LATE CENOZOIC DEPOSITIONS PALEENVIRONMENTS OF SOUTHWEST FLORIDA INTERPRETED FROM CORE LOGS

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ABSTRACT

The use of core logs from water wells and engineering-geological site investigations permitted spatial refinement of known paleo-geoenvironmental conditions along the southwest coast of Florida where the narrow continental shelf was influenced by changes in sea level and shoreline position during the late Cenozoic. Lithological materials have been formalized in terms of the Tamiami Formation (early Pliocene), Fort Thompson Formation (late Pliocene), Anastasia Formation (Pliocene-Pleistocene), Miami Limestone (Pleistocene) and Pamlico sands (Pleistocene) in southeastern Florida. The lack of good exposures, scarcity of biostratigraphically important microfossils, and other radioactive isotopes (Krupa et al. 1995). Delineation of the coastal geologic framework, including relationships between shallow paleobathymetries that included barrier bars and tidal passes (paleo-estuaries). Erosional unconformities (interpreted as irregular karstified ground surfaces with low paleotopographic relief) in the sections were frequently capped by dense subaerial weathering crusts of calcite which today act as semi-impermeable to ground water flow. Knowledge of this coastal geologic framework is relevant to understanding modern hydrodynamic conditions for groundwater models, and has practical implications for optimized water management along the southeast coast of Florida.

Keywords: sea-level change, coastal geology, carbonates, spatial correlation, Quaternary, Tertiary

INTRODUCTION

Certain aspects of the late Cenozoic stratigraphy of southeastern Florida have, in many aspects, always been problematical. The intertidal zones along the 10.20, and 30 m isobaths. It was assumed that the present reef tracts approximate the position of paleo-watertables lying along the 10, 20, and 30 m isobaths. It was further proposed that the Aquifer which seem to correlate with the first, second, and third reefs respectively. The southwestern Florida was derived from subsurface investigations utilizing drill cores. Despite the long history of investigations along the southeast coast of Florida. This study confirmed general late Cenozoic trends in sedimentation from marine conditions to more restricted environments. Lithostratigraphic interpretations of changing paleoenvironments formed the basis of a preliminary model for the coastal geological framework of Broward County. This study confirmed general late Cenozoic trends in sedimentation from marine conditions (Tamiama Formation) to nearshore (Anastasia Formation, Fort Thompson Formation) to shallow marine environments (oolithic facies of the Miami Limestone) and fossiliferous facies in the upper Pamlico sands. Late Pleistocene to Recent trends showed a shoal-parallel pattern of shallow paleobathymetries that included barrier bars and tidal passes (paleo-estuaries). Erosional unconformities (interpreted as irregular karstified ground surfaces with low paleotopographic relief) in the sections were frequently capped by dense subaerial weathering crusts of calcite which today act as semi-impermeable to ground water flow.

Knowledge of this coastal geologic framework is relevant to understanding modern hydrodynamic conditions for groundwater models, and has practical implications for optimized water management along the southeast coast of Florida.

A primary purpose of this study was to establish the late Tertiary and Quaternary paleoenvironments of sedimentary deposition for the Broward County area (about 2,800 km²) (Fig. 1). Analysis of extensive core log data, coupled with ancillary information, provided an opportunity to better understand the shallow (< 80 m deep) subsurface features of the region. Analysis of stratigraphic sequences resulted in definition of lateral and vertical variations in sedimentary properties, which in turn provided a basis for interpreting depositional environmental conditions. As the different types of sedimentary environments (open and restricted marine settings) were displaced both in time and space with decreasing depth associated with marine regressions, it was possible to broadly identify locations of barrier bar and channel systems (paleo-estuaries), shallow carbonate banks (shoals), marshes, lagoons, etc. Erosional unconformities in the sequence are often marked by thin (< 0.5 m) but dense subaerial crusts (calcrite, caliche) and calcite cements.
METHODS This project was conducted in two phases that involved firstly the collection of borehole logs and, secondly, the analysis and interpretation of the assembled lithologic information. In this urbanized coastal area, it was suspected that much unpublished information had been collected by a variety of sources (e.g. consulting engineering firms, Florida Department of Transportation, Florida East Coast Railway, Broward County School Board, U.S. Army Corps of Engineers) and that it would be useful to collate the well log data in some organized manner. Approximately 14,000 m of lithologic information was collected from previously unpublished sources. Collation of published logs accounted for about 4,367 m of sedimentologic data from Causaras (1985) and Florida Geological Survey reports. Such data were entered into a database that was later re-arranged into 68 lithologic logs in diagrammatic format.

The second phase of the project is summarized by interpretations of depositional environments based on 9 cross-sections that criss-crossed the county. Location of lithologic logs and the position of the cross-sections used in this study are shown in figure 2.

A simplified representation of three cross-sections (WE1, WE3, and WE4) each comprised by three representative logs from eastern, central, and western Broward are shown in a 3-D diagram to illustrate the main geospatial relationships deduced from this study (Fig. 3). The locations of the logs are geographically correct and elevations adjusted to mean sea level (National Geodetic Vertical Datum (NGVD), 1927). Analysis of the vertical and spatial relationships observed in the cross-sections resulted in four plan-view maps that show the distribution of paleoenvironments during the Miocene (Fig. 4), Miocene-Pliocene (Fig. 5), Early Pleistocene (Fig. 6), and Pleistocene (Fig. 7). The maps and interpretations are regarded as preliminary because they will no doubt be modified as more (unpublished) detailed information is reviewed. Lithologic logs and cross-sections were constructed using RockWorks® software, a specialized geological graphics program.

Interpretations of depositional environments were based on sedimentary properties such as granulometry, rock color, mineralogy, weathering, and fossils as described by Allen (1982) and Collinson & Thompson (1989). The recognition of freshwater limestones in marine carbonate sequences was based on the work of Halley & Rose (1977) when appropriated. Evidence of marine deposition was associated with the presence of high content (up to 30%) of phosphorite and the fossil assemblages (mollusks, barnacles, bryozoans, corals, and echinoid fragments) were compared to lists of the species common to the area as reported by Parker et al. (1955). Unconformities in the sedimentary strata were frequently marked by solution holes in limestone, neomorph calcite, and caliche crusts that are widely interpreted as being characteristic of subaerially weathered limestone surfaces (Sweeting 1973). Stratigraphic interpretations logically follow in the development of a preliminary model for the coastal geological framework, the methodology of which is summarized by Krumbein & Sloss (1963) and by Friedman et al. (1992).

DISTRIBUTION OF PALEOENVIRONMENTS

The geological framework of Broward County is dominated by carbonates formed in shallow marine environments (Finkl & Esteves 1997), as it is long recognized for the Stratigraphic succession in southern Florida (e.g. Parker & Cooke 1944, Parker et al. 1955, Hoffmeister 1974, Enos & Perkins 1977). Although the lithology is mostly comprised by limestones and sandstone limestones, siliciclastic deposits (e.g. quartzose sands and sandstones) become relatively more important at depth in older sequences and toward the present-day coastline in eastern Broward. This transition from older siliciclastics to carbonates may be a reflection of environmental evolution in an area that changed from: offshore marine deposits (silts, clays, and mixtures) during the early Miocene (Fig. 4), to nearshore carbonate deposits and inner shelf sands during the Miocene-Pliocene (Fig. 5), to subaerial and shallower submerged coastal deposits during the Pleistocene (Figs. 6 and 7).

Although there are many uncertainties surrounding the boundary conditions between the sedimentary environments and timing of deposition, the maps showing spatial distributions of sedimentary environments present a plausible interpretation of depositional conditions in the region. The first paleogeographic map (Fig. 4) shows the spatial
environmental conditions were conditioned by variations in shoreline position and associated changes in water depth. Thus, variations of sea level were the most important factor in determining depositional characteristics in Broward County. Missimer et al. (1994) conclude that major fluctuations in sea level are recorded as changes in sediment facies and/or significant time gaps across unconformities.

Paleonenvironmental change in western Broward

Core logs from the western part of the study area show a gradual change from depositional environments from Miocene offshore clays to Holocene nearshore sands. The deposits contain abundant fauna that develops under warm-water conditions that indicate subaerial exposure such as cavity-filling calcite druses. Nearshore sediments are also associated with quartzose sands and occasional clays or silts in places. The sandy limestones seem to have been deposited in a nearshore environment that was similar to modern conditions because the deposits contain abundant fauna that develops under warm-water conditions. The coarse sands were probably deposited seaward of the reeval area and the fine-grained sediments between the reefs as interreefal deposits. Depositional conditions during the Miocene changed from deep marine to shallower nearshore waters due to a drop in sea level (Peck et al. 1976). Describing a major marine regression at the top of the Tamiami Formation, Webb et al. (1978) suggested a glacio-eustatic lowering of sea level as the cause of this regression as well as several minor fluctuations within the formation.

The third paleogeographic reconstruction, for early Pleistocene time (Fig. 6), shows a more complex arrangement of depositional environments due to decreasing water depths. With a falling sea level and prograding shoreline in the early Pleistocene, nearshore sediments were deposited on top of offshore sands in the upper Tamiami Formation and the previous nearshore deposits were in turn buried by freshwater deposits containing limemuds and sand bars. The nearshore deposits are comprised by marine limestones of the Fort Thompson, Anastasia, and Key Largo formations. The large shore-parallel sand bar complex, which was at times subaerially exposed to form a barrier island, contains siliciclastic beds and calcareous sands and shells that probably belong to the Anastasia Formation (Lovejoy 1987). The limemud deposits were formed under low energy conditions with restricted water circulation (protected by the barrier bar or island complex) that favored the precipitation of carbonate ooids. Significantly, the freshwater limestones suggest that at this time there was limited and sporadic subaerial exposure of the landsurface and terrestrial deposition in the northwestern part of the area. The freshwater limestones and the limemud deposits may be part of the Fort Thompson Formation.

Steps in the Stratigraphic transition to late Pleistocene and Holocene time (Fig. 7) are complex and largely unknown. Many logs contain a discontinuity (hiatus) and evidence of erosive events (e.g. weathered calcrete surface and cavity-filling calcite in a karstified landscape). By the end of the Pleistocene, the shallow marine and lagoon deposits shown in Figure 6 gave way to subaerial (terrestrial) deposits. By the last interglacial (Sangamonian time, ~130,000 BP), sand deposits along eastern Broward were beach and bar material and estuaries of the Anastasia Formation (Evans 1987). The logs show the presence of a cross-shore tidal channel in the northeastern part of the study area that cuts through a seaward barrier bar of the type described by Evans (1987). Some locations in the western part of the study area contain peat or muck (Fig. 8), probably deposited in wetlands formed by the gradual shoaling and change from a shallow water restricted marine environment to a subaerial landsurface. Such deposits presented lateral association with terrestrial and freshwater deposits that were widely spread along central axis of Broward. Other areas in the central and western parts of the study area at this time were exposed subaerially as a landsurface that carried a mantle of peat.

Changes in environmental conditions were conditioned by variations in shoreline position and associated changes in water depth. Thus, variations of sea level were the most important factor in determining depositional characteristics in Broward County. Missimer et al. (1994) conclude that major fluctuations in sea level are recorded as changes in sediment facies and/or significant time gaps across unconformities.

Paleonenvironmental change in central Broward

In the central part of the study area, there are complex Stratigraphic successions that favor both nearshore and offshore environments simultaneously. Fort Thompson Formation sediments are also associated with Microcystis limemuds, sand and shells that lie between the upper and lower layers of sandy limestone in the Fort Thompson Formation (e.g. log G-2319, Figure 8). This increasing complexity of lithologic pattern suggests that this coastal area was more susceptible to minor changes in sea level while the western and eastern parts were relatively above...
or below marine water levels. Also, the logs show greater influence of inshore/nearshore clastic deposition than environments in the west. The influence of dynamic coastal conditions are also present in the sandy limestone layers of the Tamiami Formation, showing slight changes in quartz content, in granulometry, and in faunal content. The gradual changes in faunal content, sediment composition, and granulometry indicate that the thin sand layer at the upper part of some logs represents a bar or beach deposit, probably part of the Anastasia Formation. At the upper part of some logs, (e.g., G-2315, G-2312, G-2317, and G-2319) there is a thick sequence (3 m) of pale orange, well-cemented limestones or sandy limestones that show neomorphic and drusy cavity-filling calcite and gastropods, from the Fort Thompson Formation. The presence of cavity-filling calcite and weathered surfaces indicates that the nearshore deposits were eventually exposed to freshwater flow and subaerial erosive conditions. The presence of stratigraphic discontinuities throughout the sedimentary sequences makes it difficult to fully assess the geological evolution.

Coastal paleoenvironments in eastern Broward The eastern part of the study area shows a greater degree of spatial lithologic variability, although the sedimentological characteristics are very similar within individual logs. The similarity of lithological materials throughout the logs, from bottom to top, makes it difficult to infer changes in depositional environments with time (see logs G-2351 and G-2325 in Figure 8). Identification of boundaries between formations may be possible only on the basis of biostratigraphic zonation using microfossils. In spite of the gross similarity of the deposits, it is possible however to ascertain changes from marine conditions (clays, silts, and sands of the Tamiami Formation) to nearshore (Key Largo limestone, Anastasia, and Fort Thompson formations), and very shallow marine environments (oolitic facies in the Miami Limestone) and eolian materials in the upper part of the Panfilo sands. In the northeast part of the study area, logs G-2325 (Fig. 7), G-2323, and G-1228 represent the position of a pass or channel (paleoinlet) cut through a barrier bar. The section contains two 15-m thick sequences of coarse to very fine-grained quartz sand (G-2325; 15-30 m, 60-75 m) interbedded with sandy limestone layers. The whole sequence is about 65 m thick and the presence of sandy limestone layers may represent a situation similar to that described by Evans (1987) where there is oscillation of a shoal and channel system.

DISCUSSION Based primarily on fossil faunal assemblages seen in shell remains and the chemical properties of rocks, geologists have long recognized that the stratigraphic succession in southern Florida formed predominantly, with few exceptions, under a marine environment (e.g., Parker & Cooke 1944, Parker et al. 1955, Hoffmeister 1974, Enos & Perkins 1977). Exceptions are the lacustrine and swamp deposits of the Lake Okeechobee-Everglades depression that occurs partly in western Broward County. These deposits consist in freshwater beds of the Fort Thompson Formation, the freshwater Lake Flint marl, and organic soils, mostly Everglades peats and mucks. According to Parker et al. (1955), the clays of southern Florida are usually greenish.
in color, calcareous in composition, with 10%-15% of phosphorite, and of marine origin containing a shallow-water fossil fauna indicative of warm subtropical conditions. Exceptions to these characteristics are the surficial red-colored latites occupying filled solution holes in karstified limestones in the “Redlands” area of Dade County.

In summary, the Neogene geological framework of Broward County consists of alternating fresh, brackish-water, and marine deposits laid down under generally shallow water conditions. Generally, fine-grained calcareous marine sediments comprise the lower sections of the logs, while the upper sedimentary layers are formed under nearshore depositional sequences. The presence of fine-grained sediments (often micritic) at the base of most logs suggests deposition under low energy conditions, probably on what was then the outer continental shelf. Following, a drop in sea level resulted in changing depositional conditions from open marine to nearshore environments in central and west Broward. At the same time, the easternmost logs continue to present characteristics of continental shelf deposits. During mid-Tamianian time, no subaerial deposits are recorded in the logs and sandy limestones and reeval fauna were broadly deposited. During the early Pleistocene, the type of depositional environments increases when subaerial deposits were laid down and intercalated with marine sediments, as reported by Lidz & Shinn (1991) for the Florida reef tract. The nearshore sediments were deposited on top of offshore sands in the upper Tamiami Formation (e.g. logs G-2314, G-2346, and G-2319, in Figure 8). Freshwater deposits such as lime muds and cavity-filling neoformed calcite occur at the top of the nearshore deposits (containing shallow water mollusks, pellets, bryozans, and echinoid fragments) as described by Causaras (1985) and Fish (1988). A large sand bar (or shoal) was also present in central Broward at this time and may have acted as a barrier to water circulation, resulting in brackish conditions in western Broward. Such conditions may have been favorable for the deposition of calcium carbonate that formed the lime mud layers in a restricted-circulation marine environment as described in log G-2346 (Fig. 8). Evidences of subaerial exposure in northwestern Broward are the presence of freshwater limestones (logs G-2319, in Figure 8). Freshwater deposits such as lime muds and subaerial deposits (freshwater limestones) and subaerial deposits (freshwater limestones, peats and muck).

Fish (1988), discussing the complexity of depositional environments in eastern and central Broward County, pointed out that lithologies are variable in space and time, resulting in greater diversity between core logs there than in western Broward County where the continuity of lithologic sections is greater. This depositional pattern is evident in the cross-sections where there is greater similarity between logs in north-south cross-sections than in west-east cross-sections (see Figure 3). This shore-parallel pattern of freshwater limestones, lacustrine deposits, and subaerial crusts grading to beach sands and eolianites reflects the importance of shoreline variations and associated changes in water depth in defining the geologic framework in this area. The importance of shoreline position and sea-level changes in determining the distribution of detrital sediments and the depositional characteristics in south Florida was also observed by Lidz & Shinn (1990).

Associated with increasing complexity in the Neogene is an increase in silicilastic sedimentation. Limestones and sandy limestones are the dominant lithology but quartzose sands and sandstones become more important toward the base of the logs, toward the coast and near midsections of the county. This change in sediment supply, associated with the final disappearance of the Gulf Trough, allowed silicilastic sediments to be transported to the Florida Platform as a result of broad uplift and erosion of the Appalachian Mountains in the late Paleocene (Scott 1993). The increase in granulometry toward the top of the logs and in logs closer to the coast resulted from sedimentary processes that changed from open marine (clastic deposition) to nearshore (dominance of sandy limestones) and subaerial deposits (freshwater limestones, peats and muck).

There are many difficulties that inhibit interpretations of paleodepositional environments in southeastern Florida. Perhaps the most important factor is the similarity of materials in the sedimentary layers. Some logs have very similar lithological characteristics throughout the section (e.g. logs G-2311, G-2313, G-2314, G-2317, G-2318) and it is thus difficult to recognize true boundaries between formations or know if specific deposits are contemporaneous or syndepositional in age. The similarity of materials leads to two different interpretations: (1) the sequence formed under the same kinds of environmental conditions or (2) the environmental conditions changed with time but produced similar kinds of deposits. A further complication is that the sedimentary record contains significant gaps in time as evidenced by numerous discontinuities. Missimer et al. (1994) estimated that about one-third of the time stratigraphic record is missing based on the time gaps across the major unconformities during Miocene and Pliocene in southeastern

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Figure 8 - Lithologic logs in diagrammatic section showing changes in paleoenvironments from the Miocene through the Pleistocene to the Holocene. Lags G-2314, G-2346, G-2319, G-2351, and G-2325 represent key paleoenvironmental sections in northwestern, southwestern, central, southeastern, and northeastern Broward County, Florida. Regressive sequences (R) are shown as general trends and do not necessarily depict only one glacio-eustatic event. Marine transgressions followed hiatuses when formations were subaerially exposed as groundsurfaces.
Florida. The environmental transitions within the Pleistocene are numerous and complex due to erosive events, weathering of the landsurface, and dissolution of limestones that produced karstified landscapes. Evidence of Pleistocene sea-level oscillations shows the Florida region consists of subsurface subsaerial features such as laminated calcrite, peat, root, casts, and mold (Lidz & Shinn, 1991). Recognition of these kinds of features suggest that most of Broward County was completely emerged during mid-late Pleistocene time. Beach ridges (Pumico Sand) and unconsolidated estuarine sands of Broward County, while in western Broward peat or muck (wetlands formed by gradual shoaling) were formed. At this time, freshwater deposits became more frequent and widely spread along the central axis of Broward.

Anyway, it is essential to clarify the parameters used to differentiate the formations. Examples of the problematic similarity between sedimentary deposits are provided by attempts to separate the marine deposits of the Fort Thompson Formation from the upper Tamiami Formation (in central Broward County) and efforts to separate the interbedded layers of the Fort Thompson, Anastasia, and Key Largo formations in eastern Broward (e.g. Lovejoy 1987, Fish 1988, Missimer 1993, Scott 1993). In log G-2314, for example, the Fort Thompson sandy limestone is very similar to the Tamiami sandy limestone, the salient differences being formational color and faunal content. The Fort Thompson is yellowish-gray colored and contains mollusks whereas the Tamiami Formation is light olive-gray in color with a more diverse fauna that includes mollusks, corals, barnacles, bryozoans, and echinoid fragments. In some logs, sedimentary and stratigraphic differences are not reported, omitted from descriptions, or defined in early Pliocene time (4.5 Ma) and that the Tamiami Formation formed in late Oligocene (30 Ma) and continued through early Pliocene time (4.5 Ma) and that the Tamiami Formation formed during the Pliocene, between 4.5 and 2.8 Ma (Missimer et al. 1994).

As a result of these complicating factors, occurrences of specific formation are not reported, omitted from descriptions, or defined in different ways from previous studies. One example of these difficulties may be shown by reference to the silts and clays present at the base of many logs. Parker et al. (1955) and Causaras (1985) demonstrated that the differentiation of clays and silts of the Tamiami from the Hawthorn formations was not the main goal of this study, interpretations of depositional conditions, it was decided that although gathering of more complete and detailed descriptions of the formations was not the main goal of this study, interpretations of sedimentary environments would be simplified if formational boundaries and regional stratigraphies were completely understood.

CONCLUSION In general terms, the geological framework of Broward County consists of marine deposits laid down under shallow water conditions. The lower part of the logs is commonly constituted by clays and silts deposited on a continental shelf, while the upper sedimentary layers were formed under nearshore depositional conditions. Changes in the sedimentary characteristics were caused mostly by variations in the water depth, sometimes resulting in the development of a nearshore reeval fauna and sometimes resulting in clastic deposition of quartzose sand.

This study represents an initial attempt to identify and relate late Cenozoic paleoenvironments through space and time in Broward County. One result of this effort culminated in the preparation of four maps (Figs. 4, 5, 6, 7) showing the changes in sediments distribution and interpreted paleoenvironments during the late Cenozoic (from Miocene to Pleistocene). Boundaries between environments and/or lithologic provinces were interpolated in areas with no borehole data (mainly in western Broward) and between contemporary deposits from one log to another due to difficulties associated with facies identification and differentiation of syndepositional materials. Thus, the areal extent of different sedimentary materials, and especially their boundaries as shown in plan view, should be regarded as preliminary results. The deployment of absolute dating methods would be a significant advancement in chronostratigraphy that would provide a better basis for defining stratigraphic boundaries when discontinuities are present.

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