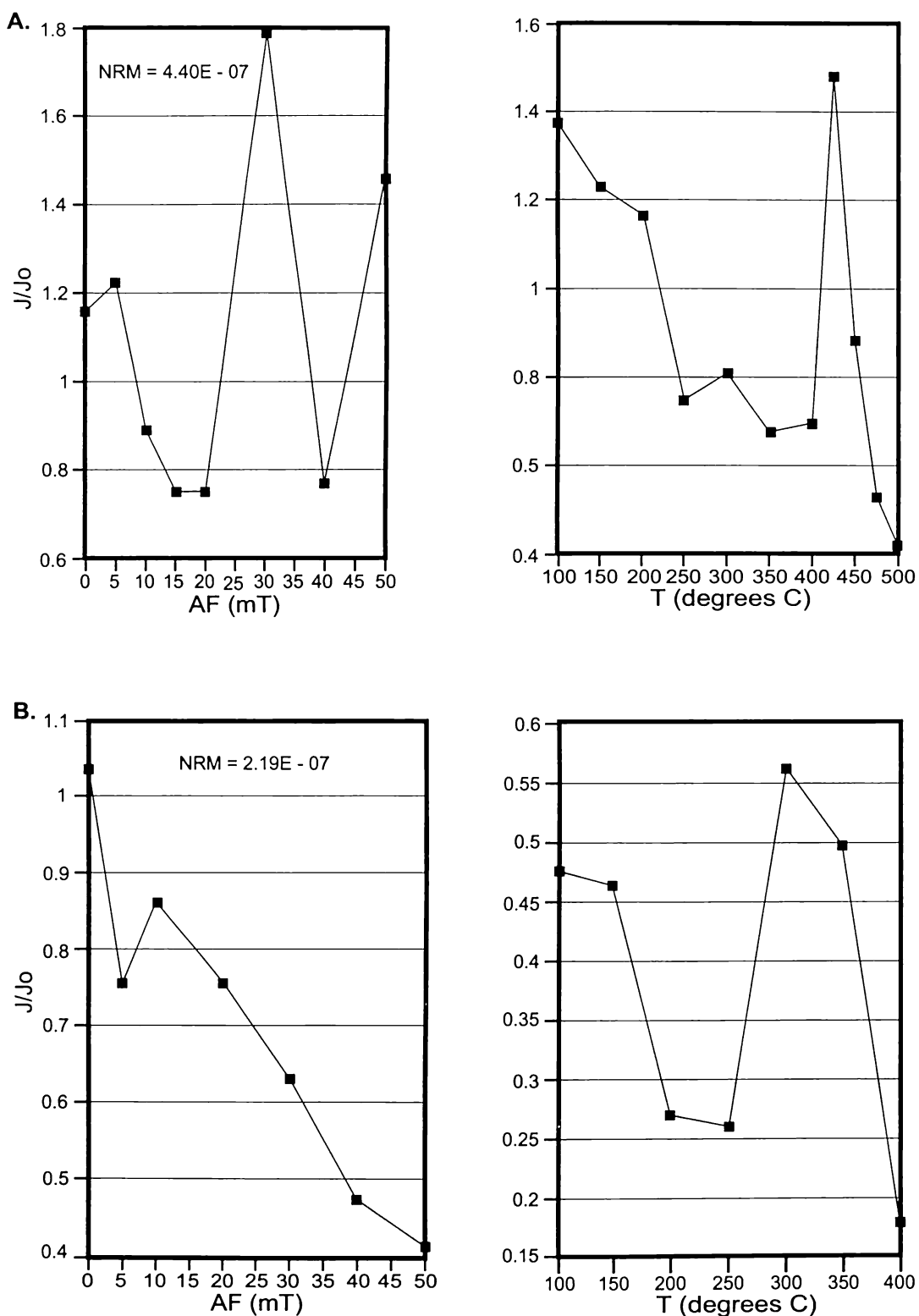


Figure 45. J/J_o plots for class D samples from core W-16242. Class D samples show instability during demagnetization. In both examples, the magnetic intensity changes irregularly, instead of consistently declining during both alternating field (left) and thermal treatment (right). Example A is the J/J_o plot for sample 38 and example B is for sample 277.

able inclination values could be determined from these samples. A special group of samples showed a relatively regular decay in the J/J_0 value with demagnetization, but the MAD during least squares analysis was greater than 20° when these samples showed a consistent inclination; they are classified as "E" samples (13%).

Rock Magnetic Results

Coercivity Spectral Data

The coercivity analyses of the sediment samples from core W-16242 were used to help characterize the nature of the magnetization in the mixed carbonate/siliciclastic sediments, particularly the Hawthorn Group. The rock magnetization data were used to help ascertain the type of remanence carrying minerals to help confirm a depositional remanence, to assess changes to remanence, and to help determine the potential for remagnetization. Despite the known presence of a siliciclastic component (mostly quartz sand and clay minerals) of the sediment, all samples tested passed the modified Lowrie-Fuller test. In that the samples often began to saturate by 100 mT and with consideration of the Lowrie-Fuller results, the remanence carrier is likely dominated by a single-domain or pseudo-single domain magnetite and/or maghemite (Figures 46 and 47). Only 12 representative samples were collected and measured and if a larger number of samples were run, it is possible that examples of a multi-domain carrier might be found, particularly in the siliciclastic-rich nearshore or beach subfacies.

IRM acquisition was similar in all samples analyzed. The intersection of the IRM and AF demagnetization of IRM was used to estimate the remanent coercive field and R values for each sample. The coercivity ranged between 13 and 35 mT. R values

were generally between 0.2 and 0.4.

ARM Results

The acquisition of ARM in single-domain-bearing sediments is a function of the degree of magnetostatic interactions between grains (Cisowski, 1981) and perhaps, also partially related to grain oxidation (Moskowitz et al., 1988). ARM acquisition was performed on all 12 samples collected for rock magnetic analysis. According to Cisowski (1981), ARM acquisition occurs more readily in grain configurations exhibiting low magnetostatic interactions with the reverse being true for grains that are highly interactive. Two end members consisting of highly interacting single-domain magnetite from chiton teeth and non-interacting, single-domain magnetite crystals from freeze-dried bacteria were calibrated for comparison to ARM data collected from samples by Cisowski (1981) and Diaz-Ricci et al. (1991). Based on ARM plots, samples collected from the Arcadia Formation and Peace River Formation are highly interacting in all samples (Figures 48 and 49).

Paleomagnetic Results

A series of 291 samples were collected from core W-16242. These samples were systematically demagnetized using AF and progressive thermal exposure. Samples that exhibited a regular or linear reduction in magnetic intensity usually had an initially high magnetic intensity compared to the average magnetic intensity of the samples as a group. An example of the paleomagnetic properties of each group (A to D) of samples are shown in vector component projection in Figure 50. A reliable magnetic polarity could be assessed from 87% of the samples measured.

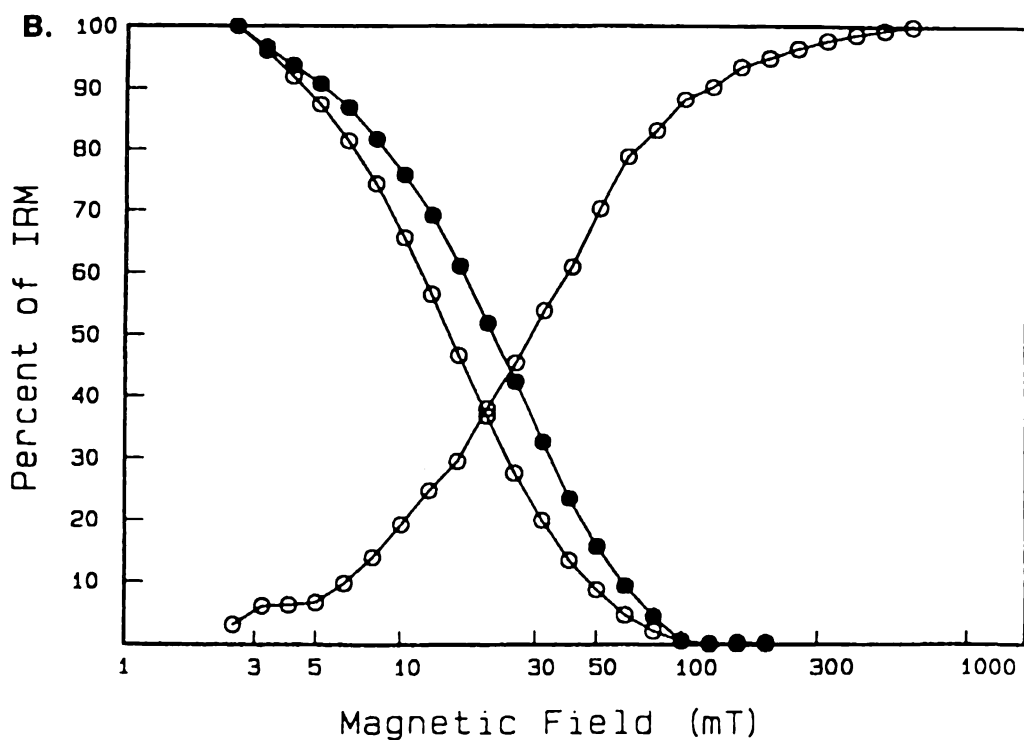
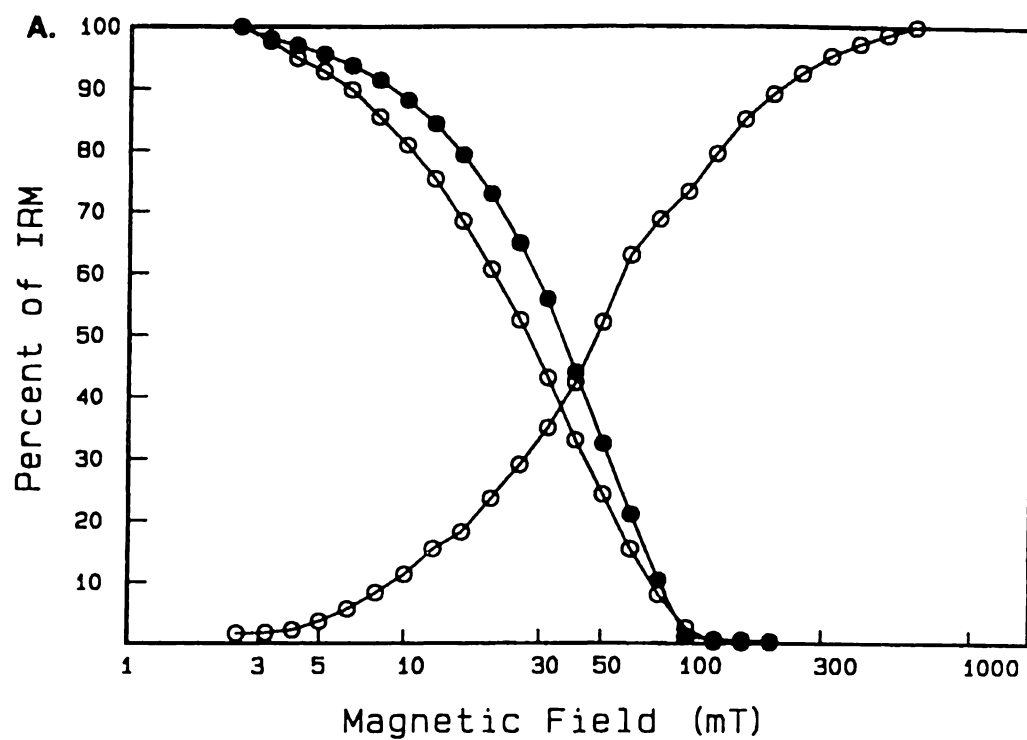


Figure 46. Coercivity spectral analysis plots of mixed carbonate/siliciclastic sediment samples from core W-16242. Open circles are IRM acquisition and alternating field demagnetization. Solid circles represent demagnetization of ARM.

A. Mixed carbonate/siliciclastic deltaic sediment from Peace River Formation at 70.84 meters.

B. Sand/sandstone from Peace River Formation at 88.47 meters.

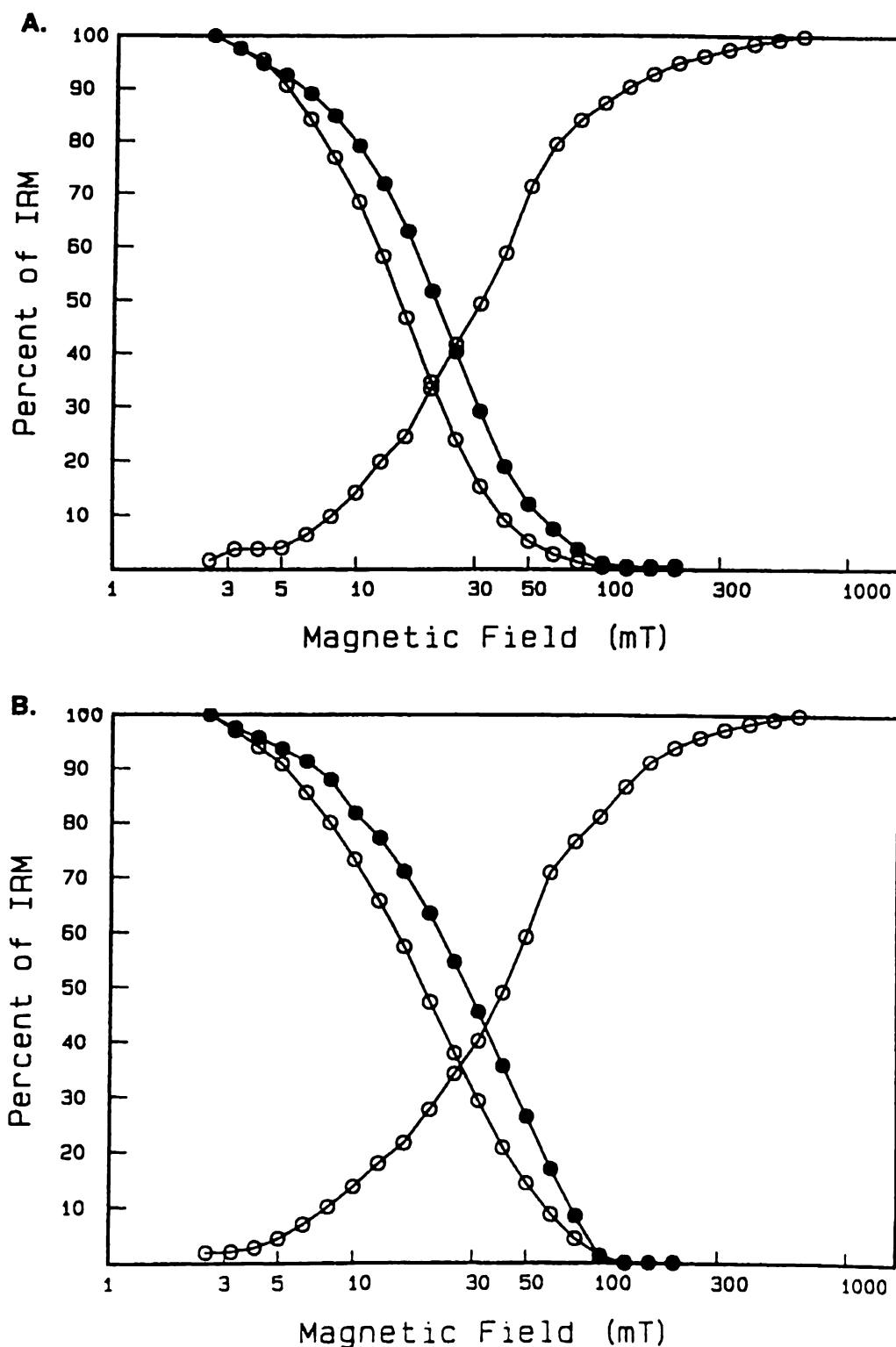


Figure 47. Coercivity spectral analysis plots of mixed carbonate/siliciclastic sediment samples from core W-16242. Open circles are IRM acquisition and alternating field demagnetization. Solid circles represent demagnetization of ARM.

A. Sandy limestone from the Arcadia Formation at 121 meters.

B. Dolomitic clay from the Arcadia Formation at 132.97 meters.

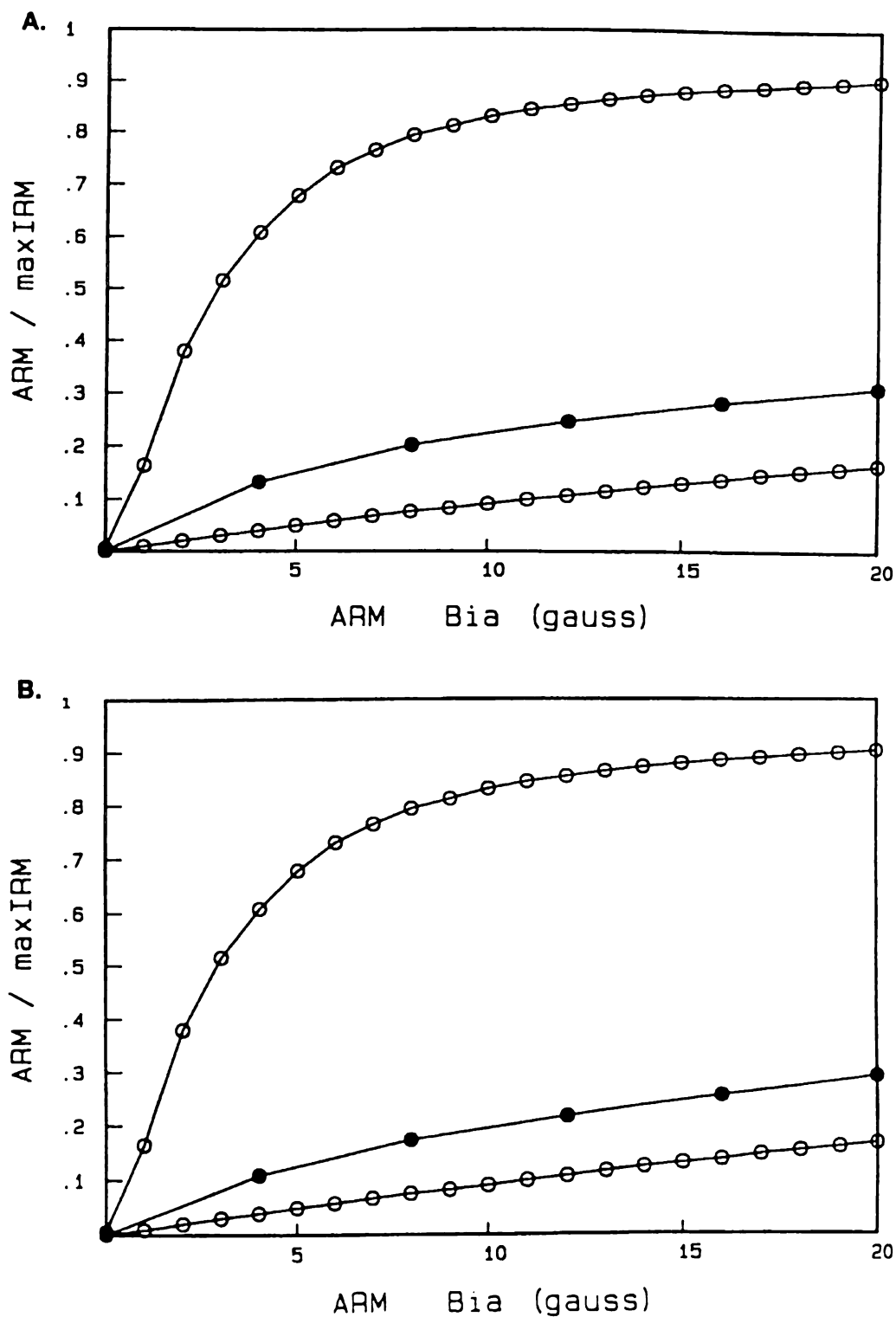


Figure 48. ARM plots of mixed carbonate/siliciclastic sediments from core W-16242. The plots shown contain a comparison of the non-interacting, single-domain magnetite crystals (upper open circles), the highly interacting, single-domain magnetite crystals (lower open circles), and the ARM acquisition of the sample (solid circles).

A. Sandy limestone from the Arcadia Formation at 121 meters. (R = 0.34)

B. Dolomitic clay from the Arcadia Formation at 132.97 meters. (R = 0.35)

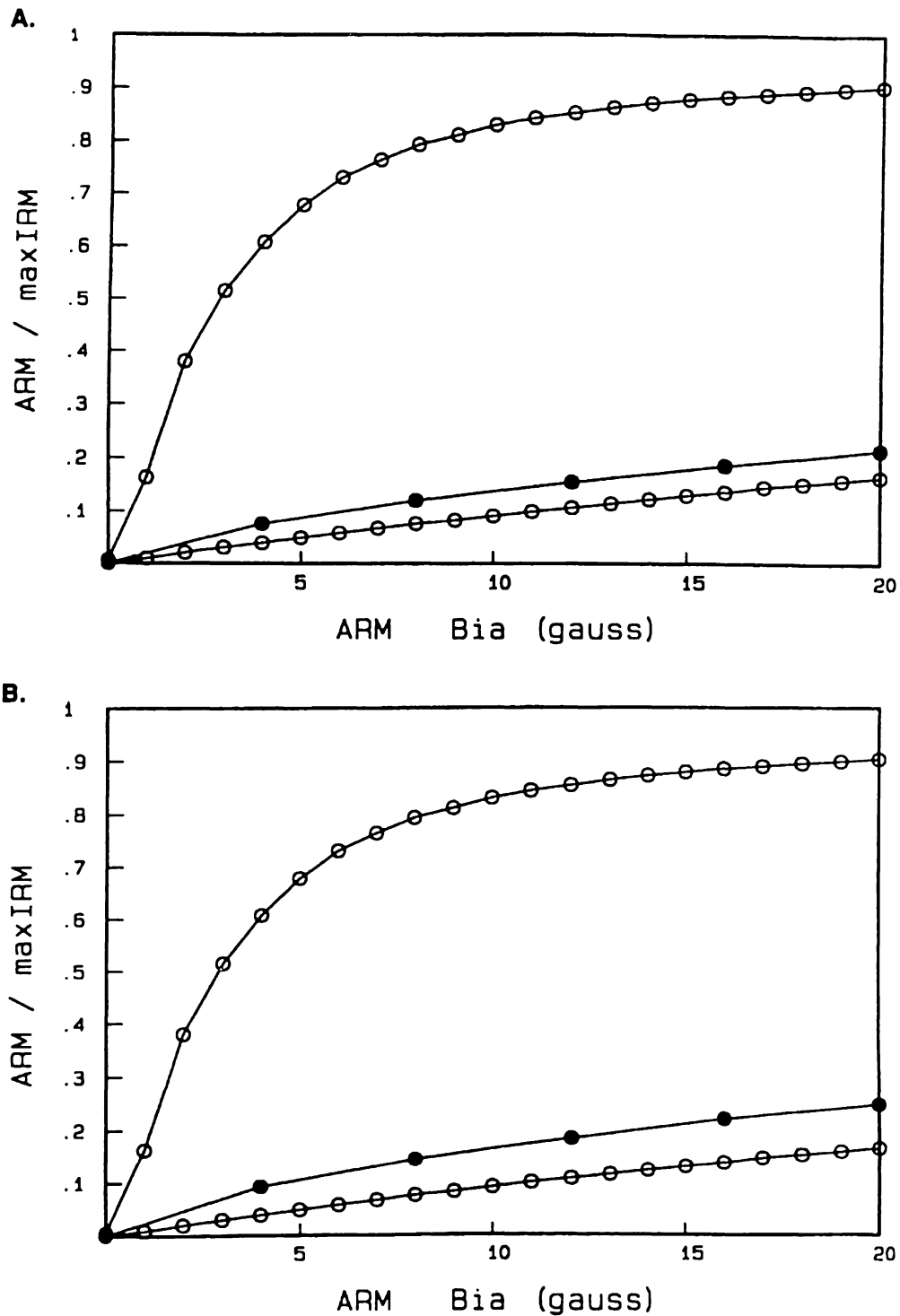


Figure 49. ARM plots of mixed carbonate/siliciclastic sediments from core W-16242. The plots shown contain a comparison of the non-interacting, single-domain magnetite crystals (upper open circles), the highly interacting, single-domain magnetite crystals (lower open circles), and the ARM acquisition of the sample (solid circles).

A. Mixed carbonate/siliciclastic deltaic sediment from the Peace River Formation at 70.84 meters. (R = 0.39)

B. Sand/sandstone from Peace River Formation at 88.47 meters. (R = 0.39)

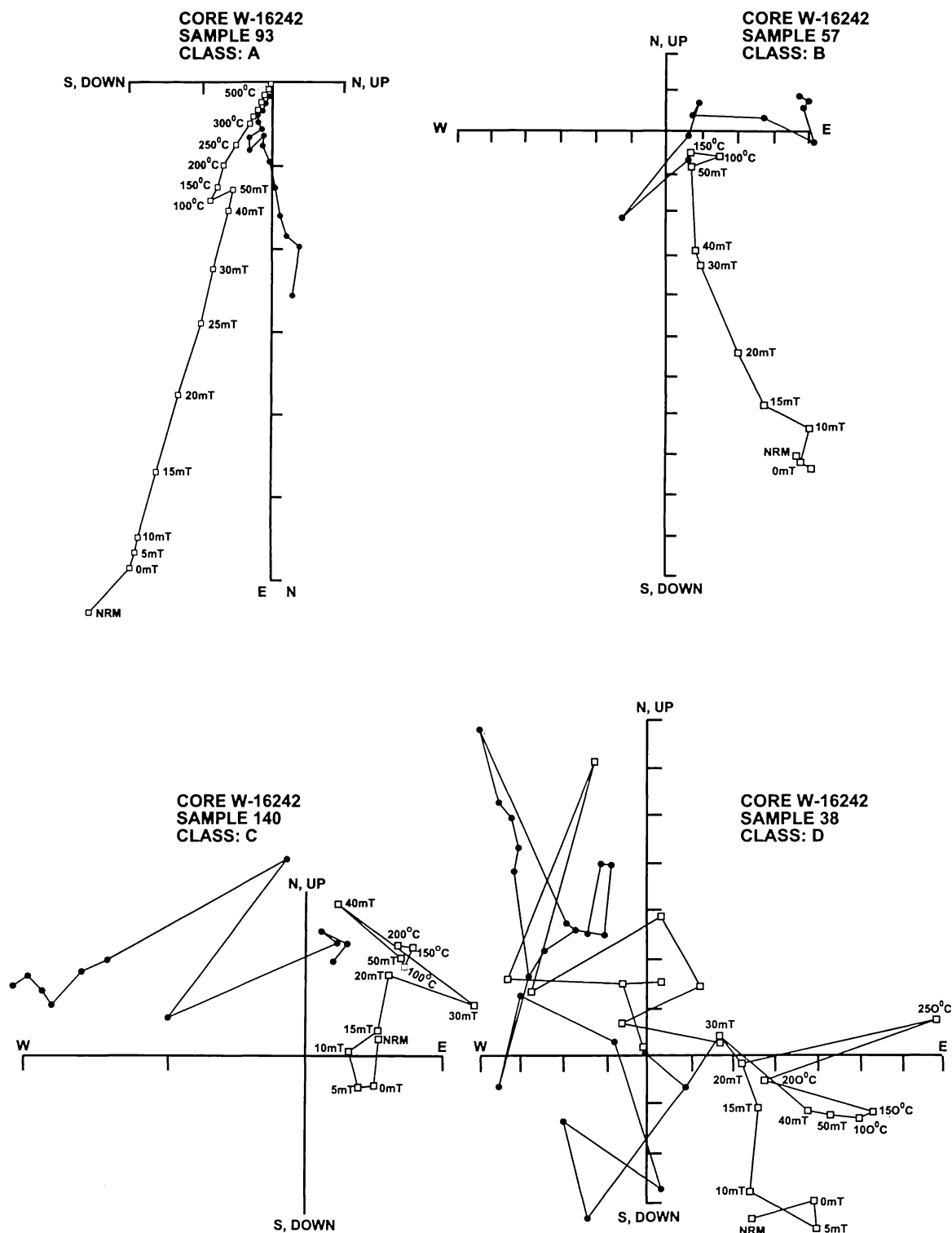


Figure 50. Representative vector component plots of class A, B, C, and D samples collected from mixed carbonate and siliciclastic sediments of core W-16242. Part of the class C sample data set was sufficient to make a magnetostratigraphic analysis. Class D samples were unacceptable for magnetostratigraphic analysis purposes.

MAGNETOSTRATIGRAPHY AND AGE IMPLICATIONS

Paleomagnetic polarity data are useful to refine and constrain the age of sediments when they can be correlated to the GPTS using other age-dating techniques, including strontium isotopes and microfossil assemblages. A plot of magnetic inclination with depth in core W-16242 is given in Figure 51. The magnetic polarities for core W-16242 in relationship to the core lithologic properties and other isotopic data are presented in Plate 1. In order to correlate the magnetic polarity data to the GPTS, the magnetic polarity data, strontium-isotope ages, and ranges of calcareous nannofossils for core W-16242 are presented in a graphic plot (Plate 4). Analyses of the magnetic polarity changes in the core are discussed for stratigraphic units, which include: 1) the Suwannee Limestone, 2) the Arcadia Formation, 3) the Peace River Formation, 4) the Tamiami Formation, 5) the Caloosahatchee Formation, and 6) the combined Fort Thompson Formation and Holocene.

Magnetostratigraphy and Age of the Suwannee Limestone

Although the Suwannee Limestone was analyzed for magnetic polarity changes, only the upper two-thirds of the formation was penetrated in core W-16242. Seven normal and seven reverse magnetic polarity intervals occur in the section of the Suwannee Limestone sampled (Plates 1 and 4).

Correlation of the magnetic polarity changes in the core to the GPTS is considered tentative, because only one strontium-isotope age was obtained from this stratigraphic interval and no time diagnostic microfossils were observed. Based on the correlation to the GPTS, the base of the core penetrates the top of Chronozone C12r, which has an age range of 33.058 to 30.939 Ma. The top of the Suwannee

Limestone terminates in Chronozone C10n.1n, which has an age range of 28.5 to 28.2 Ma. This interpretation is also based on the strontium-isotope ages of the Suwannee Limestone obtained by Hammes (1992). The lower 10 m of the formation was not penetrated and it is likely that the basal part of the unit lies within Chronozone C12r also based on the Hammes (1992) data. Also, the top of the Suwannee Limestone in core W-16242 is a sequence boundary with significant time missing.

Magnetostratigraphy and Age of the Arcadia Formation

The Arcadia Formation is a mixed carbonate/siliciclastic unit that is subdivided into four intervals for discussion. Each interval is separated by a disconformity at the base and the top. From the base of the formation to the first disconformity (sequence A), seven intervals of normal polarity and six intervals of reverse polarity were measured. There were also three short intervals of uncertain polarity, caused by unreliable samples (class D samples). Three strontium-isotope ages were available for this stratigraphic interval and no calcareous nannofossils could be found.

Correlation of the core polarity data to the GPTS shows that the sediments at the base of the Arcadia Formation were deposited during Chron C8n.2n, from 26.5 to 25.9 Ma, in late Oligocene (Chattian) (Plate 4). The sediments at the top of the unit (just below the disconformity) were correlated to either Chron C7n or the lower part of Chron C6Cr. The age range of Chron C7n is from 25.18 to 24.73 Ma and the age range for Chron C6Cr is from 24.7 to 24.2 Ma. Therefore, the sediments at the top of this stratigraphic interval may range in age from between 25.18 to 24.2 Ma.

The overlying stratigraphic section (sequence B) within the Arcadia Formation is also bounded by disconformities. The magnetic polarity within this interval is

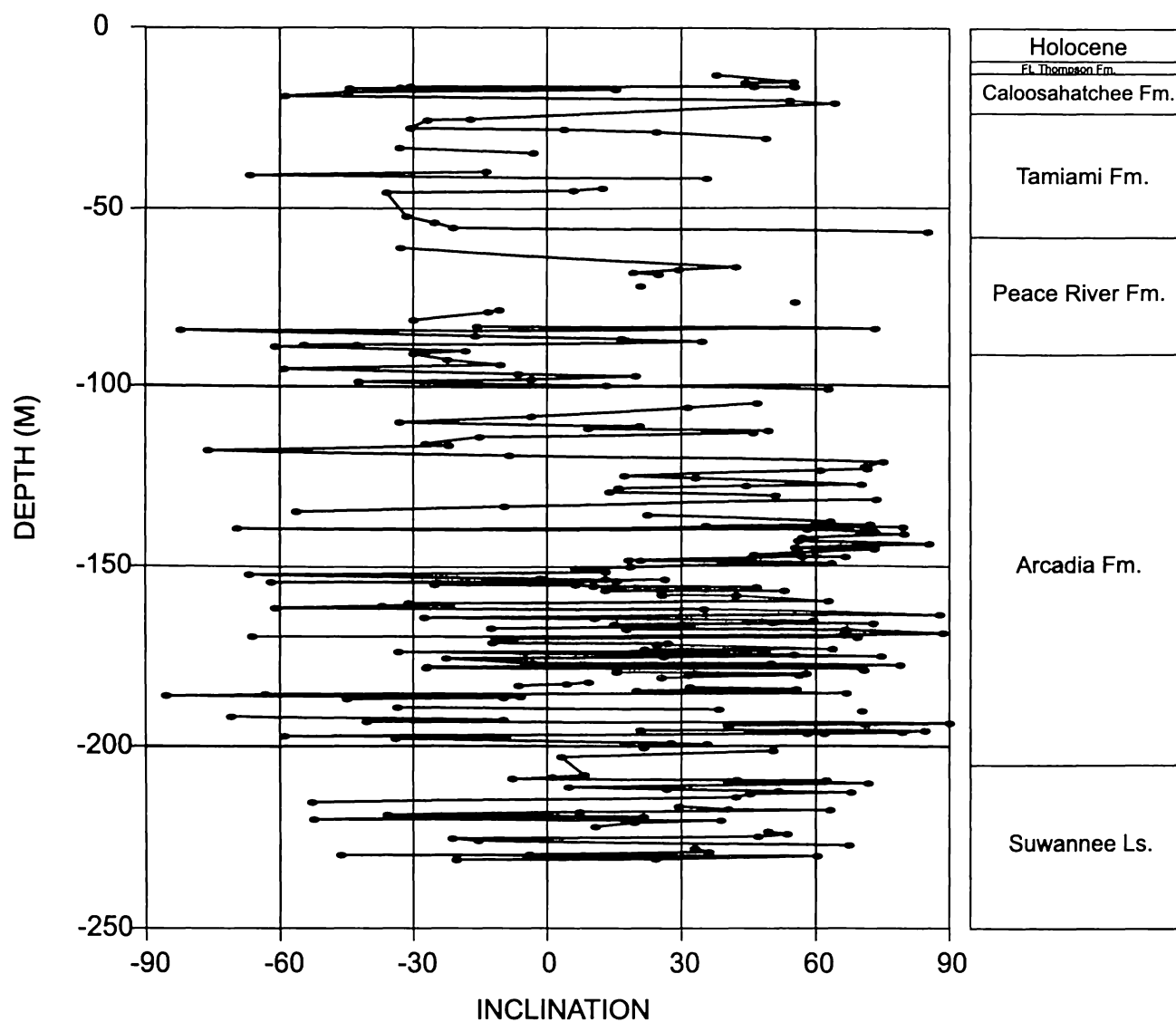


Figure 51. Magnetic inclination versus depth in core W-16242. The dots are the actual data points determined from the analysis. Unconnected points occur because of gaps in the data set caused by a lack of acceptable samples or the inability to make an accurate polarity determination on samples (class D). Depths are below land surface.

predominantly normal, but there are many reversals and the section is complex. Eleven intervals of normal and eleven intervals of reverse polarity were measured within this section (Plates 1 and 4). Four relatively short increments of uncertain polarity are noted. Five strontium-isotope ages were determined in this section and no calcareous nannofossils could be found. From the basal disconformity upward a few meters, there is a stratigraphic interval of greatly disturbed sediment containing rock clasts that produce short interval polarity changes and some discrepancies between the strontium-isotope ages and the correlation of the magnetic polarities to the GPTS. The base of this interval is correlated to Chron C6An, which has an age range of 21.32 to 20.52 Ma. The top of the stratigraphic interval correlates to Chron C5Dn, which has an age range of about 17.6 to 17.3 Ma.

From the second disconformity within the Arcadia Formation to the third disconformity in the formation (sequence C), only one normal polarity interval and one reverse interval were measured in core W-16242 (Plates 1 and 4). Two strontium-isotope age determinations were made within this stratigraphic interval and no calcareous nannofossils were found.

Based on the correlation of the magnetic polarities and strontium-isotope ages to the GPTS, the base of the unit occurs in Chronozone C5Cn.1n and the top of the unit occurs in Chronozone C5Br. The age ranges for these chrons are 16.3 to 16.0 Ma and 16.0 to 15.2 Ma, respectively. If it is assumed that the disconformity at the top of the stratigraphic interval is insignificant, then a second interpretation would be to correlate the base of the interval to Chron C5Bn2n with an age range of 15.2 to 15.0 Ma and the top to Chron C5Bn.l.r, which has an age range of 15.0 to 14.9 Ma. The first interpretation is preferred because the implied sedimentation rate for the second interpretation is too high (alternate interpretation dashed on Plate 4).

From the third disconformity to the top of the Arcadia Formation (sequence D), four intervals of normal and four intervals of reverse polarity occur (Plate 1 and 4). Three strontium-isotope ages were determined for this stratigraphic interval.

Based on correlation of the polarity data from the core and the strontium isotope ages to the GPTS, the sediments at the base of the interval occur in Chronozone C5ADr and at the top of the interval in Chronozone C5Ar.l.r. The respective age ranges for these chrons are 14.8 to 16.6 Ma and 12.7 to 12.4 Ma, respectively.

There are a number of possible correlations to the GPTS in the upper part of sequence A, because of the lack of strontium-isotope age data. If the uncertain interval located at 330 feet below surface is a reverse polarity interval and is correlated to Chron C5ABr, then a one to one correspondence to the GPTS causes the top of the unit to correlate to Chron C5Ar.3r. This correlation would give an age range of the top of the Arcadia Formation from 13.0 to 12.8 Ma. The difference between the two different correlations is considered to be trivial in consideration of the error ranges for the strontium-isotope ages used for correlation to the GPTS.

Based on the correlation of the magnetostratigraphy of core W-16242 to the GPTS, the Arcadia Formation has an age of 26.6 to 12.4 Ma. Therefore, the formation was deposited from the Late Oligocene (Chattian) to the Middle Miocene (Serravallian). The disconformities found within the unit correlate to the Oligocene/Miocene boundary, to the Early Miocene/Middle Miocene boundary, and possibly to the Langhian/Serravallian boundary within the Middle Miocene. At the disconformity between the Arcadia Formation and the underlying Suwannee Limestone, there is about two m.y. absent. At the disconformity between the Oligocene

and Miocene there is about four m.y. absent. There is about a million years of time missing across the other two disconformities.

Magnetostratigraphy and Age of the Peace River Formation

The Peace River Formation lies disconformably above the Arcadia Formation (Plates 1 and 2). It is divided into two stratigraphic units, a mixed siliciclastic/carbonate facies at the base and an angular-bedded, deltaic unit at the top (Figure 26). There is a distinct disconformity between these two stratigraphic units and between the Peace River Formation and the overlying Tamiami Formation in core W-16242.

Only about three m of the lower Peace River Formation occurs in core W-16242 (Plate 1). The lower Peace River Formation is much thicker to the south and east (Figures 35 and 36; Plates 2 and 3). The unit is bounded by regional disconformities (Missimer, 1978; Wedderburn et al., 1982). This entire interval has a reverse polarity.

Based on a single strontium-isotope age, the age restrictions placed on the unit by underlying and overlying stratigraphic units, and the age of certain calcareous nannofossils, it is believed that this interval correlates to Chron C5r (Plate 4). This chron has an age range of from 11.93 to 10.94 Ma. Based on the strontium-isotope age from this interval, the interval most likely correlates to the upper part of Chron C5r or near 11 Ma, perhaps to the earliest Tortonian. The reasoning behind this interpretation is based on the existence of a regional disconformity at the Middle Miocene/Late Miocene boundary throughout much of South Florida and continuous sedimentation across this boundary is considered to be unlikely.

Within the upper Peace River Formation, three intervals of normal and three intervals of reverse polarity were observed (Plates 1 and 4). Also, three inter-

vals with uncertain polarities were noted (Plates 1 and 4).

Correlation of the magnetic polarity data with three strontium-isotope ages and a combination of the calcareous nannofossil data, particularly the age range of *Helicosphaera selli*, to the GPTS showed that the base of the upper Peace River Formation occurs in chronozone C3n.4n and the top of the unit probably occurs in chronozone C3n.1r. Therefore, the base of the unit occurs between 5.2 and 5.0 Ma and the top of the unit occurs between 4.5 and 4.3 Ma. There is some uncertainty at the top of the unit, because no acceptable polarity determination could be made in the upper 2 m of section.

Based on the correlation of the magnetic polarities measured in core W-16242 to the GPTS, there is over two m.y. of time missing across the disconformity between the top of the Arcadia Formation and the base of the Peace River Formation. There is an even larger amount of time missing across the disconformity between the lower and upper Peace River Formation, on the order of six to 6.5 m.y. The disconformity between the top of the Peace River Formation and the overlying Tamiami Formation appears to represent a short interval of time on the order of 200,000 years. If the uncertain polarity interval at the top of the Peace River Formation correlates in part to Chron C3n.1n, then there would be no significant disconformity and continuous sedimentation would be implied. Since there is a distinctive change in sediment type and there is a distinct disconformity in the core, the first interpretation is preferred.

Magnetostratigraphy and Age of the Tamiami Formation

The Tamiami Formation in core W-16242 is a mixed siliciclastic/carbonate deposit consisting of mostly quartz sands and sandstones. A regional disconformity divides the Tamiami Formation into a

lower Sand Facies and an upper Pinecrest Member (Plate 1).

A magnetic polarity analysis of the core showed two intervals of reverse polarity and three areas of normal polarity with three intervals of uncertainty (Plate 4). Most of the section had a reverse polarity. The central interval of normal polarity is divided by an uncertain interval. The small interval of normal polarity near the base of the formation is based on one polarity measurement.

Correlation of the lower Tamiami Formation to the GPTS, using strontium-isotope ages and the nannofossil age ranges, suggests that the lowermost part of the formation, the Sand Facies, occurs in chronozone C3n.1n with an age range of 4.3 to 4.2 Ma. There is uncertainty at the very base of the formation, because the normal polarity is based on a single sample and the other samples collected from this part of the core did not yield satisfactory polarity analyses (large error angles). Therefore, it is possible that the lowermost part of the Tamiami Formation may lie near the base of chronozone C2Ar, having an age of 4.2 Ma.

Correlation of the magnetic polarity data with seven strontium-isotope dates and nannofossil data from the base of the formation upward to the contact with the Pinecrest Member, shows that the uppermost sediments within the Sand Facies lie in chronozone C2An.1r, which has an age range from 3.1 to 3.0 Ma. There is a disconformity at the top of the Sand Facies. Within the Sand Facies, the early Pliocene/late Pliocene boundary occurs at a depth of about 45 m at the base of chronozone C2r.2r (Plate 4).

A comparison of the magnetic polarity data with three strontium-isotope ages to the GPTS shows that the base of the Pinecrest Member is in chronozone C2An.1n (Gauss), which has an age range of about 3.2 to 3.1 Ma. The top of the

Pinecrest Member probably lies within chronozone C2r.2r, which has an age range of 2.58 to 2.15 Ma. There is some uncertainty at the very top of the member, because a satisfactory sample could not be collected from the core in this interval.

Based on the chronostratigraphic analysis in core W-16242, the amount of time missing across the disconformity, lying within the Tamiami Formation between the Sand Facies and the Pinecrest Member, ranges from 100,000 to 300,000 years depending on the depth of erosion into the sediments occurring within chronozone C2An.1r. There is also a disconformity lying between the Pinecrest Member and the overlying Caloosahatchee Formation. Both the uppermost Pinecrest Member and lowermost Caloosahatchee Formation may lie within chronozone 2r, but further work in other cores will be necessary to resolve this interpretation. Therefore, it is believed that the amount of time missing across this disconformity is relatively small, on the order of 100,000 years (Plate 4).

Magnetostratigraphy and the Ages of the Caloosahatchee and the Fort Thompson Formations

Magnetic polarity analysis of the uppermost part of core W-16242, showed that the normal polarity extended from land surface down into the Caloosahatchee Formation (Plates 1 and 4). Therefore, the entire Fort Thompson Formation was deposited during Chron C1n (Brunhes), as expected. The polarity changes within the Caloosahatchee Formation are somewhat problematical because it was not possible to obtain high-quality samples from the lower section in order to make measurements. Therefore, magnetic polarity was not available for the lowermost three m of the section. Based on the data obtained, the corresponding strontium-isotope age data, and

the constraints placed on the age of the basal part of the Caloosahatchee Formation by the ages of the underlying formation, it is proposed that the base of the Caloosahatchee Formation occurs in either chronozone C2n or in the upper part of chronozone C2r.l_r (Matuyama), which have age ranges of 1.95 to 1.77 Ma and 2.14 to 1.95 Ma, respectively. Based on the data presented, the Caloosahatchee Formation ranges from lower Pleistocene, from less than 0.78 Ma, to uppermost Pliocene in age with the base of the unit ranging between 2.14 and 1.77 Ma. The Fort Thompson Formation is entirely Pleistocene in age.

OXYGEN AND CARBON ISOTOPE STRATIGRAPHY

Introduction

Distinctive changes in the oxygen and carbon isotopic composition of seawater occurred during Late Paleogene and Neogene time (Vincent and Berger, 1985; Miller and Fairbanks, 1985; Miller et al., 1987; Williams, 1988; Figure 52). The general pattern of these isotopic changes should be evident within the sediments on the South Florida Platform and has, in fact, been observed by Compton et al. (1990) and Compton et al. (1993) in a core drilled in Charlotte County to the north of the study area. The general pattern of changes in the oxygen and carbon isotopic composition is useful in constraining the ages of stratigraphic units, especially when integrated with other age data. A series of 78 oxygen and carbon isotope measurements were made on unaltered mollusk shells collected from cores W-16242, W-16523, and W-17115.

Oxygen Isotope Variations and Age Considerations

There appears to be a distinct correlation between the $\delta^{18}\text{O}$ data collected in ben-

thic foraminifera by Miller and Fairbanks (1985) and the data collected from mollusks in cores W-16242, W-16523, and W-17115. The oxygen isotope data collected by Miller and Fairbanks (1985) are an indicator of global oceanic variation in $\delta^{18}\text{O}$ related to primarily climatic changes. Since the $\delta^{18}\text{O}$ data from these cores were collected from mollusks, which occurred in a variety of water depths with time and the Miller and Fairbanks (1985) data were collected from benthic mollusks at greater water depth, the correlation between the two data sets must be considered to be speculative. Although there is a very distinct relationship between the data sets, the magnitude of the $\delta^{18}\text{O}$ changes on the South Florida Platform is several parts per mil higher than those observed in the world ocean.

The $\delta^{18}\text{O}$ was measured on 37 samples collected from core W-16242 in order to assess the stratigraphic variation (Figure 53). There are some important comparisons of the Miller and Fairbanks (1985) global oxygen record to the variation of oxygen isotope record measured in core W-16242. During the Late Oligocene to the Middle Miocene, the global record shows a significant change near the Oligocene-Miocene boundary, a minor change in the Middle Miocene near the Langhian-Serravallian boundary, a very significant event at the Middle Miocene-Late Miocene boundary, and considerable variation from the Late Miocene to Holocene. The oxygen isotope record of core W-16242 appears to match the global oxygen record based on the ages estimated using strontium-isotopes and magnetostratigraphy. The variations observed between 113 and 118 m correlate to the general age of the change which occurred near the Langhian-Serravallian boundary. The change to a heavier oxygen isotope ratio occurs at about 92 m, which was dated to be Middle Miocene by the strontium-isotope data. This corresponds well with the global oxy-

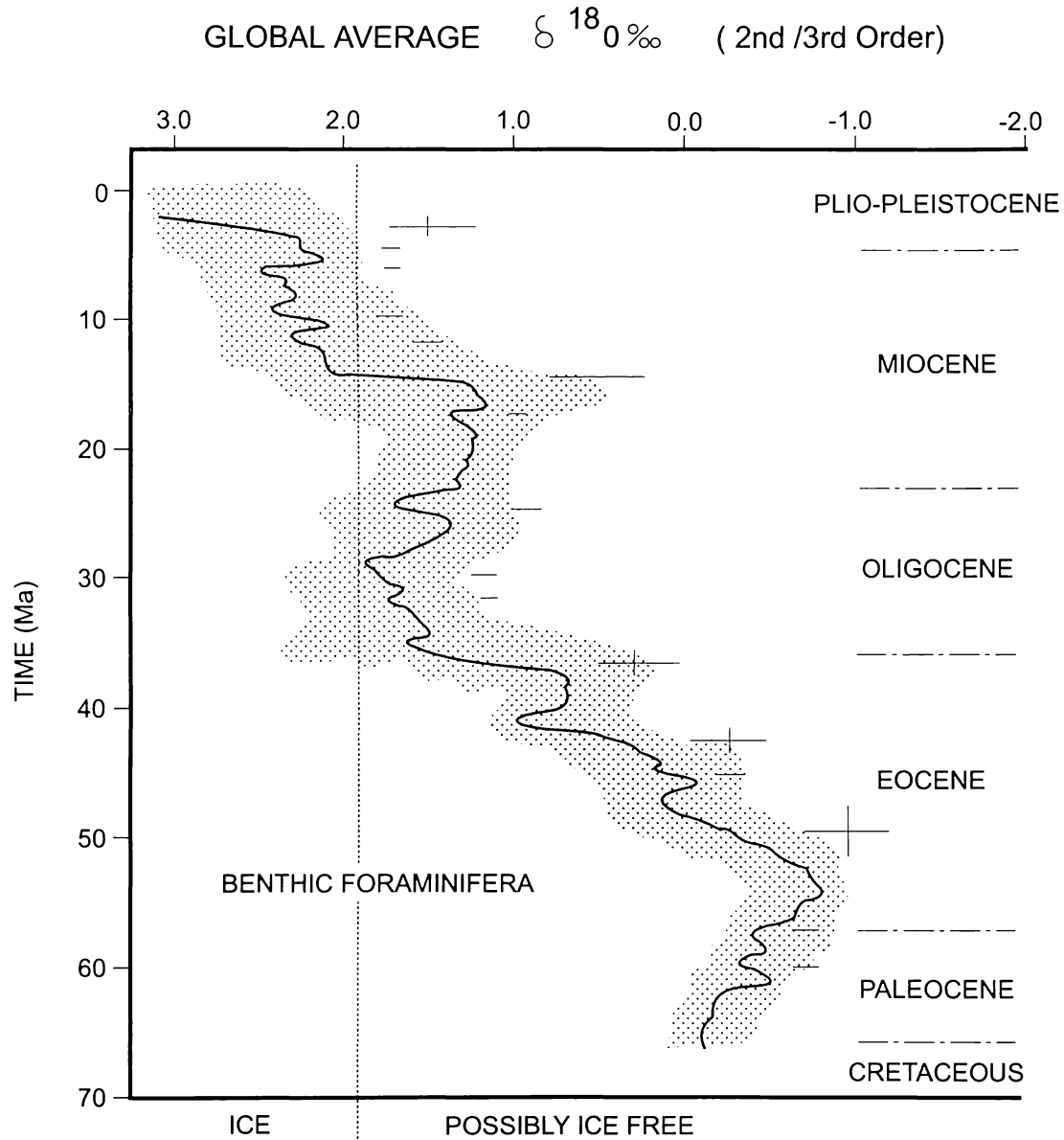


Figure 52. A composite benthic $\delta^{18}\text{O}$ record of the world ocean from Miller and Fairbanks (1985). The shaded area is the field range of data points. The shift in the $\delta^{18}\text{O}$ values in the Late Oligocene, and the Middle Miocene have been observed in the cores studied.

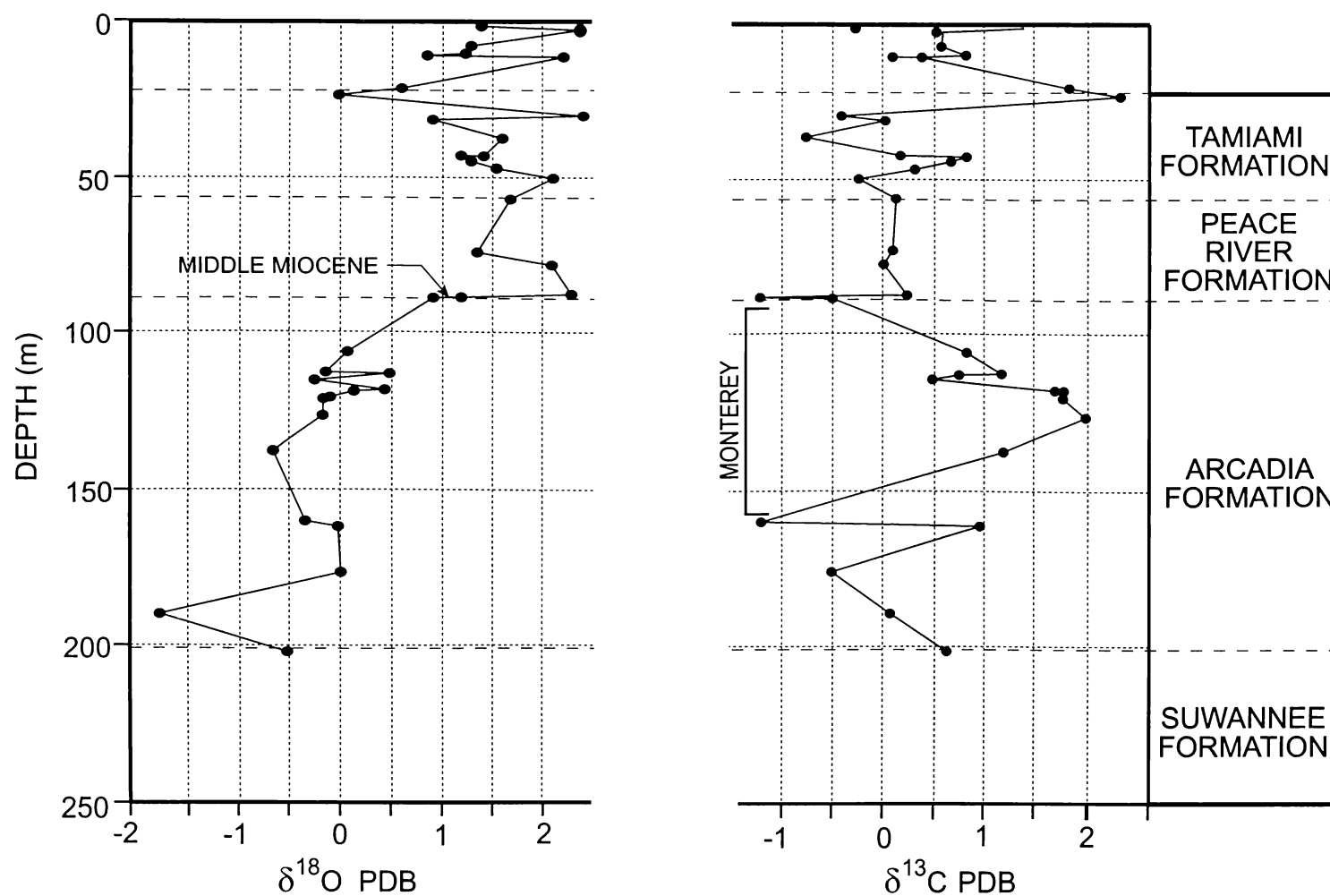


Figure 53. Variation of stable oxygen and carbon isotopes with depth in core W-16242. This plot is based on 37 samples collected from unaltered calcitic mollusk shells. Depths are below land surface. Monterey refers to the Monterey Carbon Isotope Excursion.

gen isotope change occurring in the Middle Miocene in the world ocean. The extremely variable record of isotopic ratio changes after the middle Miocene is quite evident in the record for core W-16242. The magnitude of the $\delta^{18}\text{O}$ variations observed in core W-16242 is too extreme to be related solely to temperature. It is probable that some variation is caused by salinity changes in nearshore, restricted waters. The magnitude of the change across the Middle Miocene boundary in core W-16242 is about 1‰ (parts per thousand) which is on the same order as that observed in the world ocean (Miller and Fairbanks, 1985).

The pattern of oxygen isotope data measured in core W-16523 is quite similar to that observed in core W-16242 (Figure 54). A total of 30 samples were collected and analyzed from this core. In core W-16523, the lightening of the $\delta^{18}\text{O}$ ratio during the Late Oligocene can also be observed. The minor event near the Langhian-Serravallian boundary appears to be present. However, the major change at the Middle Miocene boundary is somewhat problematical, because the formation boundary is at about 57 m, but the major shift in the isotope ratio occurs between 63 and 65 m. The strontium-isotope age estimate at the top of the Arcadia Formation in this core being Middle Miocene may be correct. The magnitude of the change across the Middle Miocene boundary is on the order of 1.0‰.

A small number of samples were run from core W-17115 in order to confirm the large scale pattern (Figure 55). The change across the Middle Miocene boundary is evident with about a 2‰ increase in the $\delta^{18}\text{O}$ ratio. Few conclusions can be drawn with regard to the overall oxygen isotope variation in this core because of the small number of samples, but the overall pattern of variation is similar to cores W-16242 and W-16523.

Based on the estimated ages of the sediments within the Late Oligocene to Neogene, the pattern of variation in oxygen isotope ratios generally matches the pattern produced by global climatic events (Figure 56). Although the oxygen isotope variations do not provide an absolutely quantitative measure of age, the corresponding pattern compared to the estimated chronostratigraphy does provide additional confirmation on the age constraints placed on the formations studied.

Carbon Isotope Variations and Age Considerations

There are distinctive features of the carbon isotope curve in the world ocean that occurred during the Miocene (Vincent and Berger, 1985; Berger and Vincent, 1986; Compton et al., 1990; Flower and Kennett, 1993). The Monterey Carbon Isotope Excursion, a significant lightening of $\delta^{13}\text{C}$, occurs both in the Atlantic and Pacific oceans beginning in the Early Miocene at about the end of planktonic foraminifera zone N6 and terminating in the Middle Miocene at about 13.8 Ma or within planktonic foraminifera zone N13 (Vincent and Berger, 1985; Flower and Kennett, 1993). Vincent and Berger (1985) proposed that the Miocene $\delta^{13}\text{C}$ excursion was a result of organic carbon buried in various deposits located around the Pacific Ocean, such as the Monterey Formation of California. Compton et al. (1993) proposed that both the Oligocene/Miocene and the mid-Miocene excursions can be explained by the burial and oxidation of organic carbon in continental shelf sequences. The Monterey Carbon Isotope Excursion is clearly defined in cores W-16242, W-16523, and W-17115 (Figures 53, 54, and 55). The Monterey Carbon Isotope Excursion was also observed by Compton et al. (1993) in core W-10761 located to the north. The

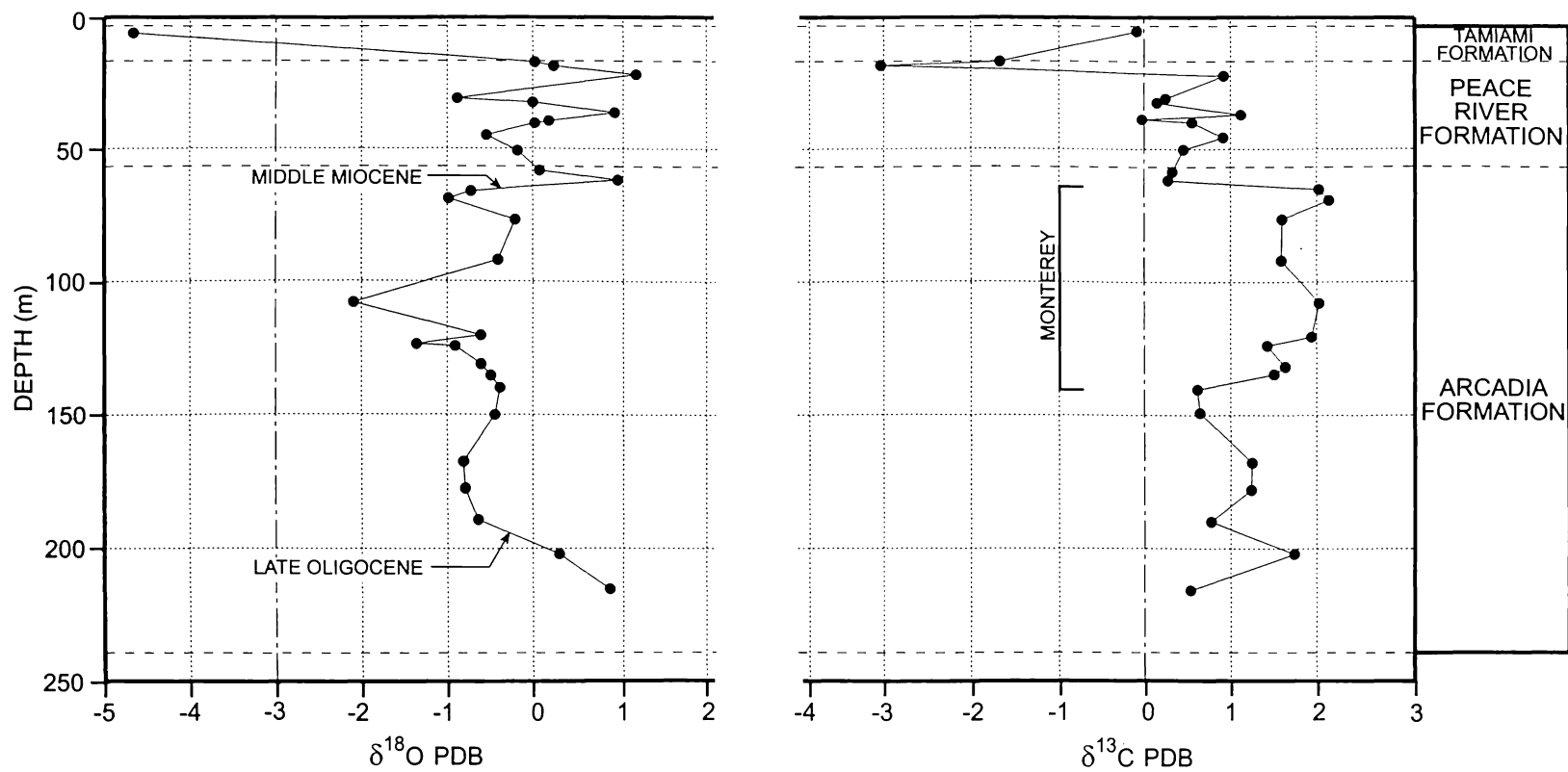


Figure 54. Variation of stable oxygen and carbon isotopes with depth in core W-16523. This plot is based on 30 samples collected from unaltered calcitic mollusk shells. Depths are below land surface. Monterey refers to the Monterey Carbon Isotope Excursion.

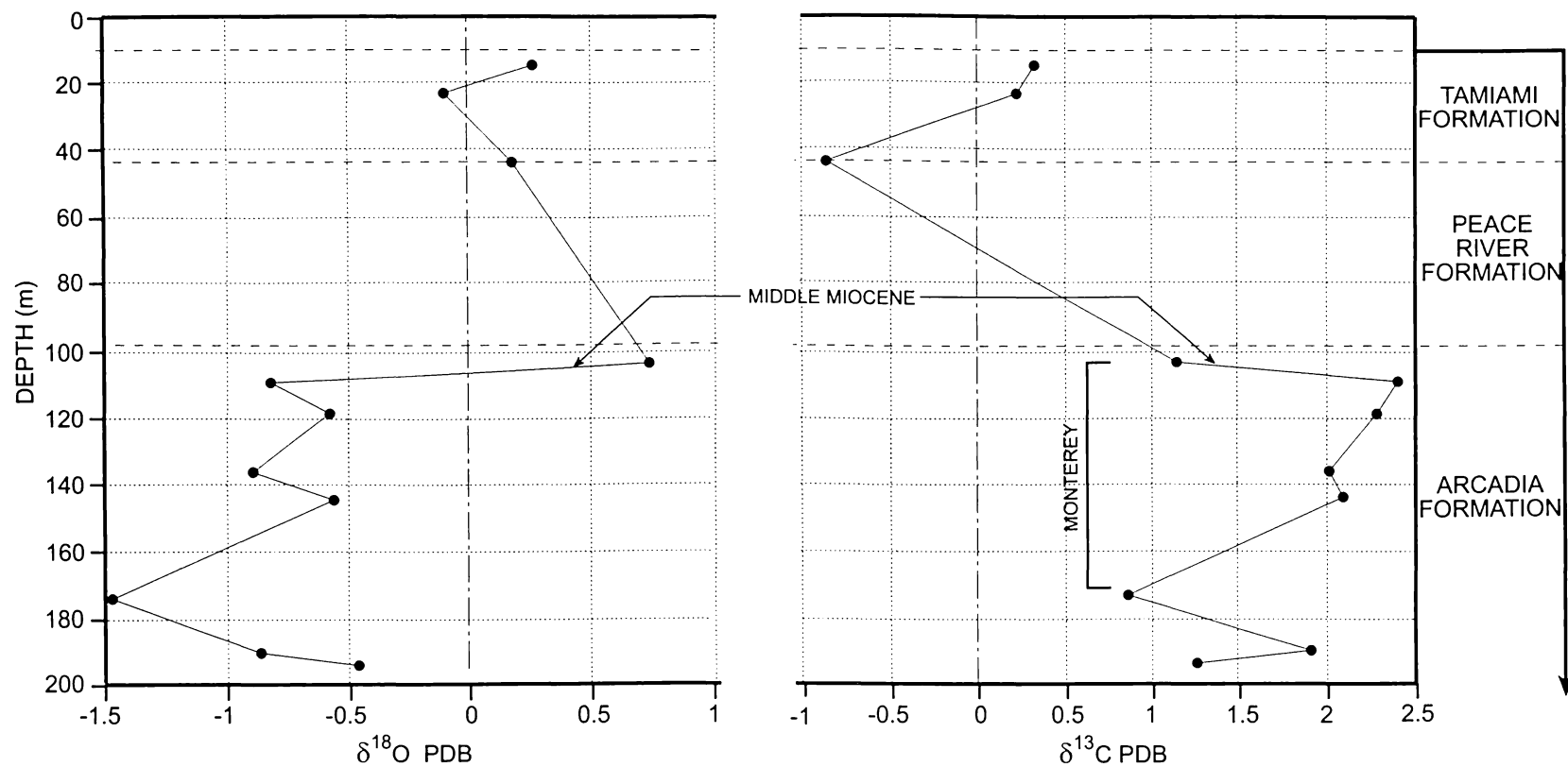


Figure 55. Variation in stable oxygen and carbon isotopes with depth in core W-17115. This plot is based on 11 samples collected from unaltered calcitic mollusk shells. Depths are below land surface. Monterey refers to the Monterey Carbon Isotope Excursion.

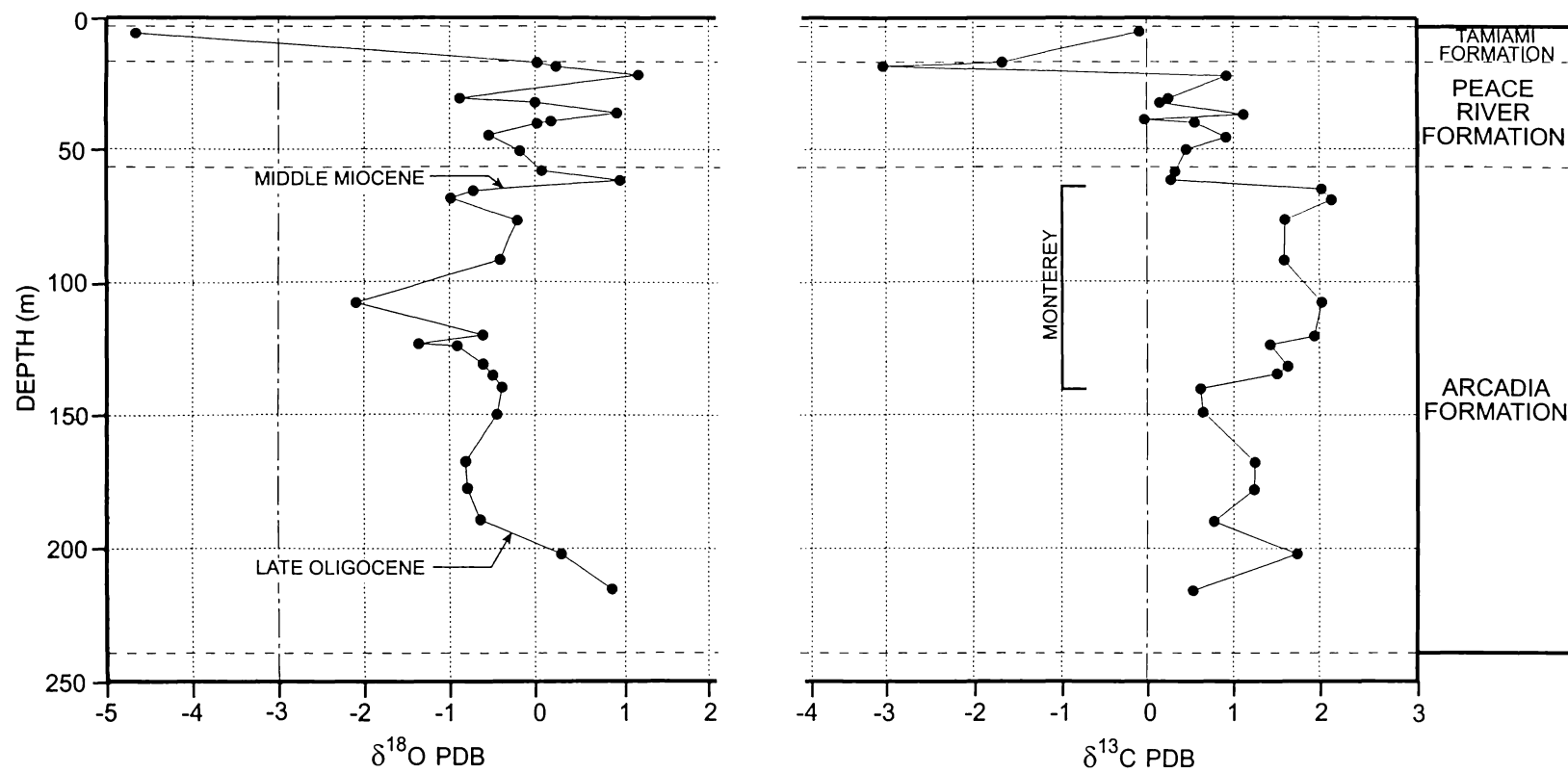


Figure 54. Variation of stable oxygen and carbon isotopes with depth in core W-16523. This plot is based on 30 samples collected from unaltered calcitic mollusk shells. Depths are below land surface. Monterey refers to the Monterey Carbon Isotope Excursion.

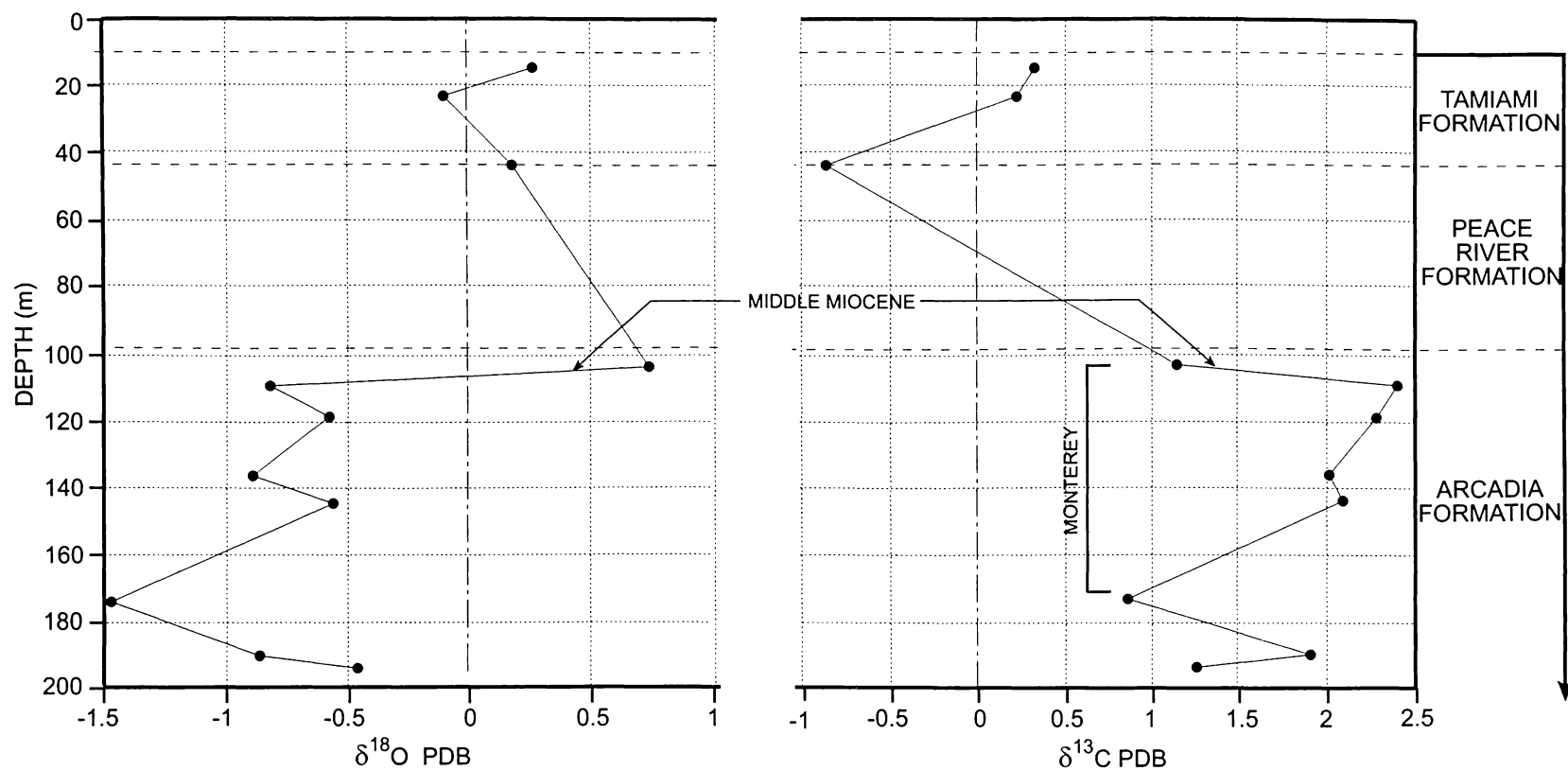


Figure 55. Variation in stable oxygen and carbon isotopes with depth in core W-17115. This plot is based on 11 samples collected from unaltered calcitic mollusk shells. Depths are below land surface. Monterey refers to the Monterey Carbon Isotope Excursion.

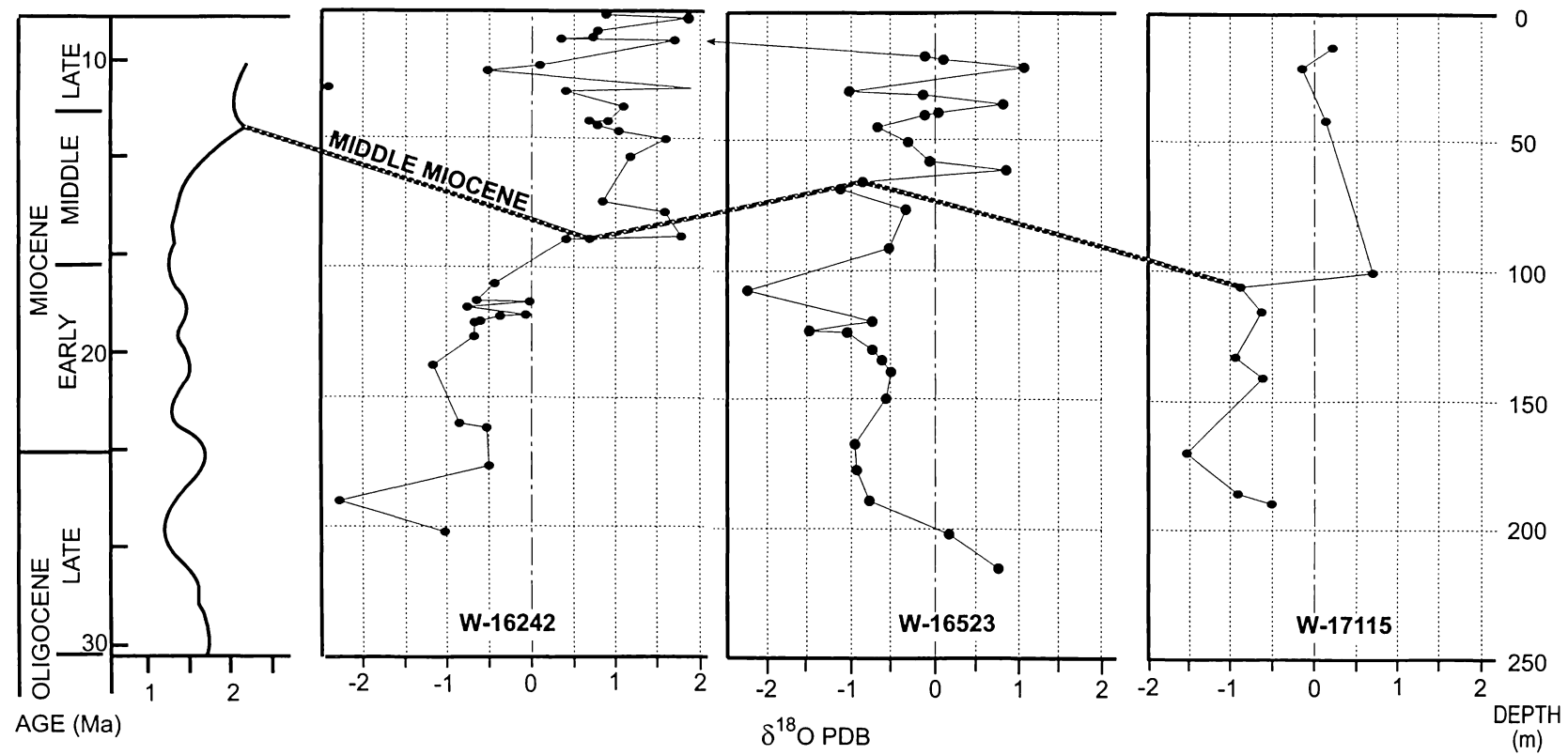


Figure 56. A comparison of the stable oxygen isotope data from cores W-16242, W-16523, and W-17115 to the generalized late Paleogene and Neogene variation from the Atlantic Ocean. Note the correspondence of the core data to the middle Miocene shift in oxygen isotope ratios.

location of this excursion within the stratigraphic section is useful in further constraining the age of the Arcadia Formation.

Distinctive shifts in the carbon isotope data from light to heavy were observed in each core (Figures 53, 54, and 55). The carbon isotope shifts in core W-16242 are rather extreme with a 3‰ change from the light values at -1‰ PDB to 1.5 to 2.0‰ on the heavy side (Figure 53). The upper boundary of the carbon excursion corresponds to the disconformity separating the Arcadia Formation from the overlying Peace River Formation at a depth of about 100 m and the lower boundary matches well with the inferred strontium-isotope ages at approximately 150 m. The shift in core W-16523 is on the order of about 1.5‰ and corresponds well to the oxygen isotope data. Again, the inferred age data from the strontium isotopes and the magnetostratigraphy match closely with the excursion boundaries at about 60 and 140 m, corresponding to an age range of 17.3 to 13.8 Ma (Berger and Vincent, 1986; corrected to time scale of Berggren et al., 1995b). The carbon isotope excursion also occurs in core W-17115 with a change similar in magnitude to the other cores, but it is not as well defined due to the lower number of samples analyzed.

Based on the observed shifts in the carbon isotope ratios, it is concluded that the Monterey Carbon Isotope Excursion is identifiable in each core studied (Figure 57). The stratigraphic position of the excursion in comparison to the chronology inferred by the strontium-isotope ages and magnetostratigraphy closely corresponds to the age of the Monterey Excursion at other locations in the world, particularly in core W-10651 to the north (Compton et al., 1990; Mallinson and Compton, 1993) and other Atlantic Ocean locations (Miller and Fairbanks, 1985).

DISCUSSION

Ages of Late Paleogene and Neogene Stratigraphic Units

Introduction

Data on the stratigraphic section from the base of the Suwannee Limestone to land surface were compiled from this and other geologic investigations on the South Florida Platform to synthesize the most current age constraints on the late Paleogene and Neogene sediments. The age ranges of each of the formations investigated, including the Suwannee Limestone, the Hawthorn Group, the Tamiami Formation, and the Caloosahatchee Formation are given in Table 8. These new age ranges for each of the stratigraphic units are compared to past age estimates and to the current geologic and paleontological time scales in Figure 58.

Suwannee Limestone

Only one strontium-isotope age determination was made on the Suwannee Limestone in core W-16242, but a large number of additional isotope age determinations were made on the Suwannee Limestone in several other cores located to the north of the this investigation (Hammes, 1992; Brewster-Wingard et al. 1997). Hammes (1992) concluded that the age of the Suwannee Limestone ranged from 33.7 to 29.2 Ma (corrected to time scale of Berggren et al., 1995) and was confined strictly to the Rupelian Age of the Early Oligocene. The strontium-isotope age determination in core W-16242 was from a sample collected from near the top of the formation. It produced an age of 29.5 to 26.8 Ma. The magnetostratigraphic analysis of core W-16242 showed a good correlation between the magnetic polarities and

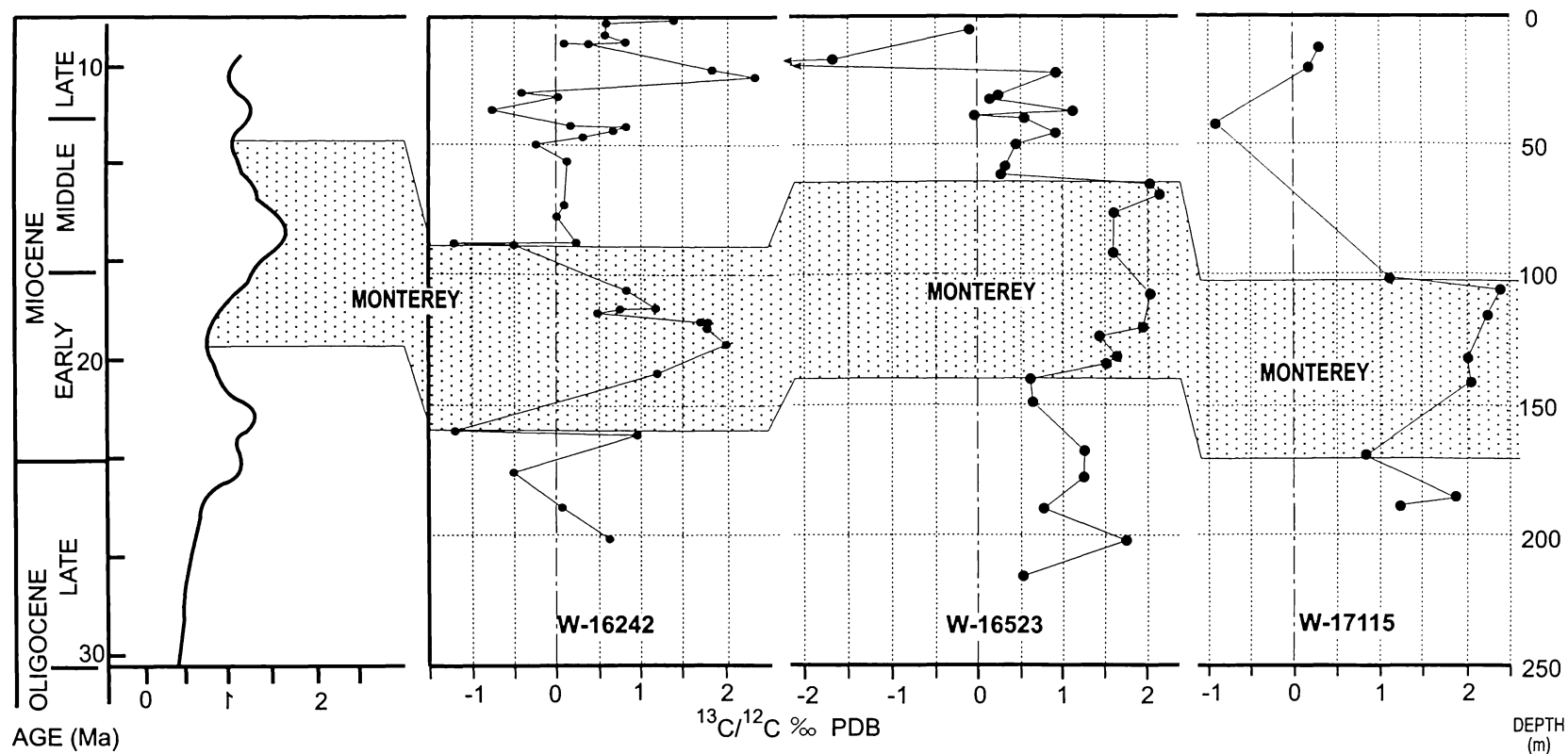


Figure 57. A comparison of the stable carbon isotope data from cores W-16242, W-16523, and W-17115 with the late Paleogene and Neogene data from the Atlantic Ocean. Note the close correlation of the core data showing the Monterey Carbon Isotope Excursion, which occurred during the early to middle Miocene. Depths are below land surface. Monterey refers to the Monterey Carbon Isotope Excursion.

FLORIDA GEOLOGICAL SURVEY

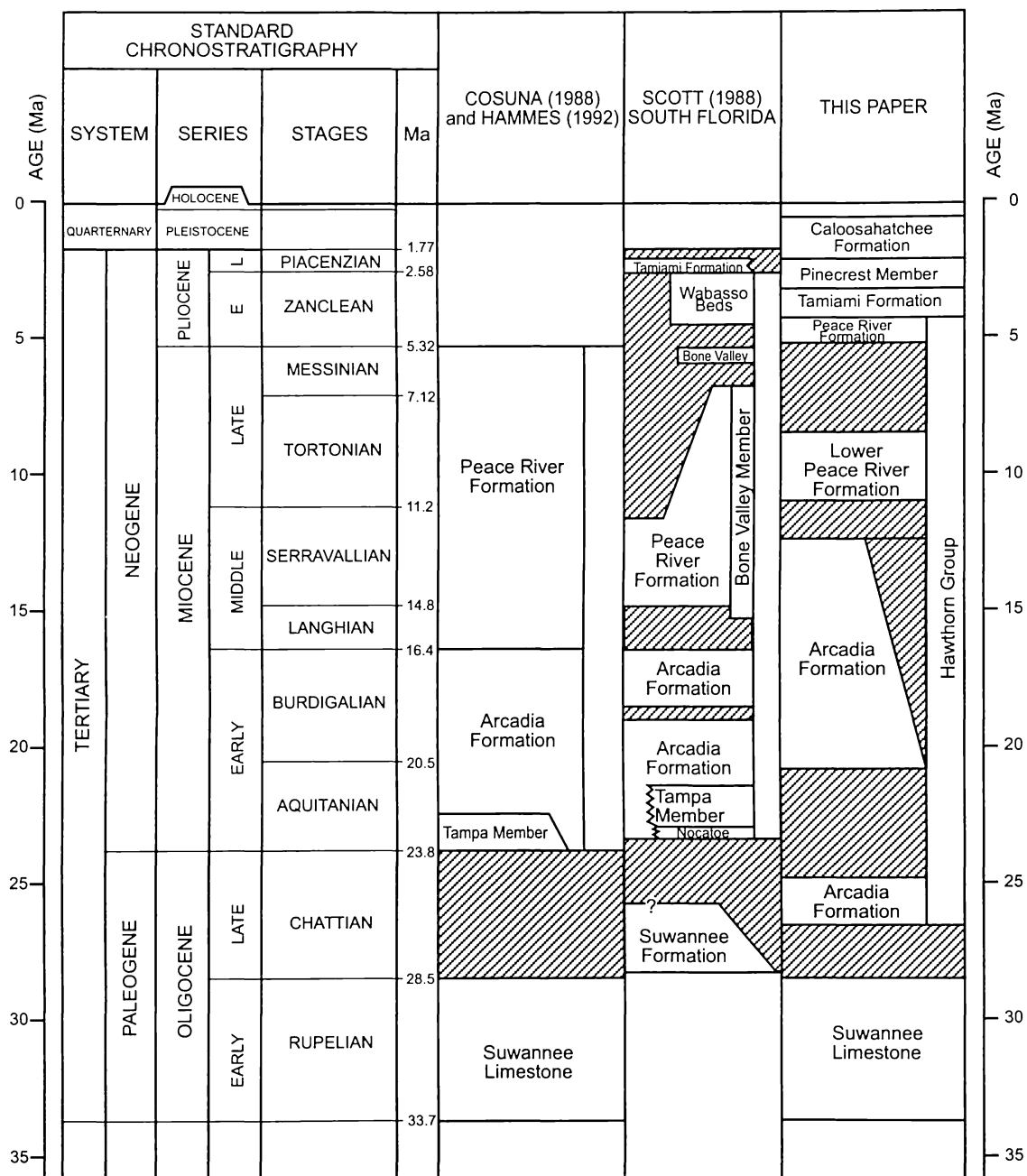


Figure 58. Comparison of the new chronostratigraphy in this paper to previous age estimates for the Neogene and Late Paleogene formations on the South Florida Platform.

Table 8. Estimated ages of selected Neogene and late Paleogene formations on the South Florida Platform.

Formation	Estimated Age Range (Ma)
Suwannee Limestone	33.7(?) to 28.5
Arcadia Formation	26.6 to 12.4
Lower Peace River Formation	11(?) to 8.5
Upper Peace River Formation	5.23 to 4.29
Hawthorn Group	26.6 to 4.29
Pinecrest Member	3.22 to 2.15
Tamiami Formation	4.29 to 2.15
Caloosahatchee Formation	2.14 or 1.77 to 0.6

the GPTS. The top of the Suwannee Limestone has a normal polarity that is correlated to Chron C10n.1n, which has an age range from about 28.5 to 28.3 Ma. Since the full thickness of the Suwannee Limestone was not penetrated in core W-16242, it is not possible to constrain the basal age of the unit. Based on the data collected from core W-16242 and the large amount of data collected on the formation to the north, it is concluded that the Suwannee Limestone at this location has an estimated age range from 33.7 to 28.5 Ma and is restricted to the early Oligocene. The disconformity on top of the unit is believed to be the mid-Oligocene sea-level event, which constrains the upper age limit to 28.5 Ma.

Hawthorn Group-Arcadia Formation

A large number (31) of strontium-isotope age determinations were made on Arcadia Formation sediments in cores W-16242, W-16523, and W-17115. Also, many additional strontium-isotope age determinations were made on the Arcadia Formation in core W-10761 by Compton et al. (1993) and in other cores to the north by Brewster-Wingard et al. (1997). Most of the age determinations range from 26.8 to

13.1 Ma for the Arcadia Formation (all ages corrected to the time scale of Berggren et al. 1995b). In the very middle of the platform, which occurs near the site of the Koreshan core (W-16523), some younger carbonate sediments were deposited. At this location a single sequence, A1 in the core, was deposited on top of the middle Miocene disconformity as suggested by the carbon isotope shift at this location. The magnetostratigraphy of the Arcadia Formation is quite complex and subject to several interpretations within the constraints of the strontium-isotope ages. The base of the Arcadia Formation has a strontium-isotope age of about 26.6 to 25.3 Ma based on the data from core W-16242. The magnetostratigraphic correlation to the GPTS indicates that the normal polarity unit at the base of the formation correlates to Chron C8n.2n, which has an age range of 26.6 to 26.0 Ma. The top of the formation correlates to Chron C5Ar, which has an age range of 12.8 to 12.4 Ma. Based on the strontium isotope data and the magnetostratigraphic data, the top of the Arcadia Formation at most locations has an age of about 12.4 Ma. It must be stated, however, that this surface is a major disconformity and is subject to rather extreme variation in erosional relief that could lead to a vari-

able age at any location. Based on all of the data analyzed, the Arcadia Formation deposition began in the Late Oligocene and terminated in the Middle Miocene.

Based on the chronostratigraphic analysis of core W-16242 and correlation to the other two cores and wells, there are three disconformities within the Arcadia Formation. The lowest disconformity correlates to the Oligocene-Miocene boundary. In core W-16242 there is a hiatus of about four million years at this depth (about 175.3 m). Another disconformity occurs at the Early Miocene-Middle Miocene boundary. The hiatus in core W-16242 is about 1 million years at this feature. A third disconformity occurs in all cores at the approximate boundary between the Langhian and Serravallian. In core W-16242, the hiatus at this boundary ranges from about 1.2 million to 0.1 million years depending on which chronostratigraphic interpretation is used.

Hawthorn Group-Peace River Formation

The Peace River Formation is divided into two distinctively different stratigraphic units by a regional disconformity. The lower part of the formation is a relatively flat-bedded, predominantly siliciclastic unit with some carbonate sediment. The upper part of the formation is a mixed siliclastic/carbonate, deltaic unit containing graded beds with topset, foreset geometries. Because of the differences in sediment facies, the presence of the disconformity, and inferred significant difference in age between the two units, they are discussed individually. The age data on the lower Peace River Formation has been determined in a number of wells in Lee and Hendry Counties by analysis of the calcareous nannofossil and planktonic foraminifera assemblage (Peck et al., 1979a; Peck et al., 1979b; Covington, 1992). A Late Miocene age was determined for the lower part of the Peace River Formation

with the general age restricted to foraminiferal zones N18 and N17 or the solely N17 based on the age of the *Discoaster quinqueramus* Zone of Gartner (1969). The strontium-isotope data of core W-16242 yielded a single age determination of 11.8 to 9.3 Ma. Single strontium-isotope age determinations were made on the lower Peace River Formation in cores W-16523 and W-17115, which yielded ages of 13.1 to 10.3 Ma and 11.3 to 8.6 Ma, respectively. Compton et al. (1993) also obtained several age determinations in the 13.1 to 10.0 Ma range, particularly on phosphorite nodules in the lower part of the Peace River Formation. The lower Peace River section in core W-16242 is only about 3.5 m thick and is therefore either a condensed section or a small part of the full section. Paleomagnetic analysis of the lower Peace River Formation in core W-16242 showed that all samples yielded a reversed polarity. A tentative correlation of this section was made to the GPTS. It correlates to Chron C5r, which has an age range from about 11.9 to 10.9 Ma. Based on the data collected in this investigation and in previous investigations, the lower Peace River Formation has a probable age range from about 11 to 8.5 Ma, which is Late Miocene. The older phosphorite nodules dated by Compton et al. (1993) are believed to be reworked from the erosion of the underlying Arcadia Formation or from erosion of the Peace River Formation to the north where it is older.

Past investigations of the foraminifera and calcareous nannofossils within the upper Peace River Formation (defined at one time to be part of the Tamiami Formation) suggested that the formation ranges from Late Miocene to Early Pliocene in age (Peck et al., 1979a; Peck et al., 1979b; Covington, 1992). Strontium-isotope age determinations from core W-16242 all occurred on the flat part of the curve, yielding an age range of 4.9 to 2.6 Ma. Ages determined by Compton et al. (1993) for the Peace River Formation in core W-10761 are

in the 5.7 to 4.9 Ma range. Because of the flattening in the seawater strontium-isotope curve, virtually all sediments having an age range of 4.9 to 2.6 Ma date about the same. The magnetostratigraphy of core W-16242 correlated to the GPTS produced some reasonably diagnostic age data for the Peace River Formation (Plate 4). The base of the core has a reversed polarity that corresponds to Chron C3n.4n, which has an age range of 5.2 to 5.0 Ma. The base of the Peace River Formation is constrained to this age range, but there is a very high probability that the age of the formation base is a maximum of 5.23 Ma. This conclusion is reached based on the assumption that the Late Miocene (Messinian) global sea level event should create a hiatus at this age. The reversed polarity section at the top of the Peace River Formation corresponds to the Chron C3n.lr, which has an age range from 4.5 to 4.3 Ma. Therefore, the top of the formation is constrained to this age range, but it is believed that the actual age is probably about 4.4 Ma based on the probable rapid deposition of the deltaic facies (Plate 4) and the age constraint provided by the overlying formation. The polarity changes measured in core W-16242 correlate well with the GPTS in this stratigraphic interval. It is concluded that the upper part of the Peace River Formation is Early Pliocene in age with the absolute age ranging from about 5.23 to 4.29 Ma. The Miocene-Pliocene contact lies between the deltaic sediment sequence and the underlying flat-bedded mixed siliciclastic/carbonate sequence. The occurrence of coarse siliciclastic and phosphatic lag deposits commonly marks this boundary (Plates 1, 2, and 3).

Tamiami Formation

Age determinations on the Tamiami Formation in core W-16242 were made primarily by strontium-isotope analysis and magnetostratigraphic analysis. The formation is divided by a disconformity, which

separates the Sand Facies from the overlying Pinecrest Member, using the terminology of Missimer (1992b). Each of these units has a different age range and they are discussed separately.

All of the strontium-isotope samples collected from the lower part of the upper Peace River Formation and the overlying Tamiami Formation yield approximately the same age, because of the flattening of the strontium-isotope curve and less stratigraphic resolution. The magnetic polarity of the lower Tamiami Formation is predominantly reversed with the exception of a very thin interval in the middle of the section and another thin interval, about one m, in the lower part of the section. A significant part of the section was unlithified sand and friable sediment from which good quality samples could not be obtained. Based on all data obtained, the base of the Sand facies of the Tamiami Formation correlates to Chron C3n.ln and the top of the unit with Chron C2Ar. This correlation gives the Sand facies member of the Tamiami Formation an age range of about 4.3 to 3.0 Ma. In consideration of the disconformity at the top of the Sand facies, the upper boundary is more likely at about 3.2 Ma and the lower boundary of the Pinecrest Member at about 3.0 Ma. This interpretation is not unique because of the uncertainty in the measurements within core W-16242. It is possible that less time is missing across the disconformity between the Pinecrest Member and Sand facies member. However, there is a significant change in faunal assemblage and mineralogy of the sediment at this point in the core from the occurrence of a much lower diversity of molds and casts with no aragonitic shell below to a multiple species of abundant aragonitic shell above the disconformity. This suggests a significant time lapse, which would be at least 0.3 m.y. based on this interpretation or as small as 70 k.y. based on correlation of each magnetic polarity change to the GPTS.

Three strontium-isotope analyses were

made in the Pinecrest section. The age ranges for these analyses are from 3.4 to 2.0 Ma with the ages being in stratigraphic order. The two younger age determinations have a higher probability of being more accurate than the older age, because of a general flattening of the strontium-isotope curve from 4.9 to 2.6 Ma (Hoddell et al., 1990). Correlation of the magnetic polarity changes in core W-16242 to the GPTS using the strontium-isotope ages as guides was made. The lower part of the Pinecrest Member in core W-16242 has a normal polarity correlating to Chron C2An.ln. This corresponds to the upper part of the Gauss Chron with an age range of 3.2 to 3.1 Ma. This normal polarity interval in the core could represent all of the Chron C2An.ln or more likely represents only part of it. However, the age constraint on the base of the Pinecrest must be placed on the maximum age of 3.2 Ma. The age constraint on the upper boundary is more problematical, because there is a small gap in the polarity data with reversed polarity underlying it (Plate 4). The reversed polarity interval correlates to anomaly Chron C2r.2r, which has a time range of 2.581 to 2.15 Ma. This time increment is equivalent to the lower Matuyama Chron. If the interpreted correlation to the GPTS is assumed to be correct, the constraint on the upper boundary is about 2.15 Ma. Therefore, based on the available data from core W-16242, the Pinecrest Member of the Tamiami Formation in core W-16242 has an age range of 3.2 to 2.2 Ma (with consideration of the disconformities bounding the Pinecrest) the most probable range is three to two Ma. This age range correlates quite well to the age determinations made for the Pinecrest Member in the Sarasota site to the north of the study area by Jones et al. (1991). Bender (1973) used the uranium/helium technique to determine the age of two corals from the Pinecrest Member. These corals produced ages of 4.24 and 3.69 Ma (corrected to time scale of Berggren et al., 1995b). Akers (1974) determined that the

age of the Pinecrest Member was mid-Pliocene based on the concurrent occurrence of *Gephyrocapsa caribbeannica*, *Reticulofenestra pseudoumbilica*, and *Sphenolithus abies*, which have age ranges of younger than 3.6 Ma, 11.9 to 3.7 Ma, and 7(?) to 3.66 Ma, respectively. It has also been noted by Olsson (1964; 1968) that there is a distinctive relationship between the fauna of the Caloosahatchee Formation and the Pinecrest Member, which may be indicative of a relatively small time gap between deposition of the two units. Based on the proposed chronologic framework suggested, the time interval is less than 0.2 m.y., which is consistent with the faunal assemblage similarity. In conclusion, the age of the Pinecrest Member of the Tamiami Formation in core W-16242 correlates with the upper portions of the Tamiami Formation to the north. The older ages for the member as determined by Jones et al. (1991) would then correlate to the age of the underlying sand facies of the Tamiami Formation.

Caloosahatchee Formation

Information was collected from core W-16242 on the age of the Caloosahatchee Formation. The strontium-isotope and magnetostratigraphic data show that the age is approximately from 2.14 or 1.77 to 0.6 Ma. This age range is considered to be uncertain because only one strontium-isotope age determination was made and the magnetostratigraphic data are not continuous to the base of the Caloosahatchee Formation in core W-16242. Further work will be required to better resolve the age of the Caloosahatchee Formation in core W-16242. Continued study of this core is merited, because the Caloosahatchee Formation is 11.3 m thick at this location. This thickness may represent one of the more complete stratigraphic sections for this unit in southern Florida.

The age of the Caloosahatchee Formation in southern Florida has been

open to dispute for many years. Dall (1892) considered the formation to be Pliocene in age based on the ratio of extinct versus living species of mollusks. DuBar (1958; 1974) suggested the entire Caloosahatchee Formation was Pleistocene in age based on the presence of a fossil horse skull, *Equus leidy* (Hay), which was found in the uppermost shell bed. Brooks (1968) and Conklin (1968) placed the Pliocene-Pleistocene boundary in the middle of the formation based on the reassignment of some specific lithologic members into the overlying Fort Thompson Formation and others into the Caloosahatchee Formation. Perkins (1969; 1977) used the mapping of discontinuity surfaces to separate the Pleistocene sediments of South Florida and his lowermost Pleistocene (Q1) surface occurred in the top of the Caloosahatchee Formation. Bender (1973) used the uranium/helium dating method to determine the age of some corals collected from the Caloosahatchee Formation. These ages were 1.97 and 1.88 Ma (corrected to time scale of Berggren et al., 1995b). Unfortunately, the corals were not specifically located within the overall stratigraphic section of the formation, making it quite difficult to interpret the significance of the ages.

Based on the historic data collected, the recent data collected by Jones et al. (1991) from the Sarasota shell pits to the north of the study area, and the data from core W-16242, the Caloosahatchee Formation is Late Pliocene to Early Pleistocene in age. The formation is separated into several depositional sequences by regional disconformities, one of which is the Pliocene-Pleistocene boundary. This boundary lies at the base of Chron C2r in core W-16242 at a depth of 19.2 m below surface (Plate 4).

CONCLUSIONS

Strontium-isotope stratigraphy, magnetostratigraphy, carbon and oxygen isotope stratigraphy, foraminifera, calcareous

nannofossils, and diatoms were collectively used to constrain the ages of the major lithostratigraphic formations in the central part of the South Florida Platform. Although this investigation concerning the age of these units may be the most comprehensive to date, the detailed age ranges of the units cannot be uniformly applied over the entire platform or even all of the southern part of it. The geometry of the sediments within each formation and the spacing of time lines was affected by a number of factors, such as topography of the shelf at the beginning of each depositional episode, the rate of sedimentation as each depositional environment responded to changes in sea level, and the pattern of erosion during sea level low stands. All of these factors and others cause spatial variations in the chronostratigraphy of the stratigraphic sequences, as even locally observed in the variation between the three cores studied in detail. However, because the Florida Platform has a relatively flat, rather narrow geometry, major sea level events have caused platform-wide disconformities to develop that help constrain the ages of the formations to general ranges in time. Therefore, the deposition of units, such as the Arcadia Formation, on the southern part of the platform began at a given point in time and deposition of the same unit in the north-central part of the platform may not have occurred until later in time or may not have occurred at all. But, the major lithostratigraphic units that can be correlated will have common age constraints within the framework of the global sea level cycles.

The Suwannee Limestone was believed to have been deposited during the entire Oligocene. Through the work of Hammes (1992), Brewster-Wingard et al. (1997), and this work, it is now clear that deposition of the Suwannee Limestone is restricted to the Early Oligocene.

It was generally believed in the past that Hawthorn Group deposition was restricted to the Middle Miocene. Based on

the new chronostratigraphic data, it is concluded that deposition of the phosphatic sediments of the Hawthorn Group began in the Late Oligocene and continued into the Early Pliocene.

For many years, researchers of Florida geology believed that virtually no deposition occurred during Pliocene time. It is now verified that deposition of the upper part of the Hawthorn Group-Peace River Formation, all of the Tamiami Formation, and the lower part of the Caloosahatchee Formation, were deposited in the Pliocene.

A number of regional hiatuses occur within the stratigraphic section, which can be correlated to global oceanographic events. The mid-Oligocene, the Oligocene-Miocene, the Middle Miocene, and the Late Miocene (Messinian) events are the most dramatic. These events produced gaps in the chronostratigraphic section on the Southern Florida Platform of two, four, one, and six to 6.5 million years, respectively.

LATE PALEOGENE AND NEOGENE SEA LEVEL HISTORY OF THE SOUTH FLORIDA PLATFORM BASED ON SEQUENCE STRATIGRAPHY

INTRODUCTION

Deposition of carbonate sediments on the South Florida Platform began during the late Jurassic and continued through the end of the Eocene with little or no influence of siliciclastic sediments (Schmidt, 1984). During the time frame from the Early Oligocene to the Early Miocene, siliciclastic sediment deposition began on the platform along with carbonate sediment deposition. The cause of this change in deposition pattern was related to infilling of a structural feature known as the Apalachicola Embayment located in the northern part of the platform (Schmidt, 1984; Huddleston, 1993). The Apalachicola Embayment was a northeast/southwest oriented channel that

blocked the transportation of siliciclastic sediment from the southern Appalachians and Gulf Coast onto the southern part of the platform. The primary part of the stratigraphic record in which the transition from carbonate to mixed carbonate/ siliciclastic sedimentation occurred is in the Hawthorn Group (Figure 3). Although some siliciclastic sediment did reach the southern part of the Florida Platform (occurring in the lower Oligocene Suwannee Limestone), the quantity of siliciclastic sediment entering the system did not significantly alter the regional sedimentation patterns and stratigraphy until Hawthorn Group time.

The lithostratigraphy of the Hawthorn Group has been studied in the past to reveal the general characteristics of the platform during this time (Scott and Knapp, 1987; Scott, 1988). However, the lithostratigraphy was not related to global oceanographic events in absolute time. It is the purpose of this section to relate the lithostratigraphy to sequence stratigraphy in absolute time and to show the relationship of sea-level changes to the observed sedimentation patterns. In order to accomplish these objectives, a series of wells and cores were studied to correlate the regional lithostratigraphic units (Figure 59). Then, the sequence stratigraphy of three cores, W-16242, W-16523, and W-17115, was studied and related to the lithostratigraphy, absolute time, and the sea-level history.

REGIONAL LITHOSTRATIGRAPHY PATTERNS OF THE ARCADIA AND PEACE RIVER FORMATIONS

Some insights into the significance of mixed carbonate and siliciclastic sediment deposition on an isolated platform can be obtained by placing the core stratigraphy into a regional perspective. A north-south section from Charlotte County to Marco

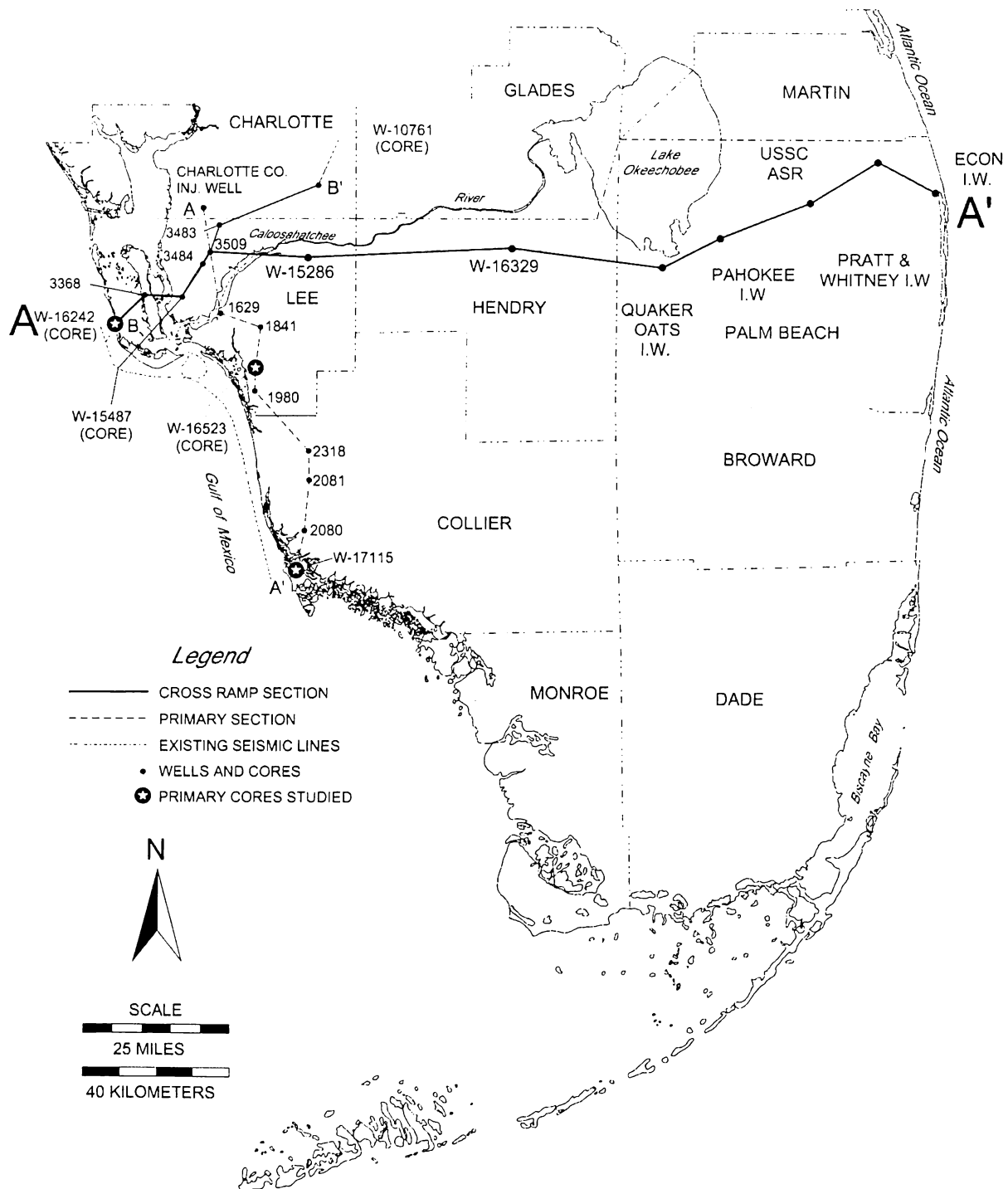


Figure 59. Map of southern Florida showing the locations of cores, wells, and cross-sections. The three primary cores studied are marked with stars. Sections A-A' and B-B' are oriented north-south and east-west and are constructed from core and well data. Section A-A' (large) is a cross-section across the entire state (from Missimer and Scott, 1995).

Island, containing data from cores W-16523 and W-17115 and several wells, shows that the Arcadia Formation has a relatively constant thickness and becomes deeper to the south (Figure 60). The lower Peace River Formation is thin on the north and thickens significantly to the south. The upper Peace River Formation thins from north to south and pinches out between wells LM-1980 and CO-2318. An east-west cross section with a slightly northern component (Figure 61) shows a thinning of the Arcadia Formation to the northeast and a relatively constant thickness for the lower and upper Peace River Formation with the exception of core W-16242. All wells shown in these cross-sections were drilled under controlled conditions with samples collected every five feet or at formation contacts.

Based on the cross-sections, the position of the central axis of the Florida Platform (strike of maximum thickness) during deposition of the Arcadia Formation was oriented approximately north-south, similar to the orientation of the current Florida west coast. The locations of the cores with regard to the center of the platform during deposition of the Arcadia and Peace River Formations are shown in Figure 62. Note that core W-16242 is located on the western margin of the platform, core W-16523 is located nearly in the middle of the platform, and core W-17115 is located on the eastern margin of the platform. The relative position of the cores does cause some variation in the sedimentation patterns at the different locations.

All three cores studied occur close to the center of the platform and near the thickest part of the Arcadia Formation. A section across the entire state of Florida from core W-16242 to coastal Palm Beach County (from Missimer and Scott, 1995) shows that the Arcadia Formation thins and nearly pinches out from west to east (Figure 63). Therefore, the thickness of the Arcadia Formation is greatest in the cen-

tral part of the platform.

Carbonate sediment deposition is predominant in the Arcadia Formation, despite mixing with siliciclastic sediments. The carbonate platform continued to grow in the central part of the South Florida Platform despite the influence of siliciclastic sediment. Throughout deposition of the Arcadia Formation, quartz sand was present in all carbonate sediments. Based on the sediment descriptions and age data from the studied cores and that from Armstrong (1980) on the Arcadia Formation of the Florida east coast, it is believed that carbonate deposition in coastal Palm Beach County ended in the Late Oligocene, corresponding to the lower part of the Arcadia Formation in the study area. Carbonate sedimentation at the eastern platform margin ceased or the section became a condensed section with a reduced sedimentation rate, producing the geometry shown in the section. Carbonate sedimentation on the Florida Platform from the Early Miocene to the Late Miocene was limited to the central part of the platform west of Lake Okeechobee. The predominantly siliciclastic sediments of the Peace River Formation infilled the platform to the eastern margin either during the Late Miocene and Pliocene or synchronously with the deposition of the Arcadia Formation from the Early Miocene to Middle Miocene. The influx of siliciclastic sediment produced a number of complex and unique lithologies in the central part of the platform, and it also caused a modification of the entire platform geometry.

SEQUENCE STRATIGRAPHY

Definitions

A sequence is defined as "a stratigraphic unit composed of a relatively conformable succession of genetically related

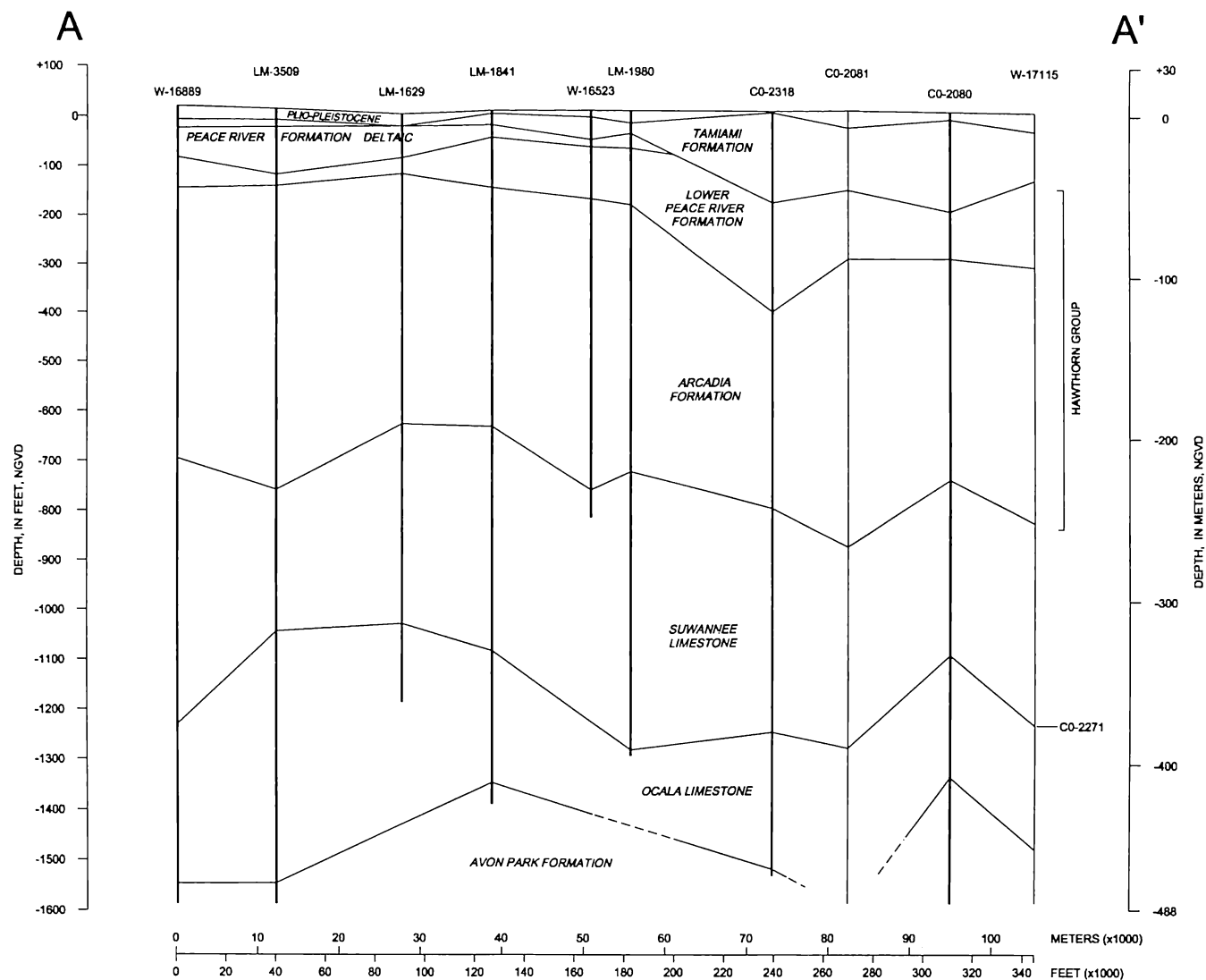


Figure 60. Section A-A' from central Charlotte County to Marco Island. The cores used in this section were collected by the Florida Geological Survey and the wells were constructed under the supervision of the author. The geologic logs of the wells are given in the appendix. Geophysical logs were available for each well. All major formation contacts were picked by the author based on current unit definitions as established by the Florida Geological Survey.

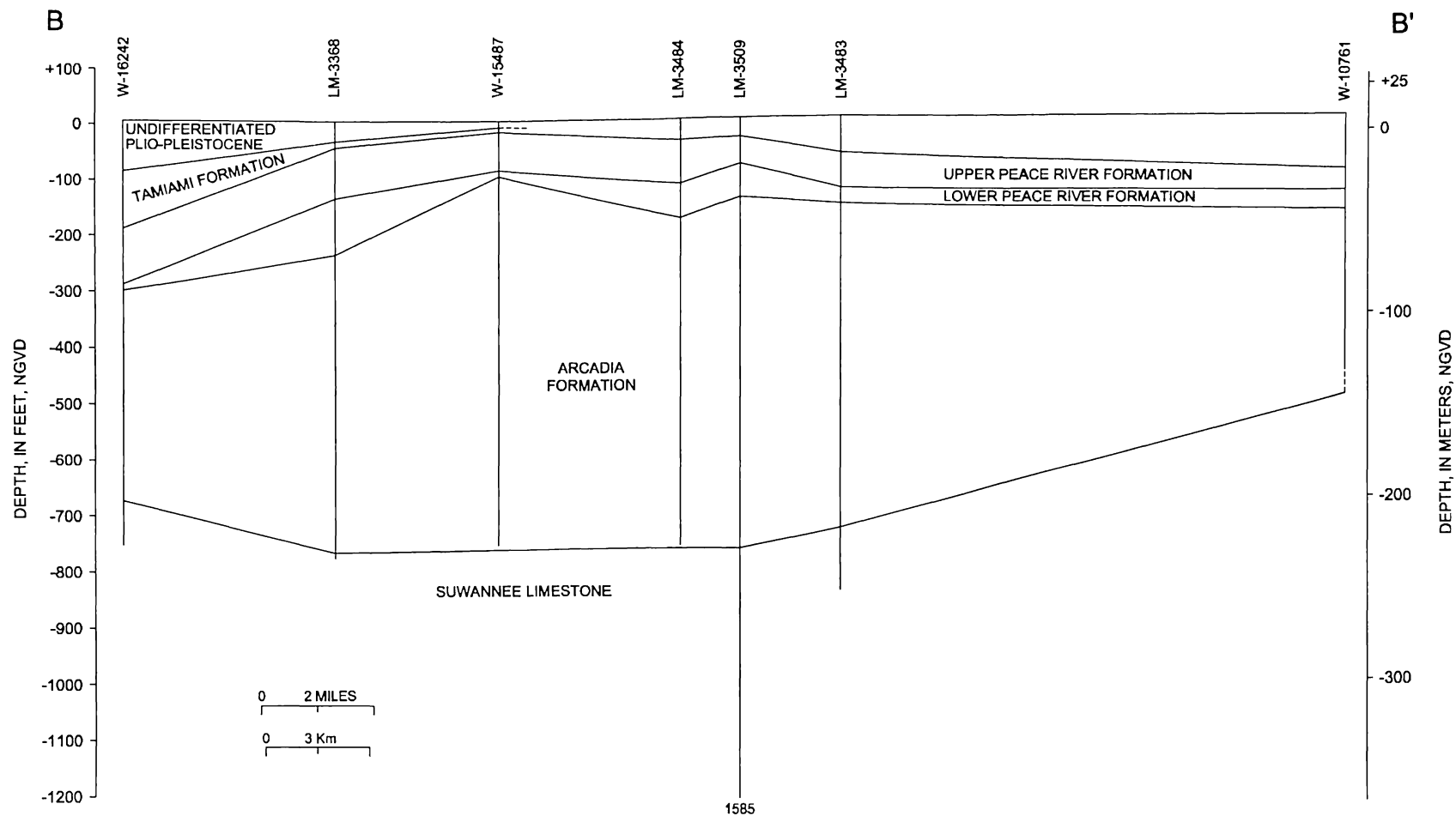


Figure 61. Section B-B' from Captiva Island to west-central Charlotte County. The cores used in this section were collected by the Florida Geological Survey. Detailed analysis of core W-10761 was conducted by Compton et al. (1990; 1993). All major formation contacts were picked by the author based on current unit definitions as established by the Florida Geological Survey.

CENTRAL AXIS OF PLATFORM

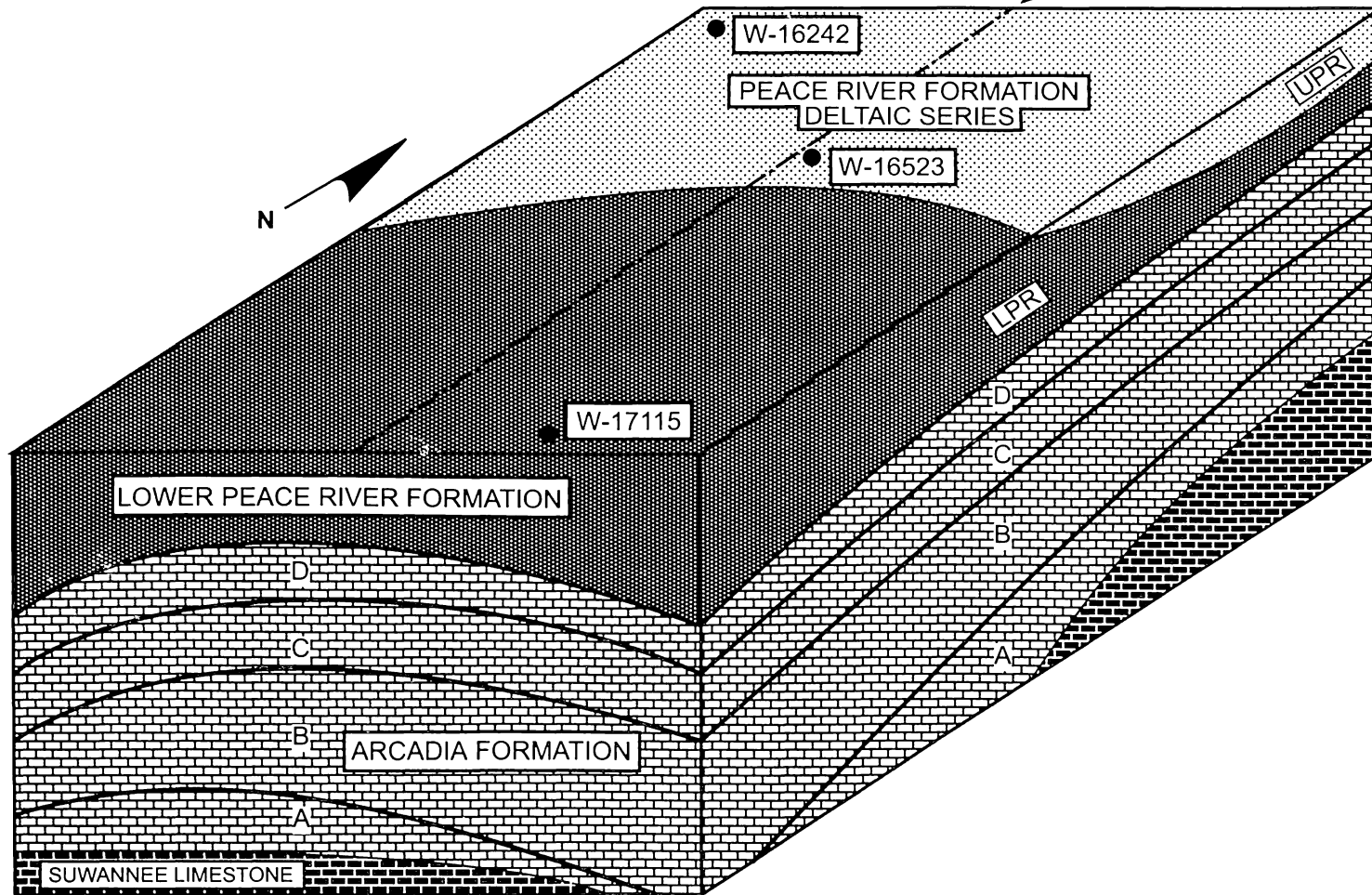


Figure 62. Block diagram of the Hawthorn Group in the study area from Charlotte County to Collier County based on sections A-A' and B-B'. The top surface of the diagram lies on the disconformity between the Peace River Formation and the Tamiami Formation. The approximate locations of the studied cores are on the surface of the diagram. Note that the deltaic subfacies of the Peace River Formation, labelled UPR, pinches out at a location just south of core W-16523. The approximate location of (super)sequences are labelled A, B, C, and D within the Arcadia Formation and both the lower Peace River Formation and the upper Peace River Formation are sequences. The approximate location of the central axis of the platform is shown running through core W-16523. This is a conceptual diagram and it is not to scale.

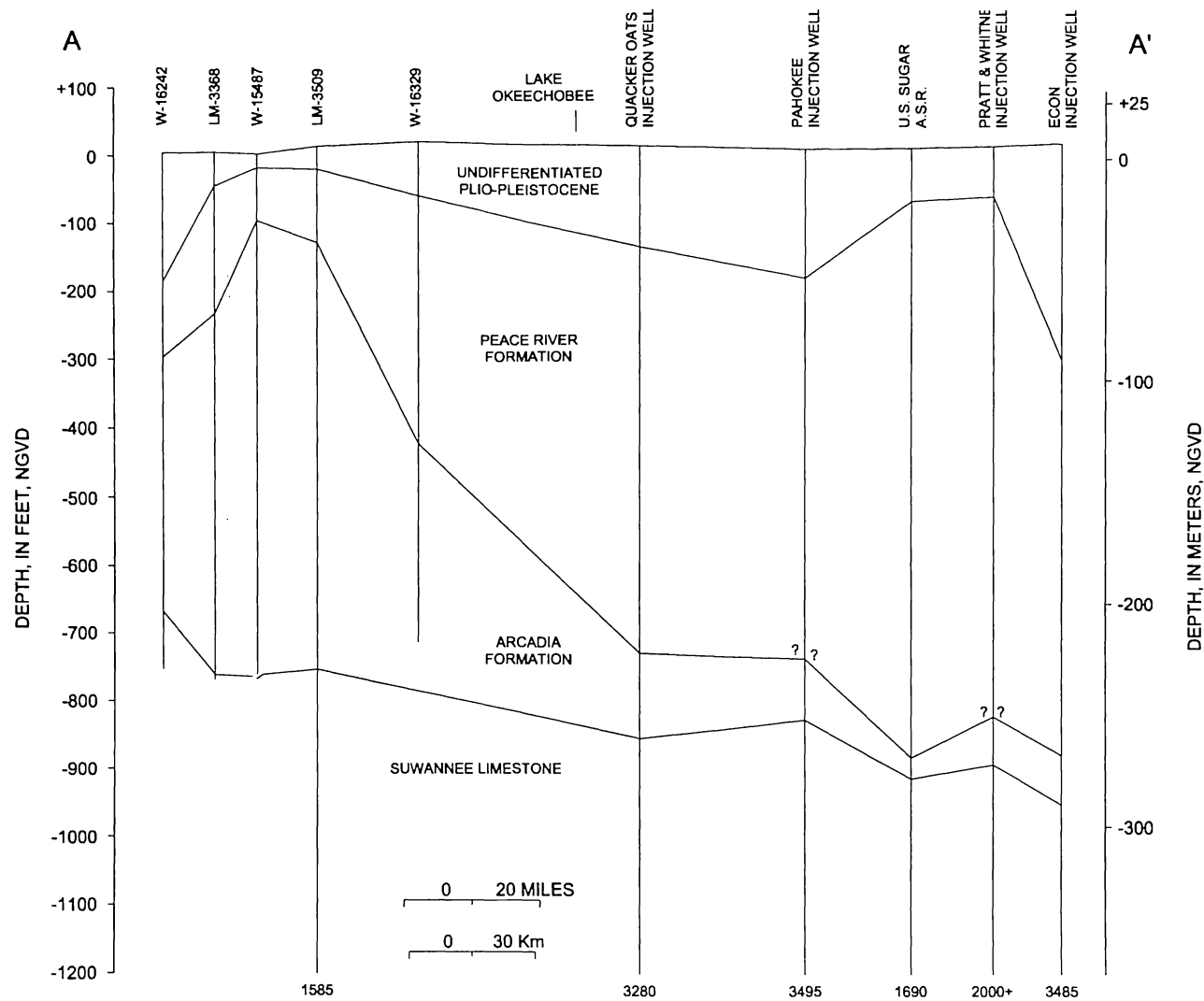


Figure 63. Section from Captiva Island (core W-16242) to north Palm Beach County. The Arcadia Formation thins both to the west and east of a central axis occurring near the Florida West Coast. The formation is quite thin to the east of Lake Okeechobee. Deposition of primary carbonate sediment ended on the east after the late Oligocene.

strata and bounded at its top and base by unconformities or their correlative conformities" (Mitchum, 1977). If several sequences are genetically related and bounded by regional unconformities at the base and top, the group of sequences can be termed a "supersequence." A sequence consists of a set of "systems tracts" composed of a set of shoaling-upward sediment packages, called "parasequences" (Van Wagoner et al., 1990). If several parasequences are grouped together based on some genetic relationship, the group is termed a "parasequence set." When applying these definitions to the sediments observed in the cores, the definition of a parasequence is not precise, because in many cases a package of shoaling-upward sediment is subdivided by one or more discontinuities that may or may not represent exposure horizons. The problem is one of determining if a given discontinuity is of significance to form a boundary of an individual parasequence. In this paper, the shoaling-upward building blocks for construction of supersequences and sequences are termed "sediment packages," because a given package may be either a "parasequence" or a "parasequence set."

Recognition of Supersequence, Sequence, and Sediment Packages in the Arcadia and Peace River Formations

The largest building blocks of this stratigraphic section are the supersequences and sequences. In all cases, these boundaries were placed at regional unconformities. The regional unconformities were defined using a number of criteria, which included: 1) missing time across the boundary (usually greater than one m.y.), 2) significant change in lithology, 3) presence of an exposure horizon, such as a laminated crust or thin clay, 4) presence of an

erosion deposit, such as a phosphorite and quartz sand and gravel, producing a significant change in the natural gamma ray signature (on geophysical logs), and 5) a significant change in the water depth of the deposit across the boundary, such as moving upward from a supratidal deposit to an outer ramp deposit. Not all of the regional unconformities showed all of these characteristics, but each one showed at least three and in all cases there was time missing across the boundary.

Definition of the sediment packages was based on the stacking patterns of a set of defined subfacies found in the Hawthorn Group and their respective depositional water depth characteristics. The 14 defined subfacies found in the Hawthorn Group are listed in Table 6 along with their estimated water depth. The detailed criteria for recognition of these subfacies are given in Table 5. Also, a diagram showing the relative water depth of the subfacies is given in Figure 25. The specific criteria for defining a given sediment sequence were: 1) the packages showed a subfacies stacking pattern that shoaled upward, 2) each package was bounded by discontinuities both at the top and bottom, 3) little time was missing across the defined discontinuities with the exception of packages occurring adjacent to unconformities, 4) an exposure horizon occurred at the top of many sediment packages, and 5) there was a distinct change in water depth between the top subfacies in a sediment package and the next higher subfacies at the base of the succeeding package. The discontinuities dividing the sediment packages are commonly exposure horizons marked by laminated crusts, selective dolomitization, brecciation, or lag deposits. In other cases, there is a substantial change in water depth of bordering deposits without an exposure horizon.

Sequence Stratigraphy of Arcadia Formation

Introduction

Lithostratigraphy and sequence stratigraphy are commonly not compatible with regard to terminology and the boundaries of supersequences and sequences that may not correspond to existing lithostratigraphic formation boundaries. However, in the area studied, the sequence boundaries are somewhat compatible with the existing formation boundaries. Therefore, for discussion purposes, the supersequences and sequences within the Late Oligocene and Early to Middle Miocene will be discussed within a lithostratigraphic framework for the study area or be assumed to form the internal structure of the lithostratigraphic unit named the Arcadia Formation. However, later in this paper the problem of sequence stratigraphic correlation with lithostratigraphic units will be discussed, particularly in terms of mixed carbonate and siliciclastic sedimentation on a ramp.

Four supersequences or sequences were found in the Late Oligocene to Middle Miocene (Arcadia Formation) in cores W-16242, W-16523, and W-17115. Each of these (super)sequences is defined based on the presence of regional unconformities lying both on top and at the base. These (super)sequences are labelled from A to D from the base to the top of the formation in Plate 5. The units labelled A and B are supersequences with A consisting of two or three sequences and B consisting of four sequences (see Plate 5). Both C and D are sequences.

Each supersequence or sequence consists of a series of sediment packages. Each sediment package is labelled A1..Ax on Plate 5 beginning at the base of the formation. The stacking pattern of subfacies (lithologies) for each of the packages is

given in Table 9. There were 59 different types of subfacies stacking patterns found in the sediment packages constituting the Arcadia Group. Some representative examples of these sediment packages are given in Figure 64.

Each of the supersequences or sequences occupies a specific increment in absolute time. A unified chronostratigraphic analysis was made on core W-16242 and a number of strontium-isotope age determination were made on the other cores. The age information for each of the supersequences and sequences described in also shown on Plate 5.

Supersequence A

Supersequence A was deposited during Late Oligocene time in each core. It lies disconformably upon the underlying lithostratigraphic unit, the Suwannee Limestone, separated by a hiatus of about 2 m.y. Supersequence A consists of primarily shoaling-upward sediment packages deposited in shallow water. No outer ramp subfacies are found in this unit. It ranges in thickness from 29.6 to 57.9 m with the thickest section in core W-16523 which lies in the very middle of the ramp (Table 10). This supersequence consists of 7, 8, and 9 sediment packages in cores W-16242, W-16523, and W-17115, respectively. Most of the sediment packages shoal upward from inner ramp to peritidal environments and are capped by an exposure horizon. The predominant subfacies deposited in supersequence A are inner ramp environments containing coral and coralgall fauna and peritidal sediments. No deep water, outer ramp subfacies were found in supersequence A.

Supersequence B

Supersequence B was deposited exclusively during the Early Miocene, predominantly in the Burdigalian. It is bounded by regional unconformities and ranges from 46

Table 9. Sediment packages in the Arcadia Formation.

Core W-16242					
(Super) Sequences	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Patterns from bottom to top ¹
A	A1	0	21.2	6.5	9,7/4,4,1
	A2	0	20.7	6.3	7/3,3,1
	A3	3	37.5	11.4	9,1
	A4	0	5.5	1.7	3,1
	A5	0	8.5	2.6	9,9/7,3,1
	A6	0	6	1.8	7/3,3,1
	A7	0	4	1.2	3
B	A8	0	4.2	1.3	9,4,1
	A9	2	20.3	6.2	10/11,9,7,3/7,3,1
	A10	3	17	5.2	10,9,1
	A11	0	16	4.9	9,8
	A12	1	17.5	5.3	10
	A13	0	13.5	4.1	10,9
	A14	1	13.5	4.1	10
	A15	2	19.6	6.0	7,4,3
	A16	1	18.4	5.6	10,9,3
	A17	1	10.5	3.2	5,6
C	A18	3	38	11.6	11,10,9
	A19	1	8.3	2.5	9,7,3,1
D	A20	2	31.3	9.5	11,10,8
	A21	3	22.9	7.0	9,8,7,4,7,1
	A22	1	19.5	5.9	8,5,6,7,4,3
	A23	0	6.5	2.0	8,5,4,3,1

FLORIDA GEOLOGICAL SURVEY

Table 9 (cont.). Sediment packages in the Arcadia Formation.

Core W-16523					
(Super) Sequences	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Patterns from bottom to top ¹
A	A1	2	31.3	9.5	9,3,1
	A2	0	1.7	0.5	3,1
	A3	0	5	1.5	3,1
	A4	4	27	8.2	7,7/9
	A5	0	10.2	3.1	9,7,1
	A6	2	30.8	9.4	9,7,1
	A7	2	20.7	6.3	9,7/3,3
	A8	4	39.9	12.2	9,1
B	A9	1	17.4	5.3	9,7,7/3
	A10	1	16.8	5.1	9,1
	A11	1	7.4	2.3	10/9,1
	A12	4	43.3	13.2	10,9,9/7,7/3,1
	A13	5	36.2	11.0	9/7,7,7/3,3,7/3
	A14	3	34.8	10.6	11/10,10,7,3
	A15	1	12.5	3.8	11,9,1
	A16	2	25	7.6	10,9,9/7,7,3
	A17	1	15.5	4.7	11/10,10,7/3
	A18	1	24.5	7.5	9/7,7,7/4
	A19	1	25	7.6	10/9,9,3,1
C	A20	2	34	10.4	10,5,6
	A21	2	25	7.6	9,4/3,3,1
	A22	2	41	12.5	9,1
D	A23	1	28.5	8.7	9,7
	A24	2	32	9.8	10,11/4
	A25	3	27.3	8.3	9,7,4,1

Table 9 (cont.). Sediment packages in the Arcadia Formation.

Core W-17115					
(Super) Sequence	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Patterns from bottom to top ¹
A	A1	0	4.9	1.5	9,1
	A2	1	8.5	2.6	9,3,1
	A3	0	3	0.9	3,1
	A4	0	4.5	1.4	9,3,1
	A5	2	11	3.4	3,1
	A6	0	8.5	2.6	9,7,3,1
	A7	0	7	2.1	9/7,7,3,1
	A8	0	6	1.8	9,9/7,3,1
	A9	0	8	2.4	9,3,1
	A10	1	21.9	6.7	7,3,1,3
	A11	0	13.1	4.0	9,1
	A12	3	19.6	6.0	9,1
B	A13	0	19.4	5.9	10,3,3/4,4
	A14	0	16	4.9	10,9,7,3,1
	A15	1	22	6.7	10,10/9,9,7,3,1
	A16	0	7	2.1	9,7/3
	A17	0	7	2.1	13,10,7/3
	A18	1	5	1.5	13,10,13,7/3
	A19	1	6	1.8	13,11,9/3
	A20	0	7	2.1	13,11,9/3
	A21	4	54.7	16.7	13/12,12/10,10,9
	A22	1	12.3	3.7	9,7/3
	A23	2	23	7.0	10
	A24	1	20.5	6.2	9,7

FLORIDA GEOLOGICAL SURVEY

Table 9 (cont.). Sediment packages in the Arcadia Formation.

(Super) Sequence	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Patterns from bottom to top ¹
B	A25	1	6.5	2.0	9
	A26	1	12.5	3.8	10,12,9
	A27	1	13.2	4.0	10
	A28	3	15.9	4.8	7/3,3
	A29	0	4.7	1.4	9,3
C	A30	1	9.7	3.0	9,3,7/3
	A31	1	18.2	5.5	9,7,7/3
	A32	0	9.8	3.0	9,7
	A33	1	22	6.7	9,4/7,7/3
	A34	0	23.5	7.2	7,7/3
D	A35	0	5.5	1.7	9
	A36	0	19.5	5.9	9,7,9
	A37	1	9.5	2.9	9,7/3
	A38	1	19	5.6	9
	A39	2	19	5.6	9,7

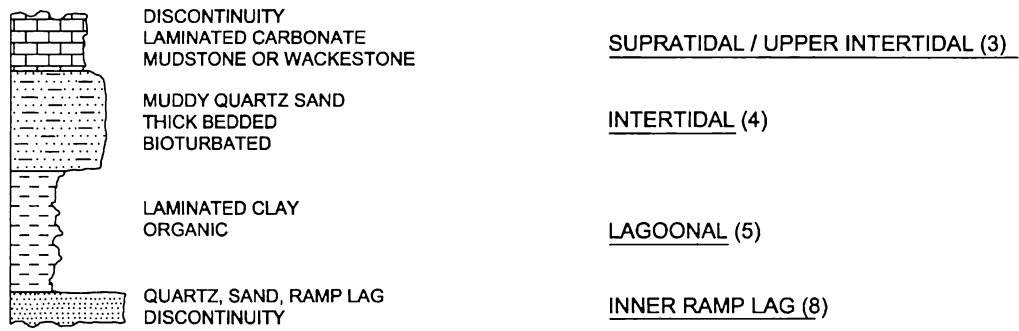
¹ Numbers refer to subfacies numbers contained in Table 6 and Figure 25.

Table 10. Thickness of sequences and number of sediment packages within sequences.

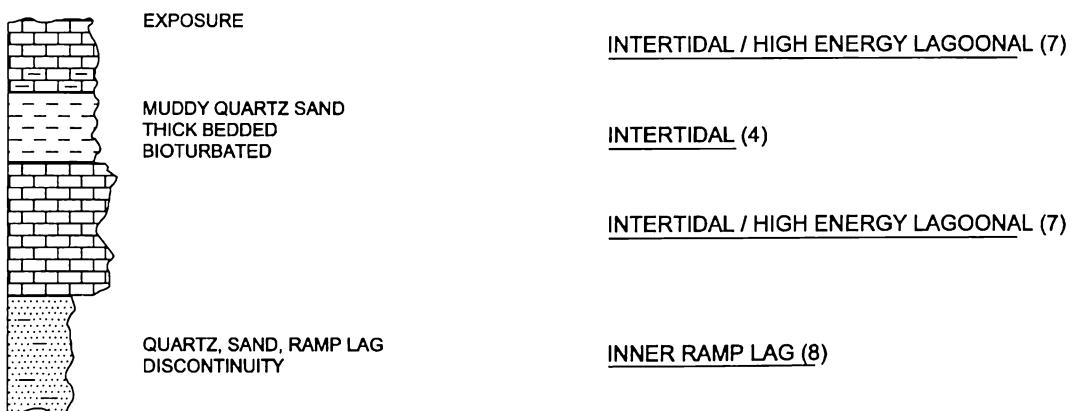
Sequence (thickness in meters)				
Core	A	B	C	D
W-16242	29.6	46.0	14.0	24.4
W-16523	57.9	83.8	28.7	15.2
W-17115	35.1	77.1	19.8	21.9
Sequences (no. of sediment packages)				
W-16242	7	9	2	4
W-16523	8	11	3	2
W-17115	9	16	4	5



LAGOONAL / SUPRATIDAL



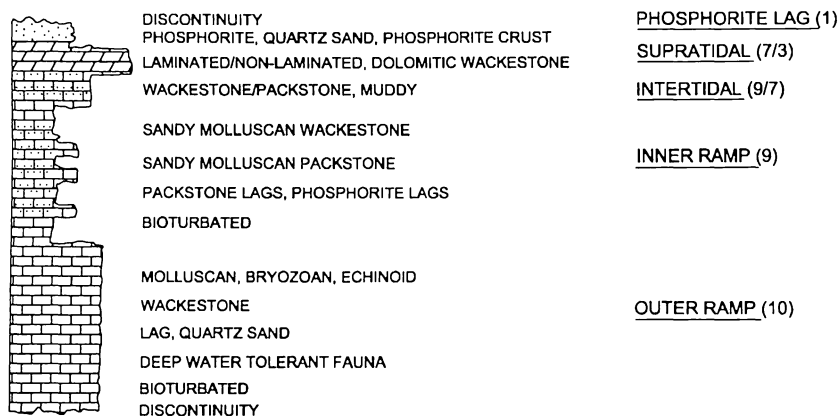
INNER RAMP LAG / LAGOONAL / INTERTIDAL / SUPRATIDAL



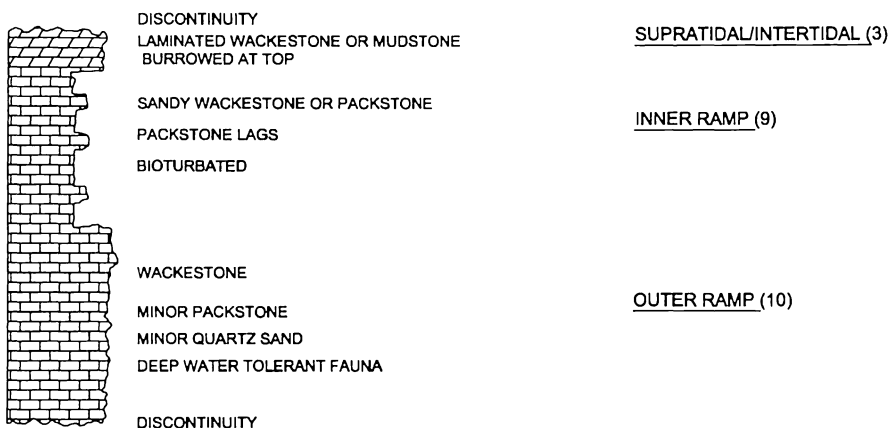
INNER RAMP / RESTRICTED / EXPOSURE

Figure 64. Some examples of the 59 sediment packages found in the Arcadia Formation. All of these examples can be interpreted as shoaling-upward.

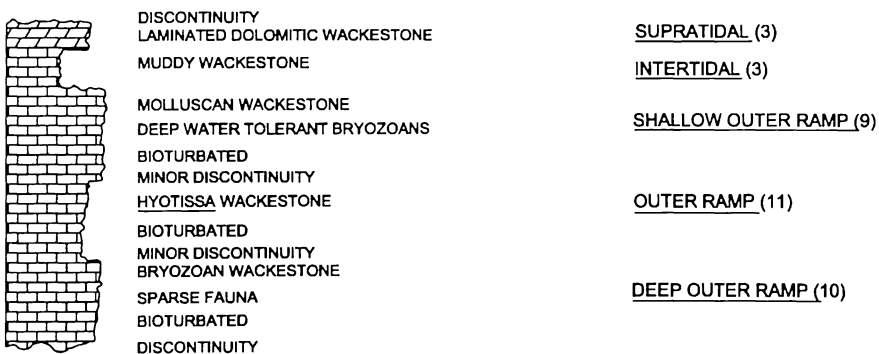
FLORIDA GEOLOGICAL SURVEY



OUTER RAMP / INNER RAMP / INTERTIDAL / SUPRATIDAL / PHOSPHORITE LAG

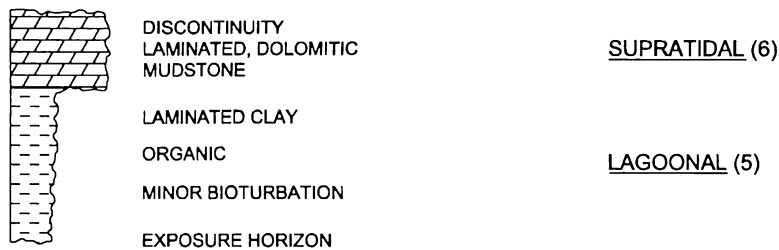


OUTER RAMP / INNER RAMP / INTERTIDAL / SUPRATIDAL

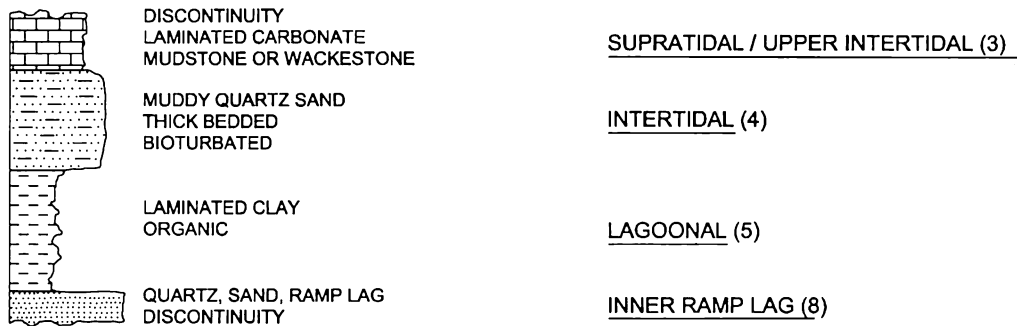


DEEP OUTER RAMP / OUTER RAMP / SHALLOW OUTER RAMP / INTERTIDAL / SUPRATIDAL

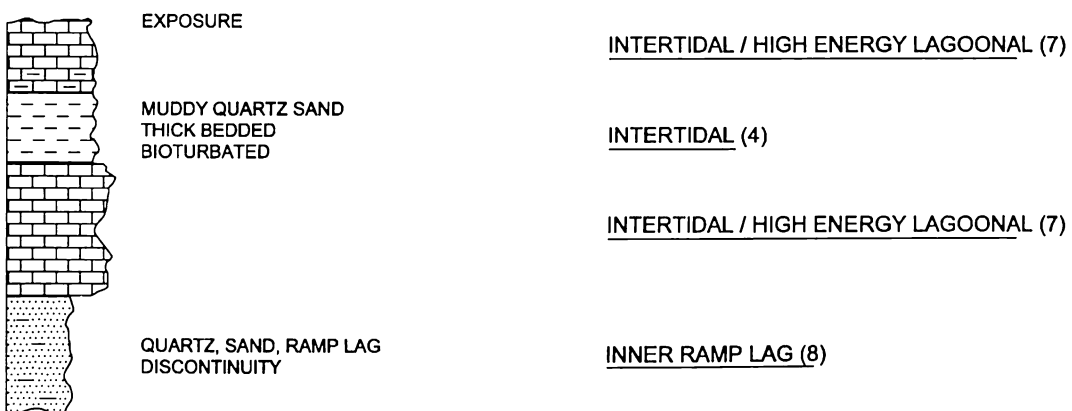
Figure 64 (Cont.). Some examples of the 59 sediment packages found in the Arcadia Formation.



LAGOONAL / SUPRATIDAL



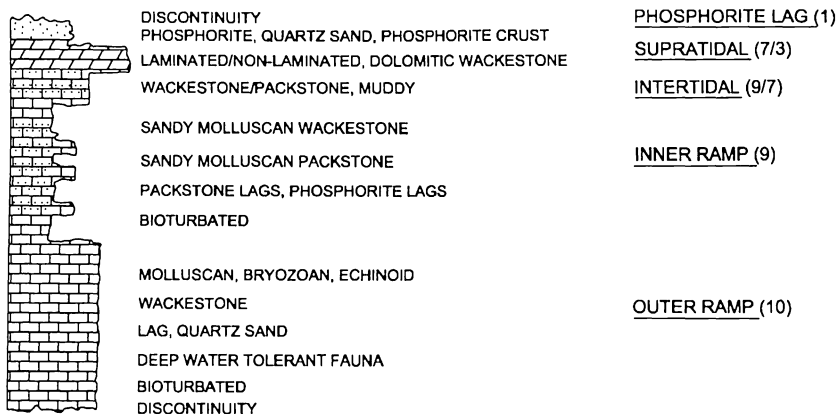
INNER RAMP LAG / LAGOONAL / INTERTIDAL / SUPRATIDAL



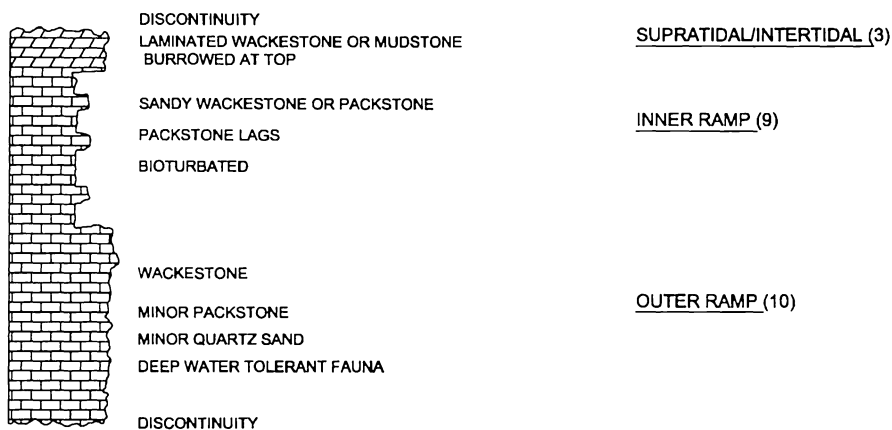
INNER RAMP / RESTRICTED / EXPOSURE

Figure 64. Some examples of the 59 sediment packages found in the Arcadia Formation. All of these examples can be interpreted as shoaling-upward.

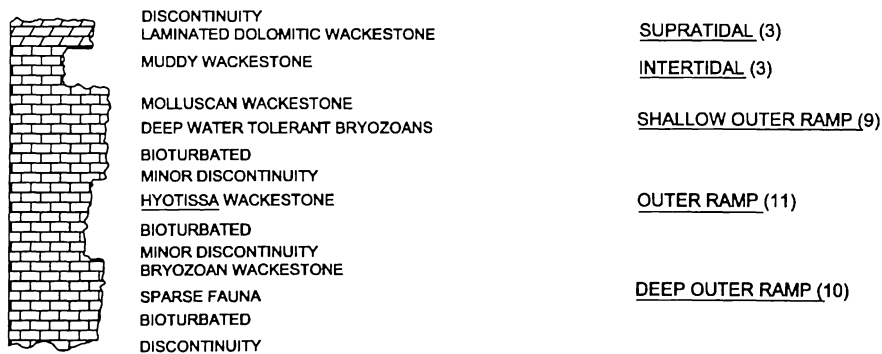
FLORIDA GEOLOGICAL SURVEY



OUTER RAMP / INNER RAMP / INTERTIDAL / SUPRATIDAL / PHOSPHORITE LAG



OUTER RAMP / INNER RAMP / INTERTIDAL / SUPRATIDAL

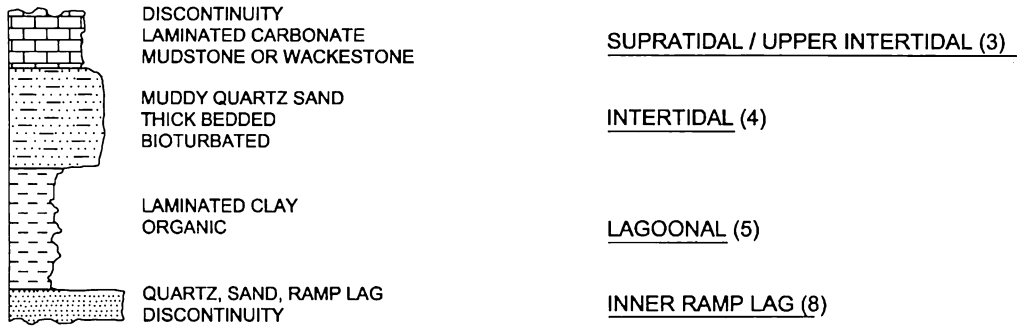


DEEP OUTER RAMP / OUTER RAMP / SHALLOW OUTER RAMP / INTERTIDAL / SUPRATIDAL

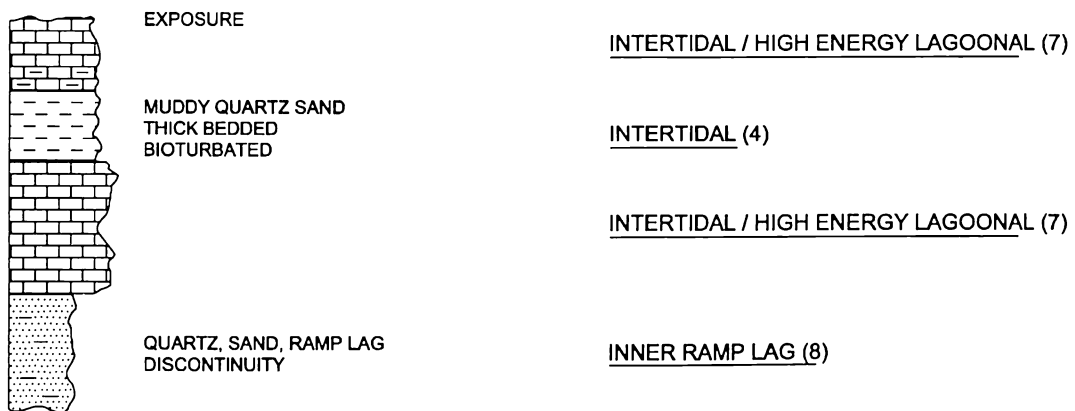
Figure 64 (Cont.). Some examples of the 59 sediment packages found in the Arcadia Formation.



LAGOONAL / SUPRATIDAL



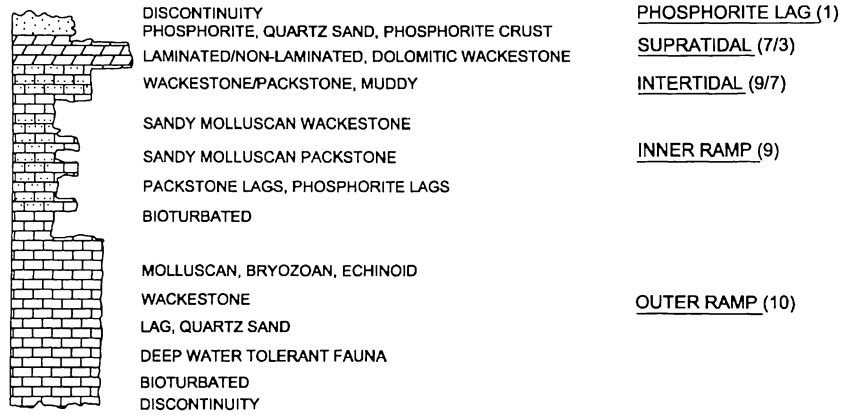
INNER RAMP LAG / LAGOONAL / INTERTIDAL / SUPRATIDAL



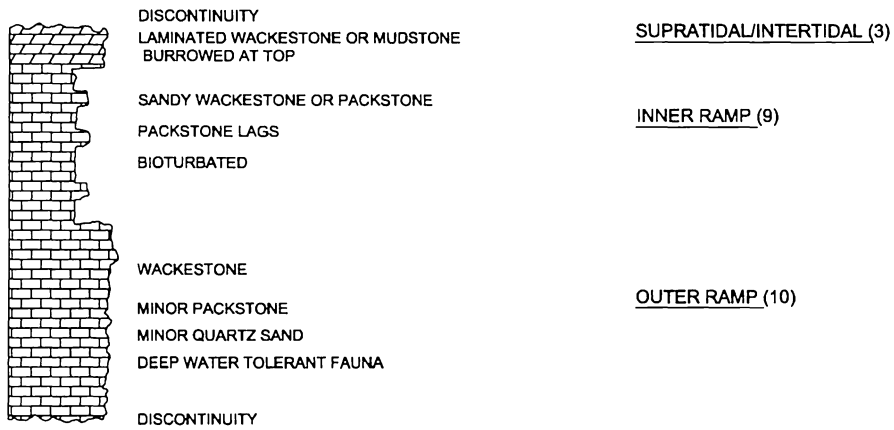
INNER RAMP / RESTRICTED / EXPOSURE

Figure 64. Some examples of the 59 sediment packages found in the Arcadia Formation. All of these examples can be interpreted as shoaling-upward.

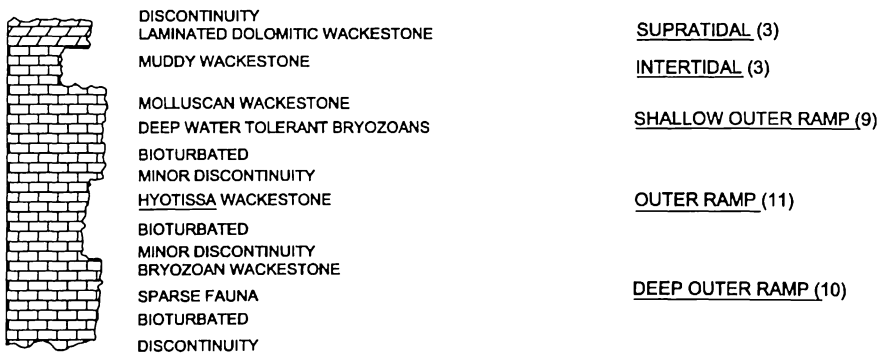
FLORIDA GEOLOGICAL SURVEY



OUTER RAMP / INNER RAMP / INTERTIDAL / SUPRATIDAL / PHOSPHORITE LAG



OUTER RAMP / INNER RAMP / INTERTIDAL / SUPRATIDAL



DEEP OUTER RAMP / OUTER RAMP / SHALLOW OUTER RAMP / INTERTIDAL / SUPRATIDAL

Figure 64 (Cont.). Some examples of the 59 sediment packages found in the Arcadia Formation.

to 83.8 m in thickness. Four sequences occur within the supersequence and are defined by discontinuities occurring at the boundaries between sediment packages with an extreme water depth variation going from shallow water at the base to deep water above it. The total numbers of sediment packages constituting supersequence B are 9, 11, and 16 in cores W-16242, W-16523, and W-17115, respectively. Outer ramp subfacies are most common in this supersequence. The period of maximum flooding of the platform occurs during this time. Deposition of primary phosphate (phosphorite crusts) was most prevalent during supersequence B as evidenced by large gamma ray peaks in the logs (Plate 5).

Sequence C

Sequence C occurs in the Middle Miocene, exclusively in Langhian time. It is bounded by regional unconformities and ranges in thickness from 14 to 28.7 m. Sequence C shows a stacking pattern of subfacies consistent with a single shoaling-upward event, but not entirely regular from deep water to shallow water. It consists of 2, 3, and 4 sediment packages in cores W-16242, W-16523, and W-17115, respectively. The abundance of outer ramp subfacies is greatest in core W-16242 and lessens to the south. Siliciclastic sediment deposition becomes significant in sequence C.

Sequence D

Sequence D occurs in the Middle Miocene, exclusively in the Serravallian. It is bounded by regional unconformities and the thickness ranges from 15.2 to 21.9 m. It is similar to sequence C in that it shows a stacking pattern with an irregular shoaling of water depth from outer ramp to exposure. Sequence D consists of 4, 2, and 5

sediment packages in cores W-16242, W-16523, and W-17115, respectively. The uppermost part of sequence D in each core is a very shallow water subfacies and siliciclastic sediment deposition is greatest within all of the "Arcadia Formation" (super)sequences at this location.

Sequence Stratigraphy of the Peace River Formation

Introduction

One supersequence and one sequence are found within the Late Miocene and Early Pliocene sediments occurring within the Peace River Formation. The Late Miocene supersequence is termed LPR and occurs in all cores. The Early Pliocene sequence is labelled UPR and occurs only in cores W-16242 and W-16523. Both of these (super)sequences are bounded by regional unconformities. The stratigraphic positions of the (super)sequences are shown in Plate 6 along with age data, lithologic data, and geophysical logs.

Each supersequence or sequence consists of a series of sediment packages with each package being labelled P1..Px on Plate 6 beginning at the base of each unit. The stacking patterns for each of the sediment packages are given in Table 11. There are 19 different types of subfacies stacking patterns. Some examples of these patterns are given in Figure 65.

LPR Supersequence

The LPR supersequence occurs in the Late Miocene (Tortonian). It represents at least one irregular shoaling-upward event or perhaps two such events. This supersequence thickens from north to south from only about three m in core W-16242 to 54 m in core W-17115. It is bounded by a regional unconformity at both the base and top

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Table 11. Sediment packages in the Peace River Formation.

Core W-16242					
(Super) Sequence	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Pattern (bottom to top)
LPR	P1	0	10.5	3.2	8
UPR	P2	0	50.5	15.4	14,4
	P3	0	38	11.6	14
	P4	0	12	3.71	14
Core W-16523					
(Super) Sequence	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Pattern (bottom to top)
LPR	P1	1	20.7	6.3	14,1,14,1
	P2	0	13	4.0	8
	P3	1	10	3.0	8,7
	P4	0	6	1.8	8/4,4
	P5	0	20	6.1	4/7,4
	P6	0	20.8	6.3	9,7,4
UPR	P7	3	31.2	9.5	8,2,7,3,1
Core W-171152					
(Super) Sequence	Sequence No.	Discontinuities in Sequence	Thickness (ft)	Thickness (m)	Subfacies Stacking Pattern (bottom to top)
LPR	P1	0	4	1.2	8,1
	P2	0	10	3.0	8,1
	P3	1	16.7	5.1	8,5,6
	P4	1	8.3	2.5	8,7,3
	P5	2	45	13.7	8,2
	P6	1	28	8.5	8,4/2
	P7	1	7	2.1	2,4
	P8	1	14.5	4.4	9,8,2,1,2,1
	P9	1	18.5	5.6	9,2
	P10	1	13	4.0	8,9
	P11	1	14	4.3	11,4

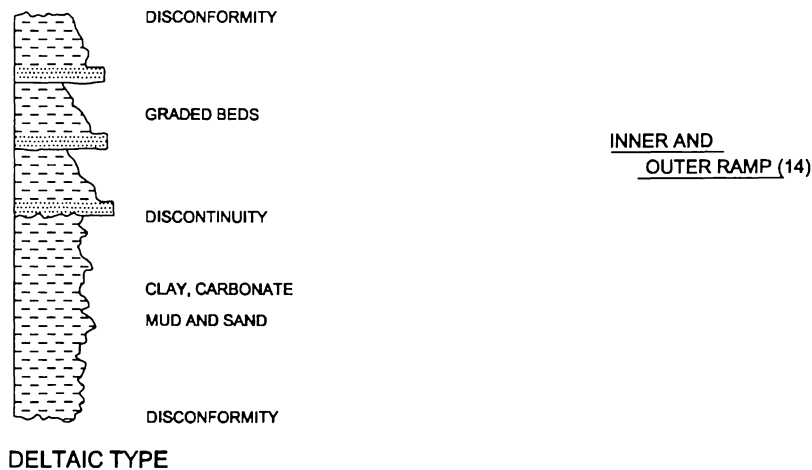
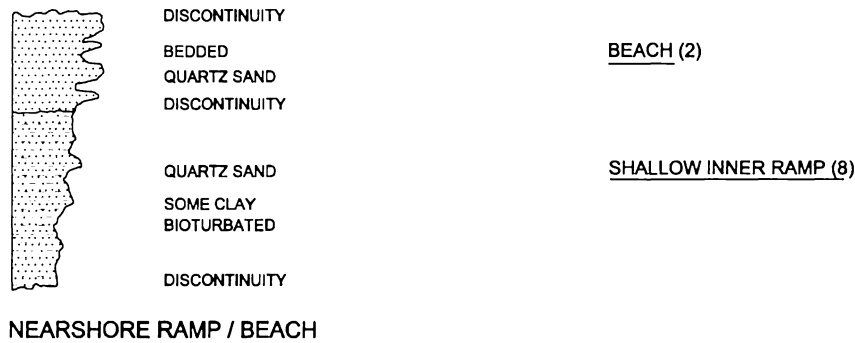
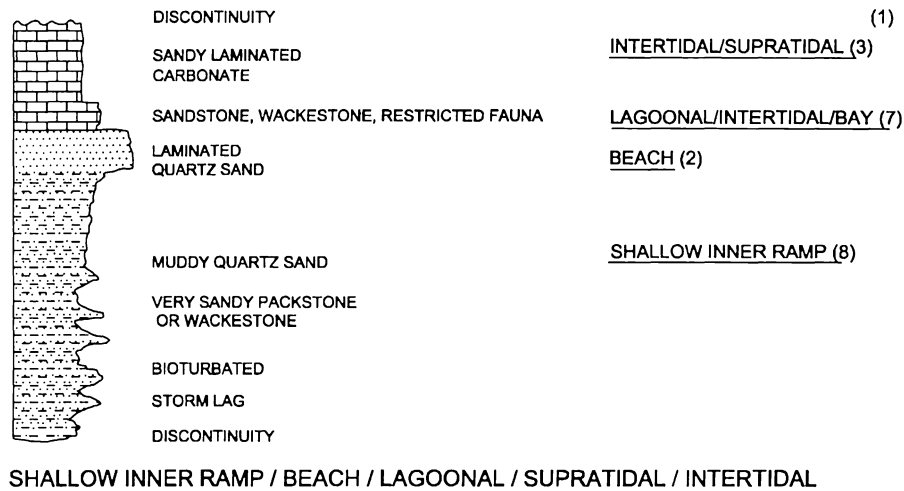


Figure 65. Some selected examples of sediment packages from the Peace River Formation. All of these packages could be interpreted as either shoaling-upward or be explained by lateral accretion.

FLORIDA GEOLOGICAL SURVEY

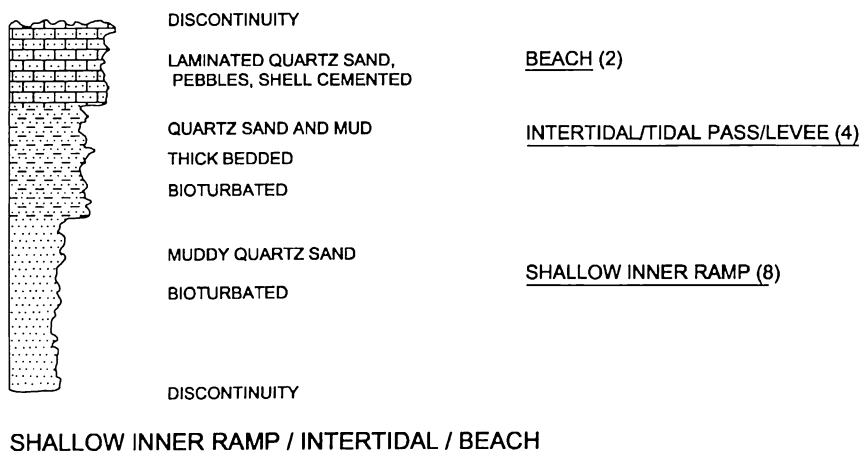
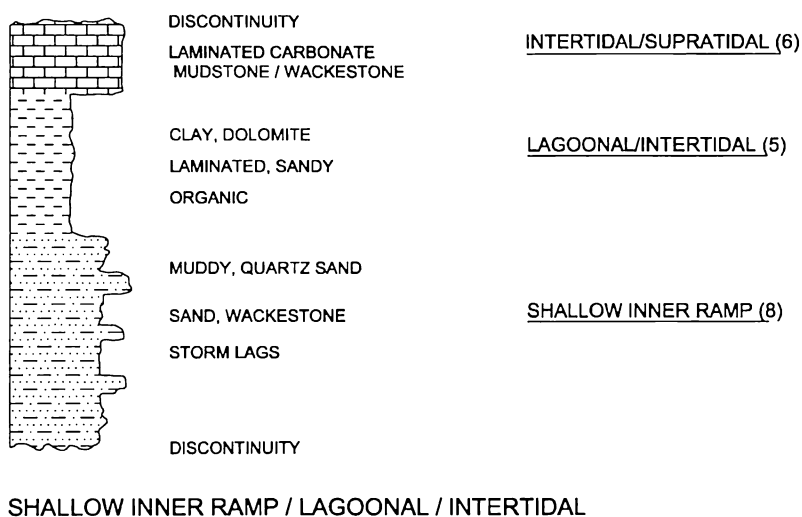
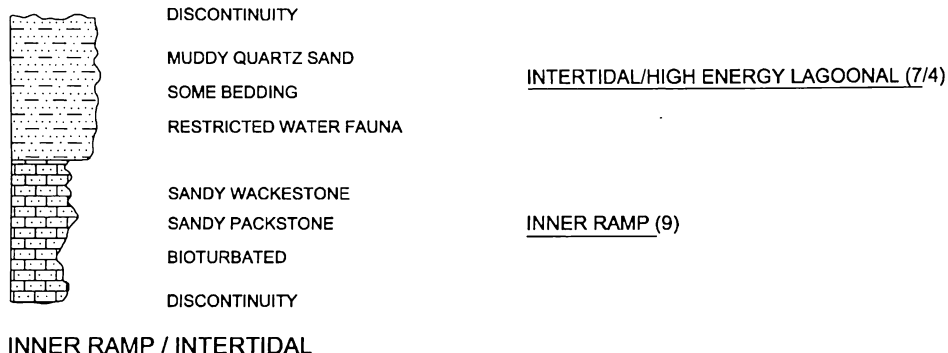


Figure 65 (Cont.). Some selected examples of sediment packages from the Peace River Formation.

and consists of 1, 7, and 11 sediment packages in cores W-16242, W-16523, and W-17115, respectively. The sediments within supersequence LPR are predominantly shallow water subfacies containing no deep ramp subfacies with the possible exception of the *Hyotissa* subfacies in core W-17115, which may be part of an overlying sequence.

UPR Sequence

The UPR sequence occurs in the early Pliocene (Zanclean). It is bounded at the base by a regional unconformity and at the top by a less distinctive unconformity and an abrupt change in lithology from a mud to a sand or sandstone. Sequence UPR consists predominantly of subfacies 14, which is an inner and outer ramp deltaic deposit. Sequence UPR pinches out from north to south at a location about five km south of core W-16523.

SEA LEVEL HISTORY OF THE SOUTH FLORIDA PLATFORM FROM LATE OLIGOCENE TO EARLY PLIOCENE

Introduction

A detailed chronostratigraphy of the Hawthorn Group has been developed from

cores W-16242, W-16523, and W-17115, located in the approximate middle of the South Florida Platform (Plates 5 and 6; Figure 66). The sequence stratigraphy of these cores was described and the water depth relationships of the sediment subfacies was analyzed based on a homoclinal ramp model. In order to assess the changes in the sea level on the South Florida Platform during the Late Oligocene to Early Pliocene time, the sequence stratigraphy showing variation in water depth was placed in real time based on the time scale of Berggren et al. (1995b). From this comparison, a sea level curve was developed for the South Florida Platform (Figure 67) and compared to the global sea level curve of Haq et al. (1988). In order to perform this comparison and develop the sea level curve, it was assumed that the subsidence rate of the South Florida Platform was relatively constant over this time period.

Sea Level History

Based on the stratigraphic record and the chronostratigraphy, a hiatus of about two m.y. occurred after the deposition of the Suwannee Limestone at the end of the Early Oligocene (Table 12). This hiatus corresponds to the global fall in sea level at

Table 12. Summary of global sea level events and effects on the Florida Platform.

Event	Duration of Hiatus (M.Y.)
Miocene/Pliocene	6 to 6.5 ¹
middle Miocene/late Miocene (Messinian)	2
Langhian/Serrevalian	1
early Miocene/middle Miocene	1
Oligocene - Miocene Boundary	4
early Oligocene/late Oligocene	2

¹ In core W-16242, the duration of the hiatus in cores W-16523 and W-17115 is believed to be less, perhaps 3 to 4 m.y.

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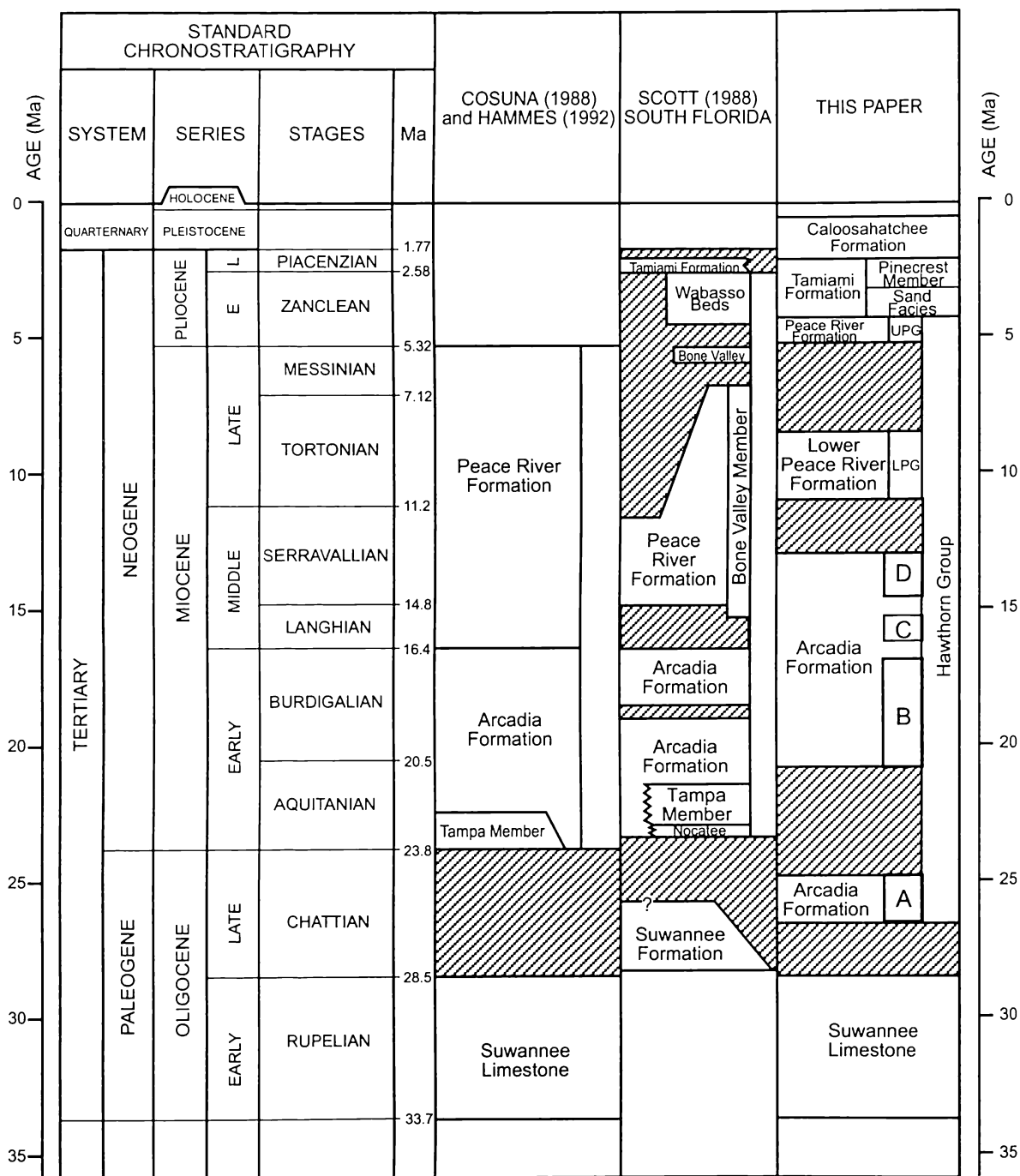


Figure 66. Comparison of the new chronostratigraphy in this paper to previous age estimates for the Neogene and late Paleogene formations on the South Florida Platform. The positions of the (super)sequences are shown as the letters adjacent to the formation names.

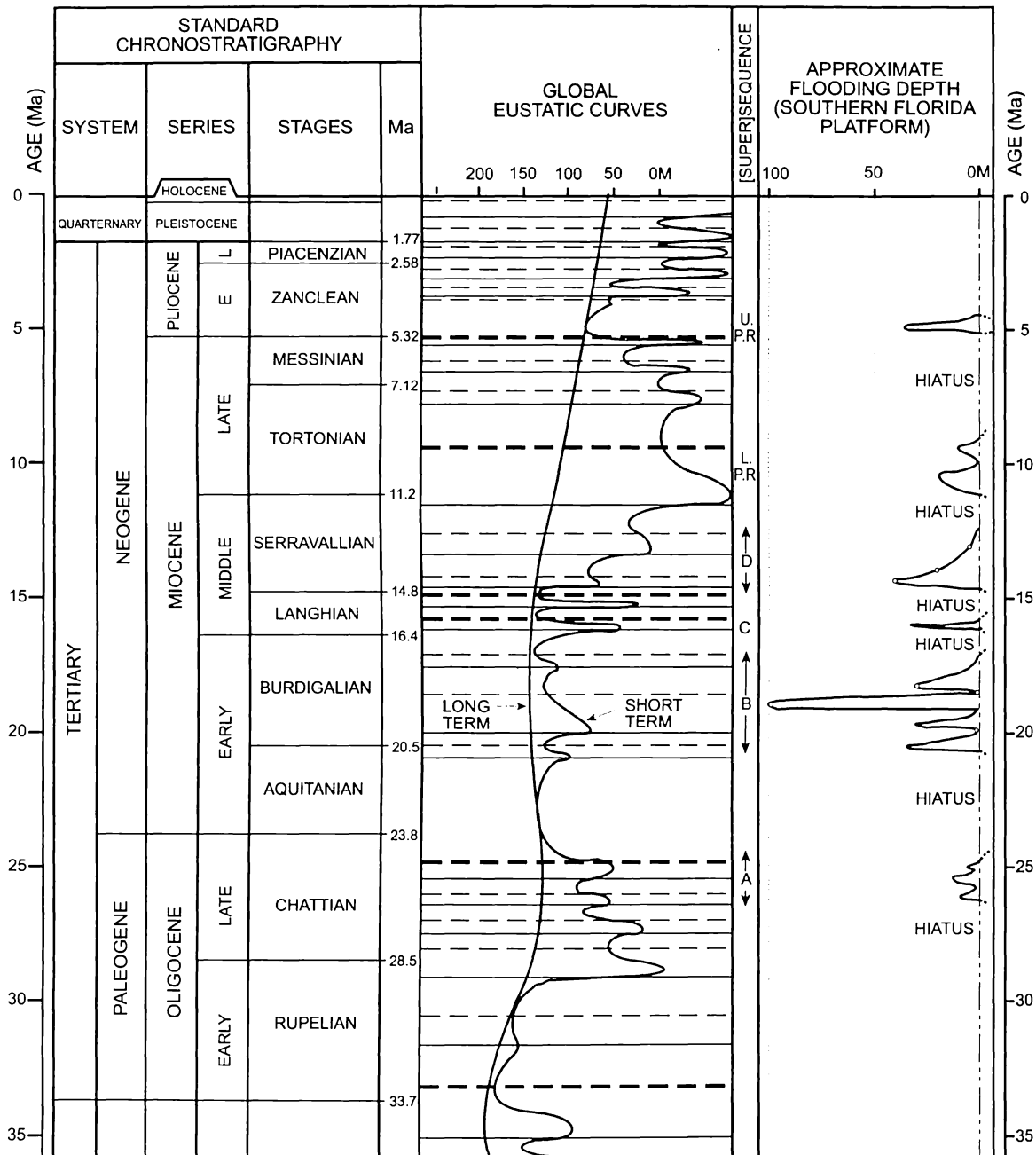


Figure 67. Sea-level curve for the South Florida Platform from late Oligocene to early Pliocene with a comparison to the global sea-level curve of Haq et al. (1988). The time scale used is Berggren et al. (1995b). The Haq sea level curve was adjusted to the new time scale comparison of the curves. The corresponding (super) sequence designations are labelled adjacent to the sea-level curve.

the end of the Early Oligocene. This event is well marked by an increase up-section in gamma ray activity corresponding to the first occurrence of phosphorite deposition and an increase in quartz sand percentages within supersequence A.

Deposition of supersequence A represents two third order sea-level events occurring in the Late Oligocene. Because of the number of shoaling-upward sediment packages occurring within this supersequence, and the number of exposure horizons, the two corresponding sequences are difficult to separate and correlate with corresponding sea-level events. These sea-level events did produce rather small changes in sea level resulting in the deposition of only shallow ramp and peritidal deposits and no deep ramp deposits. Water depth of the subfacies did not exceed 20 m. Correlation of the supersequence to the chronostratigraphy shows that the first two m.y. of the Chattian is missing and that deposition of supersequence A occurred only during about the last two m.y. years of Chattian time.

Supersequence B contains four separate sequences, each containing a deep ramp subfacies at the base and shoaling-upward to shallow water or an exposure surface. Each sequence represents a single sea-level event. Based on correlation to the chronostratigraphy, there are about four m.y. years of time missing from the early Miocene. Therefore, these four sea level events occurred from the latest Aquitanian to near the end of the Burdigalian from about 20.8 to 17.2 Ma. The first, second, and fourth sea level events that produced these sediment sequences, produced water depths ranging from 30 to 40 m based on the water depth model. However, the third sea-level event, occurring in the Burdigalian, caused the ramp to be flooded to a depth of about 100 m, the maximum flooding depth during the time period studied.

Sequence C represents a single sea-level event that is separated by a hiatus of

about one m.y. from the underlying supersequence B. Based on correlation of this sequence to the chronostratigraphy, it occurs in the Middle Miocene or early Langhian from about 16.2 to 15.8 Ma. This sea-level event produced a flooding depth maximum of about 30 m.

Sequence D also corresponds to a single sea-level event. Based on correlation to the chronostratigraphy, there is a hiatus of about one m.y. between sequence C and sequence D. The real time range of deposition of sequence D is about 14.7 to 12.5 Ma or within the Serravallian. The maximum flooding depth of the ramp during this event was about 40 m.

A hiatus of about two m.y. occurred at the end of sequence D, corresponding to the approximate end of the Middle Miocene and the Serravallian. The sea-level fall that produced this hiatus had a pronounced effect on the South Florida Platform, causing the removal of a significant part of the Serravallian section. This hiatus marks the lithostratigraphic boundary between the Arcadia and Peace River Formation in the middle of the platform.

Supersequence LPR occurs within the Tortonian between 11 and 9 Ma. It contains perhaps two sequences, both deposited in relatively shallow water, making them difficult to separate. It is likely that supersequence LPR was produced by two sea level events, neither of which caused flooding depths of greater than 20 m.

The most dramatic hiatus in the section studied occurs between supersequence LPR and sequence UPR. This hiatus correlates in time with the Messinian sea-level fall. The duration of the hiatus ranges from six to 6.5 m.y. in core W-16242 and is perhaps less in the other cores.

Sequence UPR represents deposition in a single sea level event occurring between 5.1 and 4.4 Ma within the Early Pliocene (Zanclean). This deltaic sequence was deposited in water depths up to about 40 m.

COMPARISON OF THE SOUTH FLORIDA RAMP SEA LEVEL CURVE TO THE HAQ ET AL. (1988) GLOBAL SEA LEVEL CURVE

Although there is some general correspondence between the sea level curve developed for the South Florida Platform with the global curve of Haq et al. (1988), there are some significant differences. The correlations in real time are, however, much more reasonable than the correlations of the event magnitudes.

The two sea-level events that produced supersequence A in the Late Oligocene do correlate reasonably well with Supercycle TB1, cycles 1.2 and 1.3. Also, the relative magnitudes of the events are comparatively minor, which also correlates well with the small variations in water depth shown by the subfacies stacking patterns.

The four sea level events that caused deposition of supersequence B do not correlate well with the Haq curve. From the late Aquitanian to the end of the Burdigalian, the Haq curve shows three cycles, 1.5, 2.1 and 2.2. It is likely that cycle 1.5 correlates with the first sea level event observed in supersequence B. However, two sea level events occur in the same time frame corresponding to the Haq curve cycle 2.1. Also, there is a discordance between the magnitude of the sea level changes within this time period. The fourth sea level event correlates reasonably well with cycle 2.2.

The sea level events that caused deposition of sequences C and D correspond reasonably well with cycles 2.3 and 2.4 of supercycle TB2 on the Haq curve. However, the duration of the events corresponds to Haq, but the magnitudes are not on the same order.

Supersequence LPR does correspond in real time with cycles 3.1 and 3.2 of supercycle TB3. The Haq curve shows some relatively large magnitude changes in relative water depths in this increment of time, which does not correlate well with the relatively consistent shallow water subfa-

cies found in this time period on the South Florida Platform.

Sequence UPR correlates with cycle 3.4 of supercycle TB3. The relative magnitude of this sea level change also seem to compare well with the Haq curve.

DISCUSSION

The sequence stratigraphy of the Late Oligocene through the Early Pliocene was studied in three cores collected from the middle of the South Florida Platform. The studied section lies within the lithostratigraphic unit named the Hawthorn Group. Within the late Oligocene section, a single supersequence (A) was found, which contains a series of shoaling-upward sediment packages that were deposited in water with a depth of less than 20 m in inner ramp or peritidal environments. This supersequence contains two sequences, which are difficult to distinguish, because of the shallow-water nature of the sediments.

The Early Miocene section contained a supersequence (B), consisting of four sequences. Each sequence contained a deep outer ramp subfacies and generally shoaled upward to a peritidal environment or exposure deposit. Water depth was up to 40 m at the base of each sequence and was near 100 m at the base of the third sequence upward from the boundary. This sequence contains the deepest water deposit found in the section studied.

The Middle Miocene contained two sequences (C and D), each shoaling-upward from outer ramp to an exposure horizon. The Late Miocene section contained a supersequence (LPR) that likely contains two sequences. However, all sediments were deposited in shallow water, making it difficult to distinguish the boundary between the sequences. The Early Pliocene section contained a single sequence (UPR), which is an inner and outer ramp deltaic deposit.

In the central part of the platform, the boundaries of the sequences generally cor-

respond to lithostratigraphic formation boundaries. For example, the lower boundary of supersequence A in the late Oligocene corresponds to the contact between the Suwannee Limestone and the overlying Arcadia Formation of the Hawthorn Group. The top of sequence D corresponds to the boundary between the Arcadia Formation and the Peace River Formation. However, it is likely that the sequence boundaries do not correlate with lithostratigraphic formation boundaries moving away either east or west from the central part of the ramp. It is probable that a portion of the Peace River Formation on the eastern margin of the South Florida Platform was deposited simultaneously with supersequence B, which lies within the Arcadia Formation in the central part of the platform. Additional research will be required to map the sequence boundaries from the central part of the platform to, particularly, the eastern margin.

Based on the duration of the sequences and a water-depth model based on the stacking patterns of depositional subfacies,

the 11 sequences were produced by 11 third order sea-level events. Some of these events do not correlate well with the Haq et al. (1988) global sea level curve in terms of position in real time or magnitude of the event. The Late Oligocene and Middle Miocene sea-level events do correlate well with the Haq curve. However, the Early Miocene supersequence contains four sea-level events, but the Haq curve shows only three events during this time. Also, the depth of flooding of the platform was greatest during the third event, which is not predicted by the Haq curve. The remaining sequences correlate reasonably well in time with the Haq curve, but the magnitude of the sea-level flooding does not fit the Haq model.

Low sea-level stands produced a significant hiatus at each of the following boundaries: the Oligocene/Miocene (four m.y.), the Early Miocene/Middle Miocene (one m.y.), within the Middle Miocene at the Langhian/Serravallian (one m.y.), the Middle Miocene/Late Miocene (two m.y.), and the Miocene/Pliocene (4 to 6.5 m.y.).

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PLATE 1. CORE W-16242 GEOLOGY, COMPOSITION, PALEOMAGNETIC AND ISOTOPE DATA

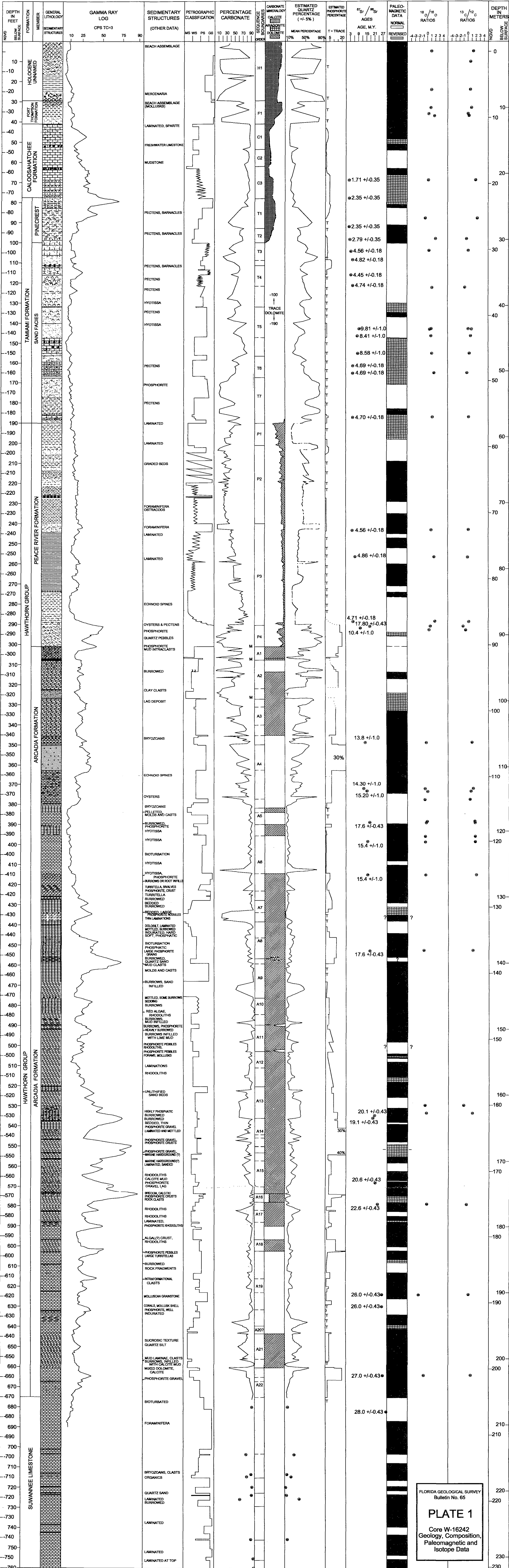
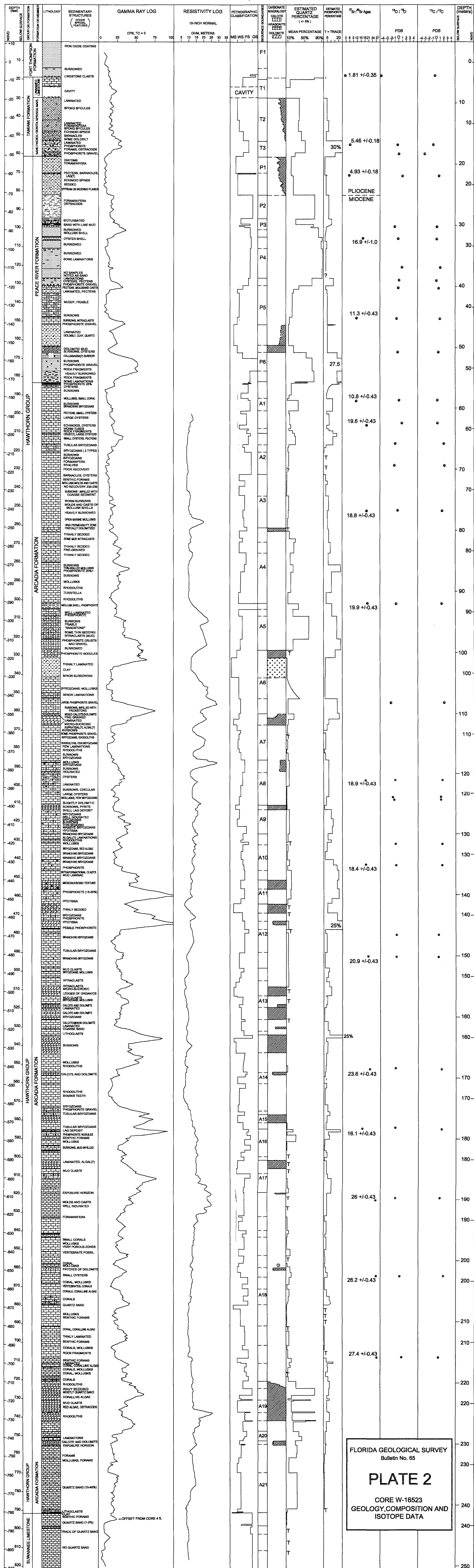
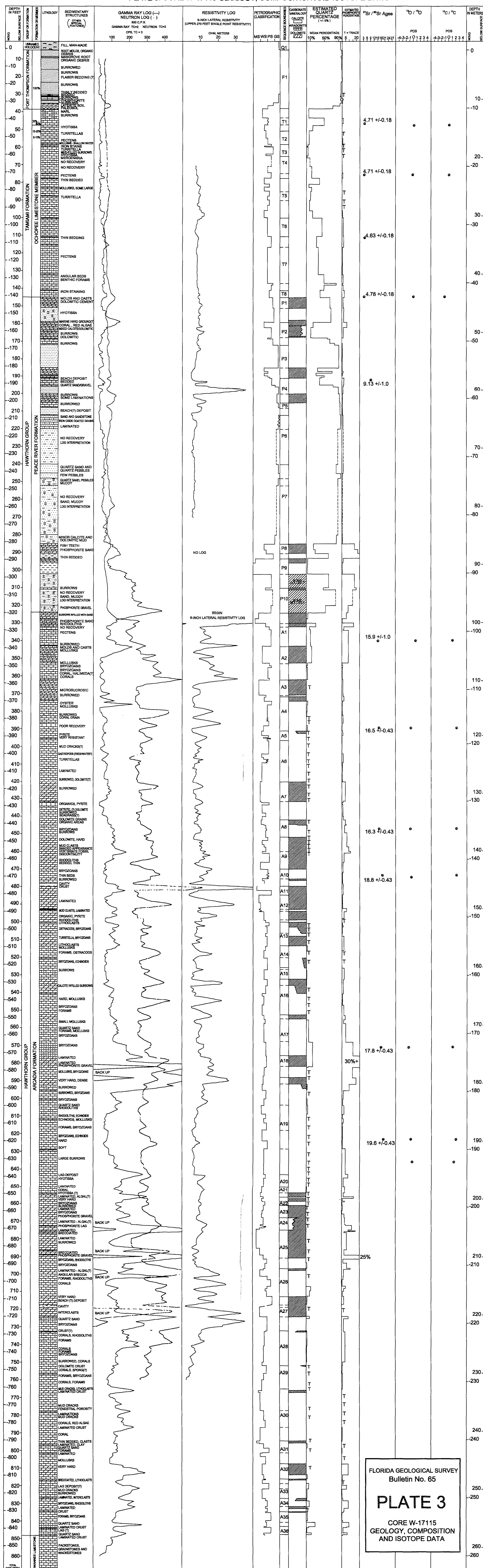


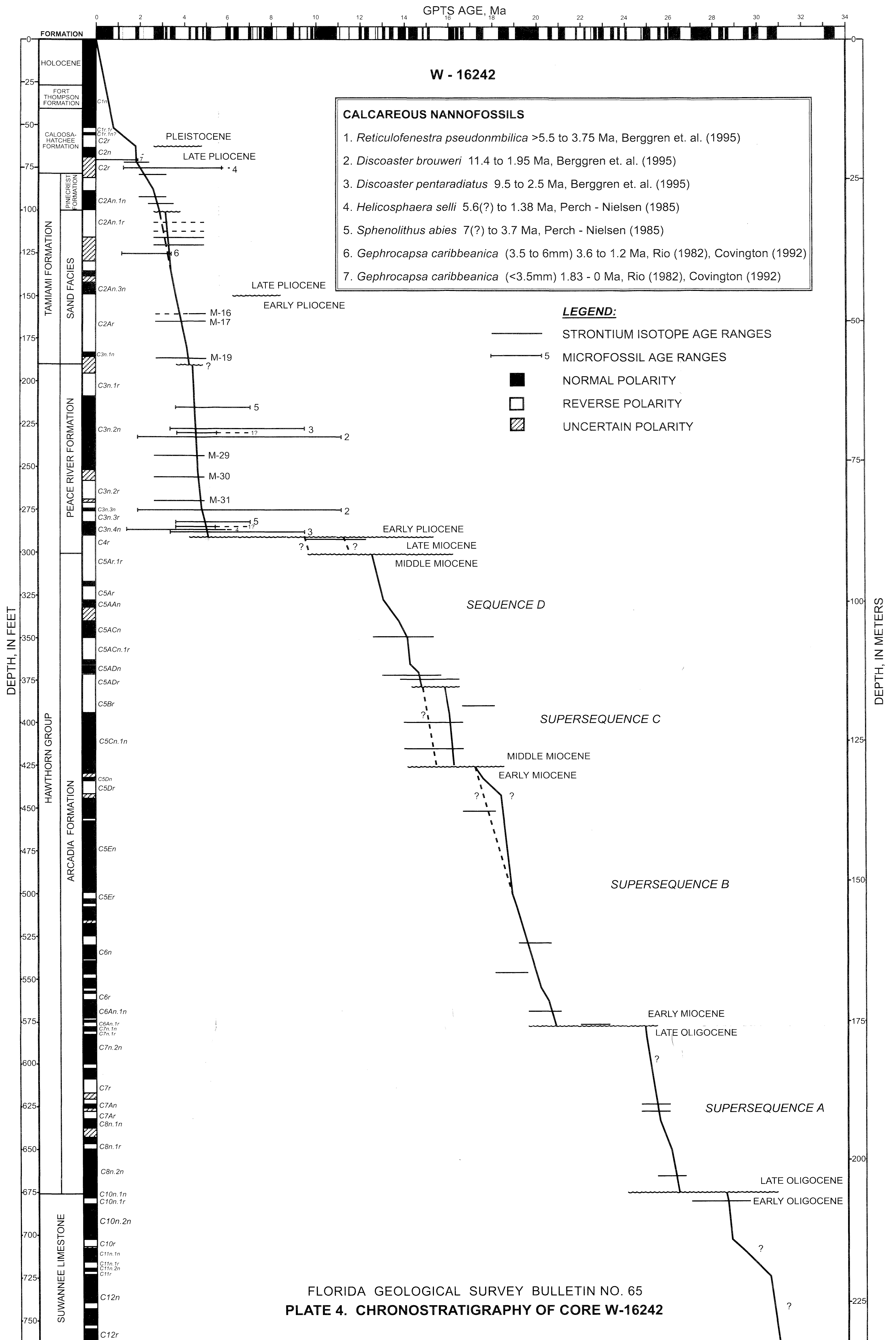
PLATE 2. CORE W-16523 GEOLOGY, COMPOSITION AND ISOTOPE DATA



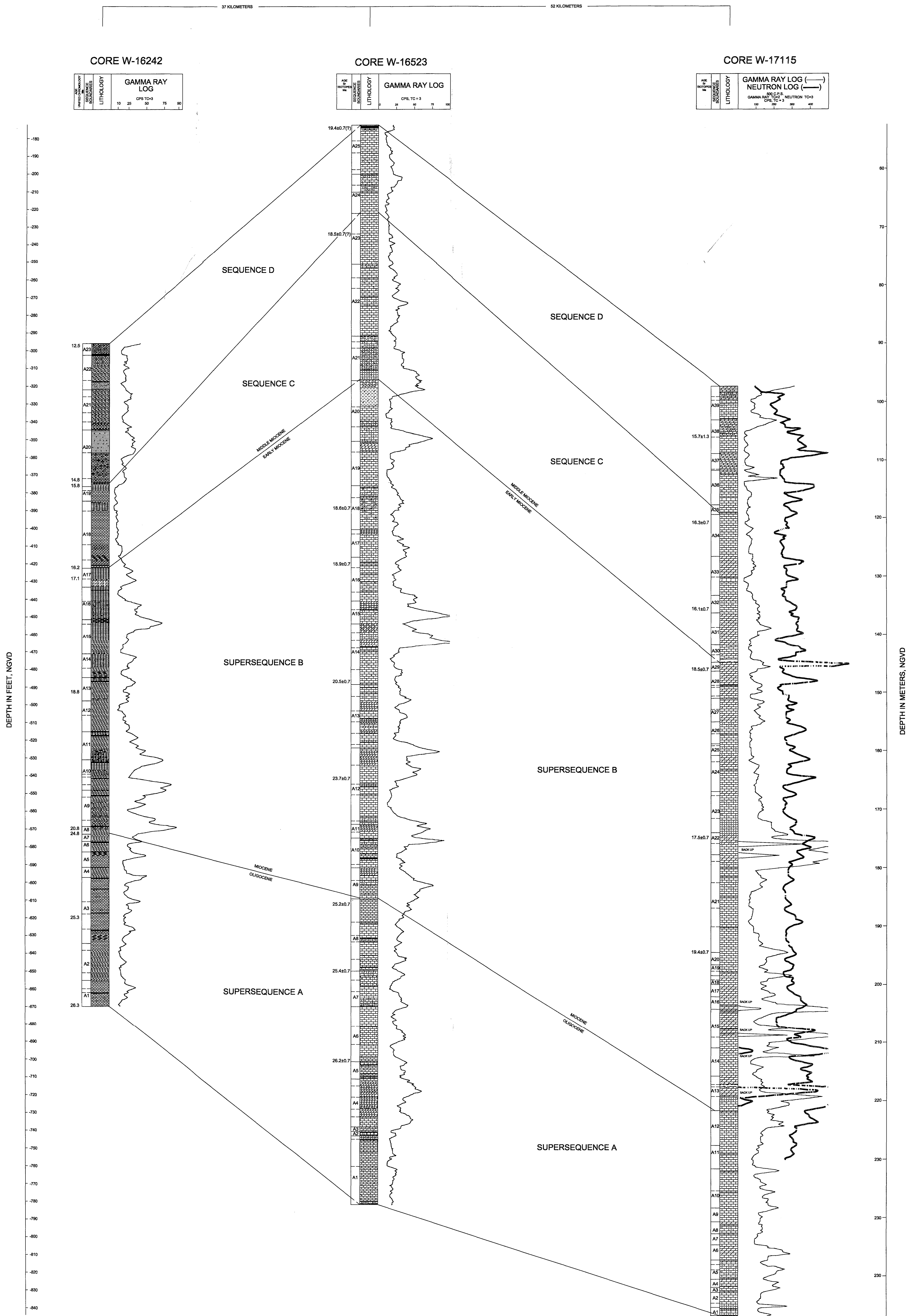
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PLATE 2
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 GEOLOGY, COMPOSITION AND
 ISOTOPE DATA

PLATE 3. CORE W-17115 GEOLOGY, COMPOSITION AND ISOTOPE DATA

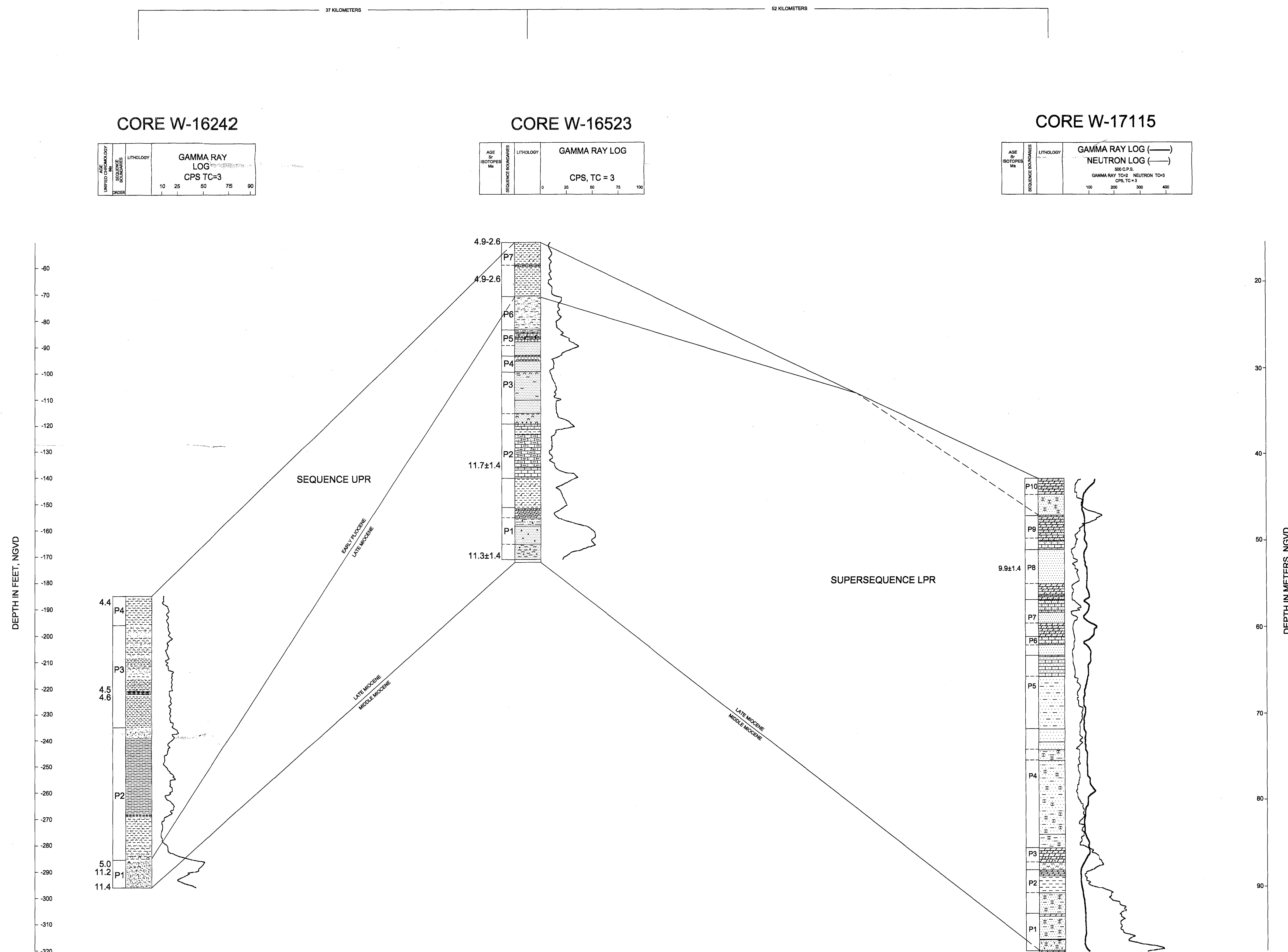




FLORIDA GEOLOGICAL SURVEY BULLETIN NO. 65
PLATE 5 - ARCADIA FORMATION SEQUENCE STRATIGRAPHY



FLORIDA GEOLOGICAL SURVEY BULLETIN NO. 65
PLATE 6 - PEACE RIVER FORMATION SEQUENCE STRATIGRAPHY



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