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VARIABILITY OF LITHOLOGIC CHARACTERISTICS OF A PLEISTOCENE OöID SAND SHOAL, ANDROS ISLAND, BAHAMAS; LINKS TO THE PAST

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ABSTRACT

Vertical and regional trends in petrographic characteristics and facies successions of a Pleistocene oolite (Andros Island) were compared to an adjacent modern oöid sand shoal (Joulters Cays). Based on megascopic examination of cores from northern Andros Island and point count analysis of thin sections from those samples, it was determined that sedimentary structures, textures, and diagenetic features provide useful and preservable information to distinguish subtidal from supratidal portions of the Pleistocene oolite. Although this information may be used to determine paleo-sea level, petrographic characteristics are not useful recognition criteria for distinguishing specific subenvironments.

Several diagenetic processes overprint primary petrographic characteristics which have been used to distinguish subenvironments of modern oöid sand shoals. Results of this study suggest that a petrographic link is poorly preserved or recognized from Holocene to Pleistocene subenvironments, and attempts to connect specific petrographic characteristics of ancient limestones to subenvironments of deposition should be made with caution.

INTRODUCTION

Petrologists have been known to interpret any rock with > 25% oöids as an "oölite" (Folk, 1962) and interpret the environment of deposition as an oöid sand shoal with little or no differentiation of subenvironments within the sand shoal complex. However, oöid sand shoals are like other major environments of deposition and can be divided into subenvironments or "second-level environments" (Crosby, 1972) which are characterized by more local and limited environmental conditions and have a distinctive set of lithologic characteristics. For modern oöid sand shoals, classification and subdivision has been based on the variations in sand shoal geometry, bedforms, and regional settings (e.g Ball, 1967). However, in the ancient, shoal geometry, bedforms and setting are not always recognizable (e.g. in wells or cores); so additional features such as petrographic recognition criteria are needed to distinguish subenvironments of oolites.

The Joulters Cays oöid sand shoal is comprised of a combination of the four types of carbonate (ooid) sand accumulations described by Ball (1967; tidal bar belts, marine sand belts, marine sand blankets, eolian ridges). Sedimentologists who examine ancient oöid shoals often use this shoal as a model for the study of oöid deposition and diagenesis and sand shoal evolution. The objective of this study is to provide a petrographic link between a modern oöid sand accumulation and ancient oolites. This will be done by examining the extent to which the vertical and regional variability of lithologic characteristics of a Holocene oöid shoal complex (Joulters Cays) is preserved in the lithology of the adjacent Pleistocene oolite on Andros Island, Bahamas (Fig.1).

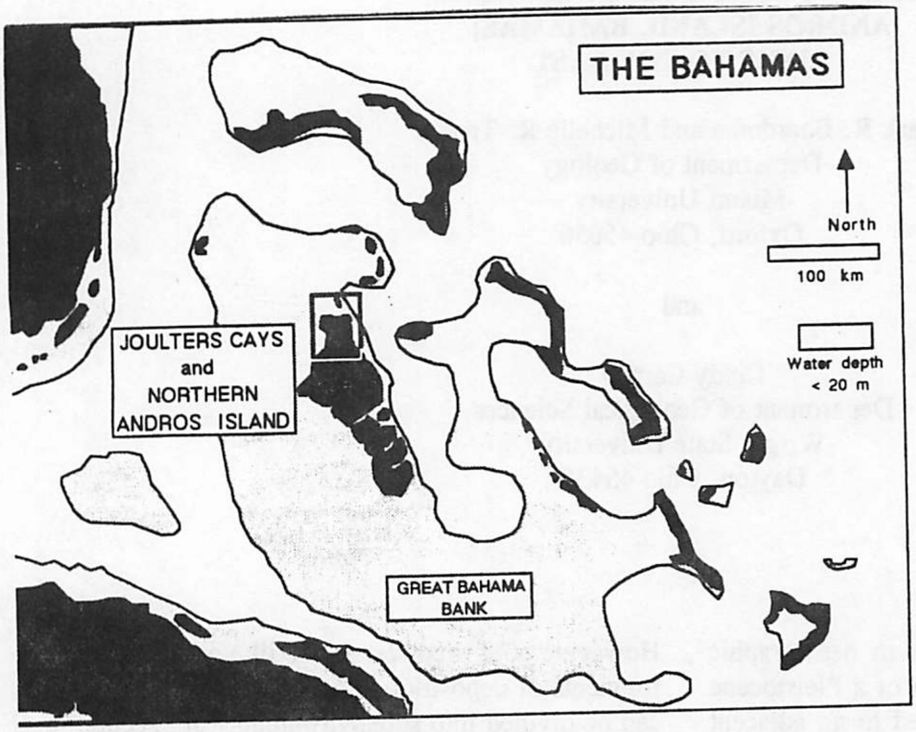

Figure 1 Map of the Bahamas. Joulters Cays are located just north of Andros Island.

Joulters Cays

Eight subenvironments of Joulters Cays were recognized by Harris (1979) based on sedimentologic and geomorphic characteristics including bedforms, water depth, benthic cover, grain composition, and texture. His work was corroborated and amplified by the studies of Carney and Boardman (1991; 1992) which had greater sampling density (but were more limited in areal extent) and were based primarily on petrography of surface sediments. Their research provided information on the petrographic variability of oöid grains and lateral trends of sedimentary microfabrics of the windward margin of Joulters Cays ("mobile fringe" of Harris, 1979). They concluded 1) that oöids add laminae (grow) as they are moved from the south to the north, 2) the percent oöids is highest in the areas where sediment is being moved (e.g. deltas, shoals, beaches) and decreases both seaward and bankward where peloids increase in abundance, and 3) bioerosion including micritization and borings within and across oöid laminae is minimal in the mobile fringe and increases in more stabilized areas both bankward and seaward (Fig. 2).

Andros Island Oolite

Northern Andros Island is similar to Joulters oöid sand shoal complex in relative size, oöid distribution, position on the platform, distribution of reefs and geomorphology (Boardman et al., in press). On both Andros and Joulters, a linear core of sediments/rocks with high oöid concentration (>50%) is present. Seaward and bankward of this core the concentration of oöids decreases (Fig. 3). Dune ridges are located along the windward (eastern) margin parallel to shore at both localities. These linear features are separated by narrow, sinuous, low-lying areas oriented perpendicular to shore (tidal channels on Joulters; marshy areas on Andros Island). The leeward portions of both Joulters and Andros are flat and low (Fig. 4). Modern reefs are located seaward (to the east) of Joulters and elevated Pleistocene reefs dated at 128,000 to 120,000 years BP (Neumann and Moore, 1975) are located on the eastern margin of Andros Island. Based on these similarities, Boardman *et al* (in press) proposed that Andros Island formed by lateral accretion of oöid shoal complexes similar to that forming on Joulters today. In particular, northern Andros Island is a Pleistocene equivalent of Joulters Cays and formed approximately 125,000 years ago.

Questions Yet to Answer

Is it possible, by petrographic means, to recognize subenvironments in ancient oolites like those seen in the Joulters Cays oöid sand shoal complex? What types of diagenesis have occurred and how extensive is this diagenesis? To what extent do subenvironments of oöid sand shoals control diagenesis? This information of Quaternary processes is critical to more detailed evaluation of Paleozoic oolites.

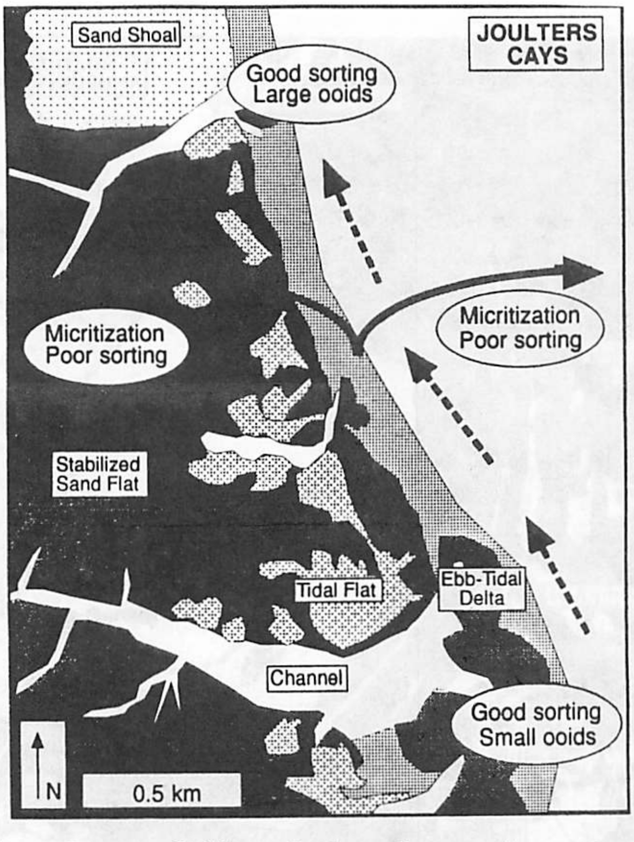

Figure 2 Ooids on Joulters Cays are larger, have more laminae and are better sorted in the northern region. In the offshore regions and in the stabilized sand flat ooids are less abundant and are intensely micritized, and the sediment is poorly sorted. (from Carney and Boardman, 1992).

METHODS

Field

The field of study is a portion of northern Andros Island (approximately 100 km2) which extends from the eastern margin of the island to as far west as the Main Highway Road, and from Nichollstown to as far south as San Andros Airport (Fig. 5). A closely-spaced sample design was employed to insure that subenvironments, when sampled, could be mapped. For example, the islands of Joulters Cays are only 1-2 kilometers long and tens to hundreds of meters wide, and channels may be as narrow as a few meters (Harris, 1979). Twenty-eight cores were extracted from six general locations using a gas-powered portable drill. Cores, 5 cm in diameter, were taken in 30 cm sections. Samples were selected from elevations ranging from 2 m below present sea level to 14 m above present sea level.

Transects along and across several ridges were sample to evaluate possible Pleistocene beach-dune-tidal flat lithologies, east-west transects were sampled to evaluate across-island variability, and one transect of cores was taken across a linear marshy area (Fig. 5).

The Nichollstown outcrop (site #1) is approximately 200 m in length with a crest 6 m above sea level. Twenty hand samples were taken in the 4.2 meters of vertical exposure. In addition, a 2 m core (#1) was extracted at the base of this section; so the total interval sampled at this site is 6.2 m.

An east-west transect of seven cores (sites #2 -8) and 12 surface samples were taken along 1500 m of a logging road which passes Uncle Charlie's Blue Hole. Cores (2 meters in length) were retrieved as close as 80 m apart to no greater than 500 m apart on low ridges and on troughs between ridges. The composite interval of cores is 4.6 m (highest core top was 5.9 m and lowest core base was 1.3 m above sea level).

The Packing Plant outcrop is located on the western margin of the study site and spans approximately 108 m with a maximum relief of 2.6 m (5.5 m

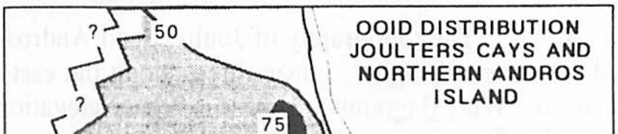

Figure 3 Distribution of ooids on Joulters Cays and northern Andros Island (from Boardman et al., in press).

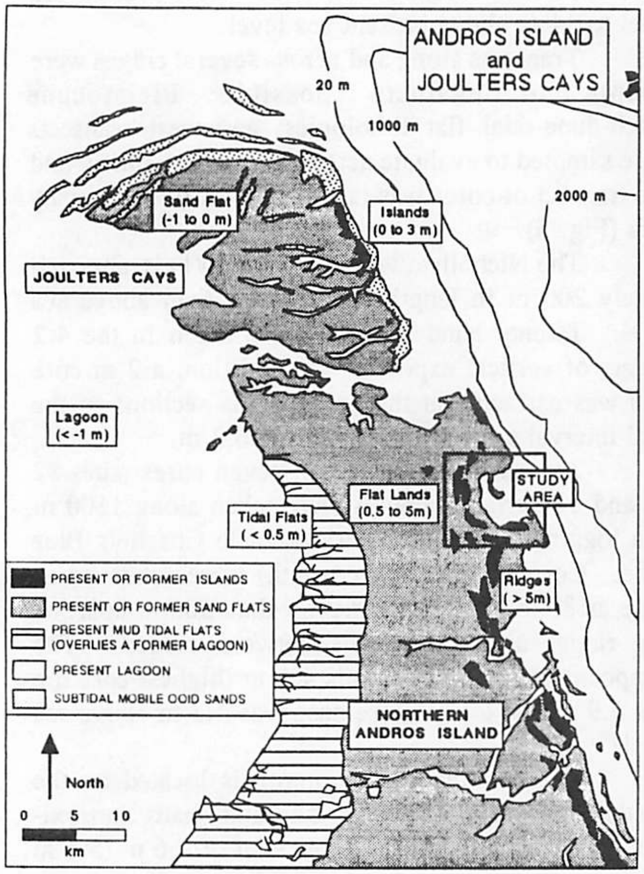

Figure 4 The topography of Joulters and Andros includes a series of higher, linear ridges along the eastern margin. West (lagoonward) of this higher elevation are low, flat areas. (from Troksa, 1992)

above sea level). Two cores (#9 and 10), one on each side of the road and each approximately 1.8 m in length, were taken at the base of the outcrop; so total vertical interval sampled at this locality is 4.4 m.

Four cores (sites 11-14), each approximately 2 m in length and approximately 50 m apart, were taken across the width of a low marshy area, oriented perpendicular to the ridges, which we suspected was a paleochannel.

Four cores (sites 15-18) were taken across the width (290 m) of a solitary ridge located 1.1 km north of San Andros Airport. Core lengths were 2 m and spanned a vertical interval of 0 to 4 m above sea level.

Ten one-meter cores (sites 19-28) were taken over a lateral distance of 60 m with a sample spacing of approximately 6 m down the south side of a high ridge located about 0.8 km northeast of San Andros Airport. The composite interval of cores is 12.2 m and spans the elevation interval from 0.2 m below sea level to 12 m above sea level.

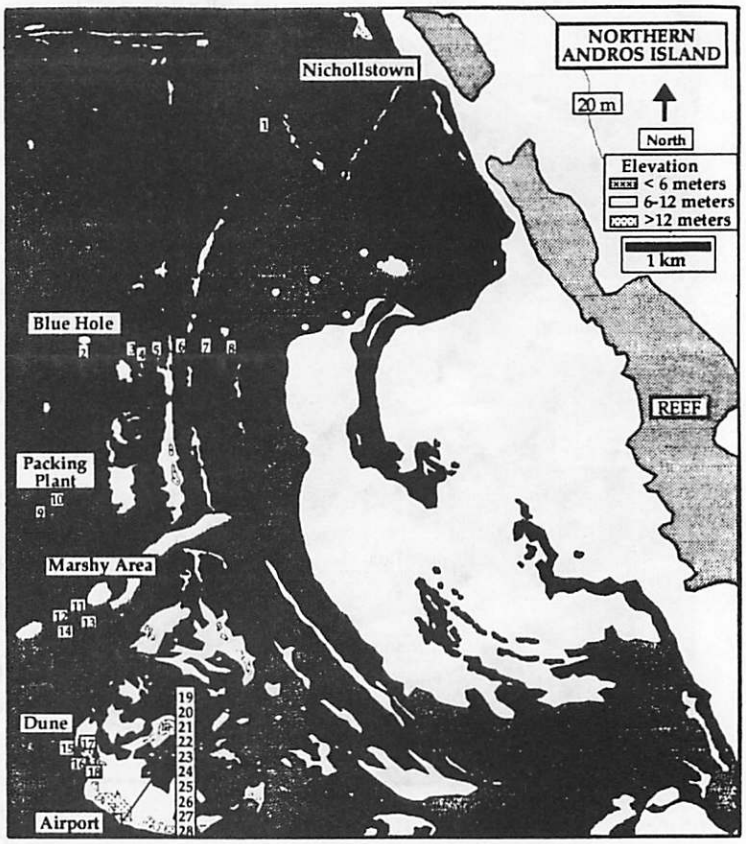

Figure 5 Location of core and sample sites on Andros Island.

Laboratory

All core were cut lengthwise, and both halves were used for megascopic description. Seventy-three thin sections were prepared and point counted. Rock chips could not be cut from vuggy, extremely friable (crumbly), or muddy portions; so the petrographic analysis is based upon the solid, granular portion of the core. In addition, 11 thin sections selected from a suite of Joulters samples (rocks and empregnated loose sediment samples) were point counted using the same techniques.

The data gathered from point-count analysis includes composition, size of each grain, percentage and type of cement, and percentage and type of porosity. Grain-size measurements were taken across the long axis of each grain, and recorded to the nearest 0.01 mm. Textural and compositional data from point-count analyses are provided in Troksa (1992).

Results and Discussion

Evaluation of outcrops and thin sections indicates that substantial variability in sedimentary structures, texture, composition, and diagenesis exists on northern Andros Island. Is this variability related to subenvironments of a Pleistocene oöid sand shoal complex? Can supratidal, intertidal, and subtidal deposits be recognized in the Pleistocene based on megascopic and petrographic recognition criteria? Is it possible to interpret the diagenetic history of rocks based on petrographic characteristics and relate diagenetic processes to specific subenvironments?

Sedimentary Structures

Rocks on Andros Island are commonly laminated or mottled, and a few are massive. Sedimentary structures such as these may be important recognition criteria for different subenvironments (Howard, 1972; White and Curran, 1988; Frey et al., 1989).

Thirty percent of the 42.9 meters of Pleistocene rock studied contain even, parallel, cross-laminations. Forty-nine percent of the rocks have a mottled appearance characterized by irregular bodies of material of different texture (including large vugs). The mottled appearance may have been created by the burrowing activity of marine organisms. In some outcrops burrow structures stand out in relief and are 1 to 2 cm in diameter. They branch both vertically and laterally and have burrow walls which have a lumpy exterior surface like Ophiomorpha (a trace fossil formed by a shrimp-like organism; Frey et al., 1978; Curran and White, 1991). Other trace fossils include cemented "V"-shaped structures ("nested cone" structures or "cone in cone" structures) which may be the product of burrowing sea anemones (Shinn, 1968). It may be that these rocks were originally laminated, and the primary structures were destroyed by animal burrows (White and Curran, 1988). On Andros Island, when both laminated and mottled rocks are found together, the mottled rock is always located stratigraphically lower than laminated deposits.

Rocks which appear massive comprise a lesser proportion of the rocks on Andros Island (17%). Samples are termed massive if they contain no visible structures (i.e. have a homogeneous texture). Rapid sedimentation may produce a deposit without internal layering, or the grains of a deposit may be so homogeneous both texturally and compositionally that sedimentary structures are not recognizable (Reineck and Singh, 1980). In some core sections features produced by subaerial exposure (e.g. paleosols) obliterate original sedimentary structures. Massive units may be also be produced by the complete destruction of sedimentary structures by the progressive burrowing of organisms or roots (Reineck and Singh, 1980; Frey et al., 1989).

Sedimentary Structures and Sea Level

In modern sediments and rocks of Joulters Cays oöid shoal complex, laminations are most commonly recognized in upper intertidal and supratidal subenvironments (Harris, 1979). Laminations also may be preserved in areas of rapidly shifting sands such as upper portions of the sand shoal, shallow subtidal portions of offshore bars, and intertidal and subtidal sand waves of tidal deltas, where few organisms are able to live (and churn) in the mobile substrate (Imbrie and Buchanan, 1965; Harris, 1979). Some sand shoal sediments contain cm-thick coarse sand layers alternating with 1-2 mm-thick fine-sand layers. Beach sediments contain cm-thick layers of coarser and finer sand, and low-lying hummocky dunes on islands at Joulters contain laminations of fine sand about 1-2 mm thick inclined at various degrees and directions.

Mottled sediments are common in the low intertidal to subtidal subenvironments on Joulters because burrowing organisms and/or penetrating roots of algae or seagrass have destroyed most or all primary sedimentary structures (Harris, 1979). On Joulters, bioturbation and root disruption of sediments are distinct features in the shallow subtidal (0 to 1 m below sea level) stabilized sand flat, seagrass-covered bottom sediments of tidal channels (2 to 4 m deep), offshore areas (> 4 m deep), and subtidal portions of the ebb-tidal delta and tidal flat (Harris, 1977; 1979; Carney and Boardman, 1991).

Dunes, ebb-tidal deltas, and upper portions of the sand shoal and beach contain similar types of laminations. Likewise, tidal flats, tidal channels, offshore areas, and stabilized sand flats contain similar burrow-mottled sediments (Harris, 1979; Reineck and Singh, 1980). Because different subenvironments contain similar structures, structures alone are inadequate to differentiate subenvironments.

Although specific subenvironments of deposition may not be delineated based on sedimentary structures alone, sedimentary structures may be useful as paleo-sea-level indicators. On the modern Joulters

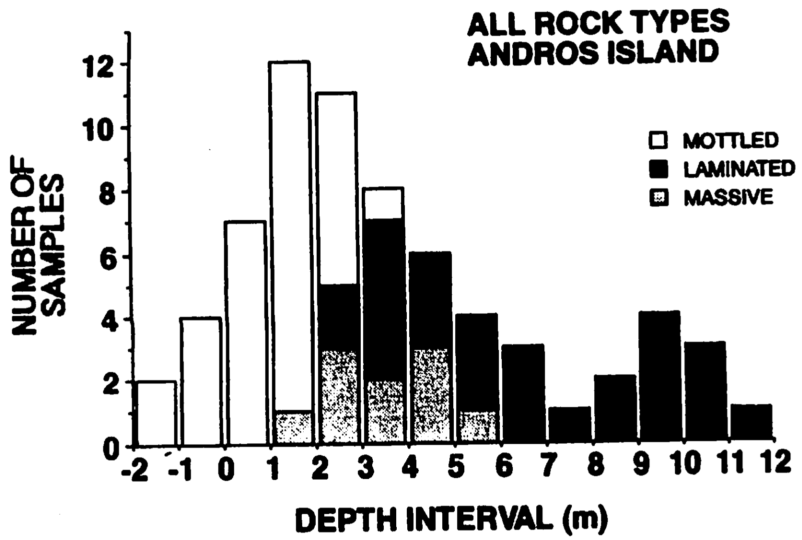

Figure 6 Sedimentary structures are correlated with elevation. Mottled sediments are located below 4 meters; whereas laminated sediments are located at elevations above 2 meters. Massive sediments are located between 1 and 6 meters. Sea level at the time of deposition of these sediments was approximately 3 meters; thus sedimentary structures are probably related to paleo-sea level.

Cays oöid shoal complex, laminations are most commonly present in subenvironments above sea level (see above), but may exist in upper intertidal and less commonly in shallow subtidal portions of the shoal complex. Mottled sediments are most commonly found in subenvironments below sea level (see above). It is possible for massive (homogeneous) sediments to exist in supratidal, intertidal, and subtidal portions of the shoal complex because the processes which control the formation of massive deposits may occur below, at, or above sea level (see above).

In rocks from northern Andros Island, most samples which are laminated are located at elevations greater than 3 m above present sea level, and most mottled samples lie below 3 m (Fig. 6). Massive rocks are located between 3 and 5 m above present sea level. Chi-square test of independence shows that mottled versus laminated sample elevations are statistically different. A common sequence observed in outcrops on northern Andros Island is laminated beds (upper intertidal or supratidal deposits) overlying rocks which are mottled (subtidal). This relationship may result from the migration of rippled shoal sediments over stabilized sand flat sediments, or the seaward progradation of beach and dune sediments over subtidal offshore sediments (Halley and Harris, 1979; Hunter, 1977; Strasser and Davaud, 1986). Laminated sequences overlying bioturbated sequences are common not only in recent settings and Andros Island, but also in other Pleistocene carbonate rock records such as in those from Bermuda (Land et al., 1967), the Yucatan Peninsula (Ward and Brady, 1979), in the Miami Oolite (Evans, 1982), on New Providence Island, Bahamas (Garrett and Gould, 1984) and on Grand Bahama Island (Gerhardt, 1983).

Thus, these data suggest that sea level (post subsidence) was approximately 3 m above present when these sediments of northern Andros Island were deposited. Support for this elevation of Pleistocene sea level come from a Pleistocene coral reef at Nichollstown which is located about 1.5 m above present sea level. Two Th/U dates from corals from this reef are 120,000 and 128,000 years BP (Neumann and Moore, 1975). We suggest that this reef was thriving in subtidal conditions (approximately 1.5 m below paleo-sea level) seaward of a prograding dune / beach / offshore environment of an oöid sand shoal system. Subsidence during the late Pleistocene is thought to be about 3 m / 100,000 years (Lynts, 1970); so, based on the data presented here, eustatic sea level was approximately 6 meters above present.

Although the general vertical distribution of laminated and mottled rocks is established, there is some overlap or scatter around the 3 m elevation which may be a natural product of peritidal deposition during sea-level fluctuations. Sediments may be deposited as sea level is rising, or as sea level is falling (Read et al., 1986; Chen et al., 1991), effectively creating an overlap in the location of supratidal, intertidal, and subtidal facies in the rock record. For example, overlap is seen in the transgressive Holocene dunes of San Salvador where eolian bedding is found below present sea level (Boardman et al., 1987; White and Curran, 1988). At the Nichollstown dune outcrop on Andros Island (approximately 2 km from the elevated reef of Neumann and Moore, 1975), the contact between laminated, fine-grained, well-sorted rock (interpreted as supratidal) and mottled, coarse-grained, poorly-sorted rock (interpreted as subtidal) is about 2 m above present sea level, or 1 m below paleo-sea level. Perhaps, then, the eolian dune at Nichollstown accumulated as sea level was rising or sea level was falling. Additionally, in this area of the Bahamas, tidal variations are approximately 1 m

(Halley and Harris, 1979), and it is reasonable to expect the elevation of mottled rocks (interpreted as subtidal) and laminated rocks (interpreted as supratidal) to overlap by a meter of paleo-sea level (Fig. 6). In general however, the fidelity of the elevation of structures to paleo-sea level (at +3 m after subsidence) suggests that the sediment which formed the North Andros oolite accumulated only during a single highstand rather than during multiple highstands of slightly different heights.

The estimate of +3 m for the (post-subsidence) sea-level highstand during the late Pleistocene (approximately 125,000 years ago) is in general agreement with other estimates. Chen et al., (1991) report late Pleistocene coral reefs as high as 2.25 m above present sea level. They estimate that these reefs grew in water depths of up to 4 m and, thus, arrive at a late Pleistocene sea-level highstand of +6 m. The maximum elevation of Pleistocene corals dated by Neumann and Moore (1975) is +2.3 m. Other estimates of the maximum elevation of the late Pleistocene sea level are +9.7 meters derived from keystone vugs in upper beach-face deposits (Garrett and Gould, 1984) and + 5.6 m derived from elevated erosional notches (Neumann and Moore, 1975).

According to Chen et al. (1991), the last highstand began about 132,000 years ago and remained high until 120,000 years ago. The fact that the preponderance of stratigraphic data from many locations from northern Andros Island converges on an elevation of + 3 m supports the idea that there was a single highstand which lasted for several thousand years, and not several highstands of short duration (Boardman et al., 1986; Chen et al., 1991).

Texture

Rocks on Andros Island contain variable textures which range from fine, well-sorted sediment to coarse, poorly-sorted sediment. Grain size and sorting measurements in sediments or rocks provide information on the availability of different grain sizes in the source material and the processes which have transported and deposited the sediment. Results of many studies have shown that the use of textural parameters for environmental interpretations has merit (e.g. Folk and Robles, 1964); however, it is evident that textural parameters are highly variable within a single subenvironment because of rapidly changing environmental conditions or because the sediments are being reactivated from a previous depositional system (e.g. palimpsest sediments).

The mean size of all grains from northern Andros Island samples is 0.33 mm with a range from 0.04 to 4.0 mm (standard deviation 0.20). The average sorting value observed in Andros oolites is 0.72 phi with a range from 0.44 to 1.11 phi. No distinct groupings of subenvironments are recognized based on mean grain size and sorting measures, and determination of subenvironments solely on the basis of texture is not warranted.

However, texture may be useful as a paleo-sea-level indicator. Those samples taken above paleo-sea level (> 3 m above present sea level) are characterized by finer, better sorted grains, and those taken below paleo-sea level (< 3 m above present sea level) contain coarser, more poorly-sorted grains (Fig. 7). T-tests and Chi-square tests of independence show that the separation of paleo-supratidal and paleo-subtidal environments based upon mean grain size and sorting is statistically valid.

Some of the overlap in mean grain size and sorting measures between supratidal and subtidal samples may be the result of tidal fluctuations which exert an influence on sedimentary depositional processes at or near mean sea level.

Grain Composition

The rocks on northern Andros Island are composed predominantly of peloids, oöids, skeletal grains coated grains, and aggregates. Grain compositions range from oöid-rich to peloid-rich, with lesser amounts of coated grains, skeletal grains and aggregates. Knowledge of grain composition is useful for

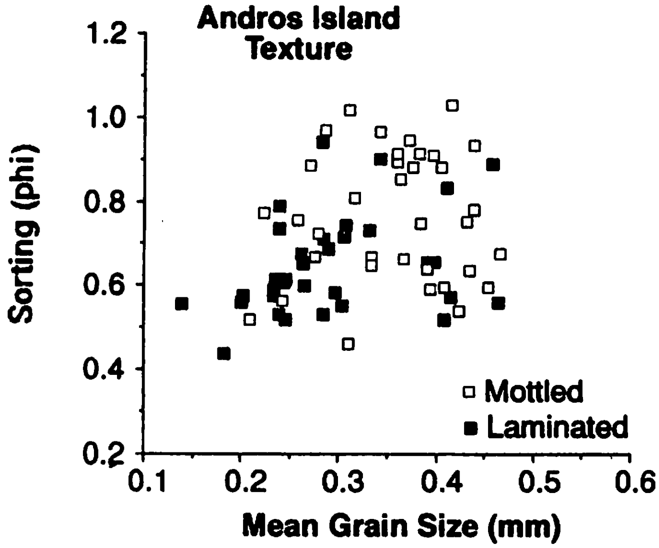

Figure 7 The texture of mottled and laminated sedimentary rocks on Andros Island are statistically distinct; although there is some overlap.

broad environmental interpretations (Dunham, 1962; Folk, 1962; Wilson, 1975); however, the reliance on grain composition to delineate subenvironments of oolites is not documented.

Peloids comprise the highest percentage of grains (skeletal and nonskeletal) in rocks on Andros Island with an average of 73% (range from 37% up to 99%). Peloids are spherical, ellipsoidal, or irregular in shape with an average diameter of 0.29 mm (range 0.04 to 2.5 mm; standard deviation 0.17).

The average percentage of oöids on Andros Island is 18% (range from 0% to 56%). A grain is termed an "ooid" if it contains 2 or more laminae. A "superficial oöid" is a spherical or ellipsoidal grain surrounded by only one concentric layer. oöids on northern Andros Island have an average diameter of 0.36 mm (range 0.08 to 0.93 mm; standard deviation 0.14). The nuclei of the oöids are dominantly peloids (> 98%). Skeletal nuclei occur, but are not common (< 2%). No pristine oöids are found in these Pleistocene oolites. Dissolution of selected laminae, recrystallization, or complete dissolution of oöids is common. Some oöids have not undergone a complete transformation from aragonite to calcite as indicated by the presence of the pseudo-uniaxial indicatrix figure (Bathurst, 1971; Dravis, 1977). The number of laminae is generally impossible to determine because of extensive micritization.

In this study, a coated grain is any grain (other than an aggregate) with less than two oolitic coatings that is irregular or ellipsoidal in shape. If the nucleus of the grain were an aggregate it would be called a coated aggregate (see Troksa, 1992). Coated grains in samples from Andros Island are a minor component (average = 3%; range is 0% to 12%) of the allochems observed and are generally large (average diameter = 0.51 mm; range is 0.17 to 1.33 mm; standard deviation is 0.18). The shape of coated grains varies according to the shape of the nuclei.

Aggregates refer to the grains formed when two or more particles become bound and cemented together. On Andros Island, aggregates are commonly highly micritized, and recognition of individual grains comprising the aggregate is difficult. The percentage of total aggregates on Andros Island is low with an average of 2% (range 0% to 8%). The aggregates are ellipsoidal to irregular in shape and have an average size of 0.63 mm (range 0.21 to 1.68 mm; standard deviation 0.23). Skeletal grains observed include foraminifera, bivalves, gastropods, red algae, green algae (Halimeda and unidentified green algae), and other unidentified skeletal fragments. The average skeletal component of Andros Island rocks is 4%, and the most abundant skeletal grains are green algae and foraminifera. Skeletal grains usually occur as fragments which are well-worn and rounded, and only rarely occur as large, whole, virtually unaltered grains.

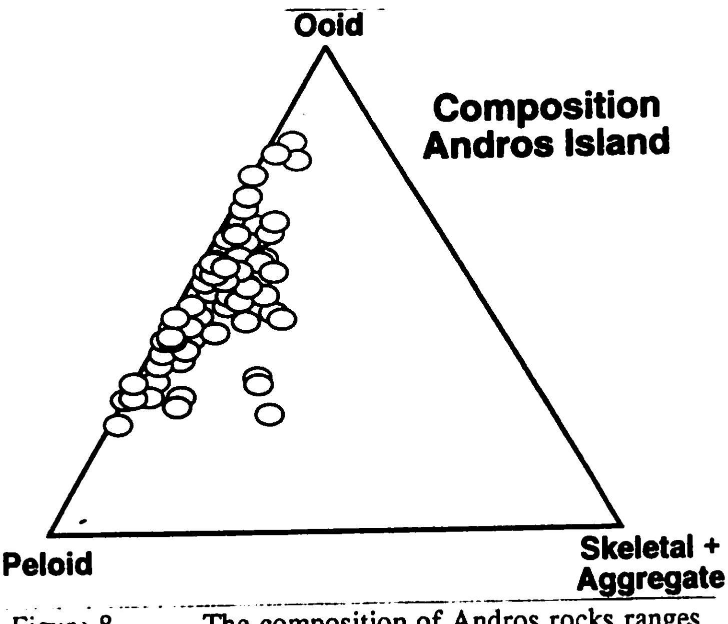

Figure 8 The composition of Andros rocks ranges from ooid-rich to peloid-rich. Composition is not clearly related to paleo-sea level, lithology, or subenvironment.

Three petrographically distinct groupings of subenvironments are recognized on Joulters Cays based on evaluation of grain composition (Table 1; Harris, 1977; 1979; Carney and Boardman, 1991; Troksa, 1992). One group contains sediment dominated by oöids with lesser amounts of peloids, skeletal grains and aggregates. This petrographically distinct group contains samples from tidal channels, ebb-tidal deltas, dunes, shoals, and beaches. A second group is dominated by peloids, skeletal grains and aggregates with a lesser amount of oöids and contains samples from tidal flat and stabilized sand flat environments. The third group contains the fewest oöids and greatest amount of peloids, in addition to skeletal grains and aggregates and is composed of offshore sediments.

In contrast to Joulters Cays, there are no petrographically distinct facies observed on Andros Island, but rather a mixture of compositions between an oöid-rich facies and a peloid-rich facies (Fig. 8).

Subenvironment	Structures and Bedforms (Harris, 1977 & Carney and Boardman, 1991)	Averge Grain Size (Harris, 1977; Carney and Boardman, 1991)	Grain Sorting (Harris, 1977; Carney and Boardman, 1991)	Grain Composition		Diagenesis* (Harris, 1977; Carney and Boardman, 1991)
				(Harris, 1977)	(Carney and Boardman, 1991)	
Dune	Cross-laminated ridges	Fine; (ooids avg. 0.33 mm, range 0.1 - 0.45 mm)	Very good; avg. 0.5 phi	no analysis	ooids-93% peloids-7%	freshwater cementation; 2.2
Ebb-tidal Delta	Bioturbation; rippled sands	Medium; (ooids avg. 0.3 mm)	Moderate; avg. 0.73 phi	no analysis	ooids-90% peloids-4% skel.-3% agg.-4%	no analysis; 2.1
Sand Shoal	Megaripples; spill-over lobes	Medium; (ooids avg. 0.45 mm, range up to 0.8 mm)	Good to very good; avg. 0.67 phi	ooids-83% peloids-9% skel.-4% agg.-4%	ooids-94% peloids-4% skel.-0% agg.-2%	cemented clasts, cobbles, and layers; 2.4
Beach	Beachrock; laminations	Fine to coarse; (ooids avg. 0.35 mm, range 0.1 to 0.7 mm)	Moderate to good; avg. 0.84 phi	no analysis	ooids-93% peloids-6% skel. plus agg.-< 2%	no analysis; 2.3
Tidal Channel	Bioturbation; spill-over lobes; sand waves and ripples	Fine to very coarse; (ooids bimodal at 0.2 and 0.4 mm)	Poor; avg. 1.1 phi	ooids-52% peloids-27% skel.-13% agg.-8%	ooids-82% peloids-8% skel.-6% agg.-4%	organic binding, cemented rock mounds; 2.4
Stabilized Sand Flat	Bioturbation	Very fine to medium; (ooids avg. 0.41 mm)	Poor to moderate; avg. 1.34 phi	ooids-52% peloids-26% skel.-12% agg.-10%	ooids-69% peloids-20% skel.-7% agg.-4%	cemented clasts and crusts, organic binding; 2.8
Sand Tidal Flat	Bioturbation	Very fine to medium; (ooids bimodal at 0.15 and 0. 3 mm)	Poor to moderate; avg. 1.4 phi	ooids-60% peloids-23% skel.-11% agg.-6%	ooids-62% peloids-34% skel.-0% agg.-3%	no analysis; 3.0
Offshore (Inner Platform)	Bioturbation	Fine to very coarse; (ooids avg. 0.2 mm)	Very poor; avg. 1.95 phi	ooids-78% peloids-11% skel.-7% agg.-4%	ooids-40% peloids-37% skel.-13% agg.-10%	clasts; 3.2

Table 1. Summary of structures, textures, sediment compositions, and grain alterations from Joulters Cays ooid shoal complex. Mud fraction not included in composition. *Numbers represent relative scale of ooid grain micritization (1 = none, 2 = partial rim; 3 = total rim; 4 = pervasive; 5 = obliterative).

TABLE 2

EVENT	EVIDENCE
SEA LEVEL HIGHSTAND (125,000 years ago)	
a. Sediments accumulate in subtidal environments on the Andros Island ooid shoal complex. The environments are inhabited by marine floral and faunal assemblages.	poorly-sorted sediment with an abundance of peloids and whole, skeletal grains
b. Penetrating root networks and burrowing organisms churn the sediment.	burrow-mottled structure seen in rocks
c. Burrows (e.g. *Ophiomorpha*) are filled with reworked material.	coarser-grained material fills burrows
SEA LEVEL LOWSTAND	(120,000 to 2000 years ago)
a. Sea level drops and exposes the rocks to vadose conditions.	karst landforms; paleosols
b. Fluids undersaturated with respect to calcium carbonate (rain water, ground water) percolate through the exposed sediment	selective leaching of ooid laminae and/or whole grains
c. Early freshwater cementation occurs.	large, blocky calcite fills pores; vadose and phreatic cements
d. Fine-grained burrow walls become preferentially cemented. Coarser-grained material within burrows does not lithify as rapidly; consequently, these grains may be washed out during repeated flushing by fluids leaving voids in the form of molds of the original burrow.	in outcrop some burrow structures are hollow and some are filled with partially lithified sediment; in core section, vugs and vugs filled with coarse grains
e. Burrow molds channel fluids through the vadose zone. Undersaturated solutions widen channels and leach ooids.	large, irregularly-shaped vugs and filled vugs which interconnect both laterally and vertically; existence of oomolds
f. Carbonate is reprecipitated as cement in nearby interparticle voids.	cement concentration is higher in mottled rocks than in laminated rocks

The oöid-rich facies on Andros contains a lower concentration of oöids than the comparable facies on Joulters (56% versus >95% oöids). Boardman et al. (in press) suggested that the Andros oöid shoal was either more peloid-rich than the Joulters shoal, or the peloids on Andros are micritized oöids. Because micritization is extensive on Andros (see next section), the latter hypothesis is preferred. Thus, the Pleistocene oolite of Andros cannot be divided into subenvironments based on composition.

T-tests show that samples above or near paleo-sea level and those below paleo-sea level can be differentiated based upon average percentage of oöids and peloids; however, Chi-square tests of independence show that the relative percentages of oöids and peloids are similar above and below paleo-sea level.

Diagenesis and Sea Level

In addition to sedimentary structures, texture, and composition, diagenetic features such as micritization, cementation, dissolution, and recrystallization were evaluated for rocks of northern Andros Island. The remainder of this study focuses on the relationship of micritization, cementation, and porosity development to sea level.

Micritization

The presence of micritized grains suggests that at some time in its history of development, the sedimentary deposit was in an environment subjected to the destructive activities of boring algae and other endoliths. In modern sediments/rocks of Joulters Cays, the degree of micritization of oöid grains can be used to delineate subenvironments (Carney and Boardman, 1992). Quiet-water environments such as stabilized sand flats and tidal flats contain many micritized grains; however, in high-energy environments, where grains are actively moving such as in dune, beach, or shoal environments, grains are less affected by micritization (Fig. 3; Table 2; Harris, 1977; Carney and Boardman, 1991; 1992). Micritization on Joulters is thought to have occurred in the marine environment rather than the subaerial environment as evidenced by the fact that oöids in dunes exposed at least 1,000 years show no significant micritization (Carney and Boardman, 1991).

On Andros Island, however, nearly every oöid grain has been micritized to some degree, and even those grains which are clearly oöids and which are thought to have been deposited as eolian dunes (based on structure, texture, and elevation), have been extensively altered. Evidently, micritization has occurred in subaerial environments during diagenesis and renders the degree of micritization useless as an environmental indicator for rocks on Andros Island.

Cementation.

In addition to micritization, cementation contributes to the diagenetic alteration of rocks. Most samples on Joulters are uncemented. Patchy cementation is seen in the marine environment around worm tubes, in lithified clasts in the stabilized sand flat, or in crusts found between subtidal sand waves (Harris, 1977; 1979; Carney and Boardman, 1991). Cement commonly occurs in dune sediments at grain contacts and forms rounded pores characteristic of meniscus cements of the vadose zone (Harris, 1979; Halley and Harris, 1979).

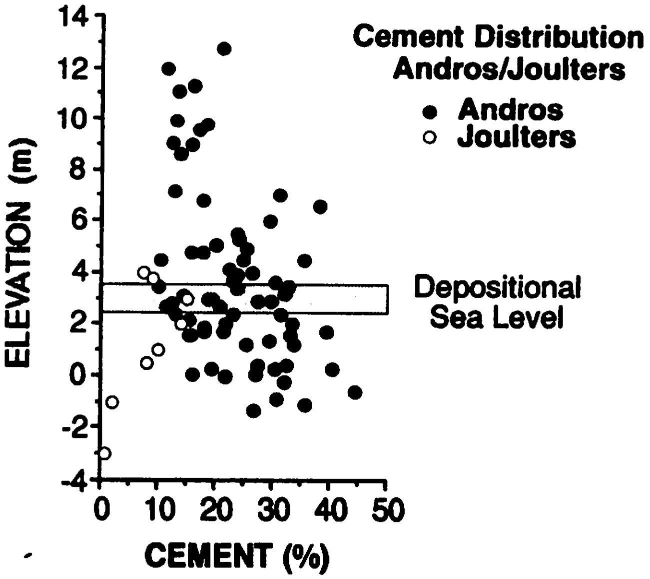

Figure 9 As expected, the rocks of Andros Island are better cemented than the dune rocks from Joulters Cays.

Halley and Harris (1979) examined a 7 m core on South Joulters Cay (Holocene) and provided estimates of the percent calcite cement versus depth. The most abundant cement is found between 50 cm above and up to 1. 5 m below the water table, and a drastic decrease in % cement occurs to about 5 m below the water table which is within centimeters of sea level on Joulters Cays (Halley and Harris, 1979).

Vadose cements are evident in virtually all rock samples from Andros Island. The dominant cement, however, is coarse, blocky calcite crystals or isopachous calcite rim cements typically produced in fresh-water, phreatic environments. It is unclear if the phreatic cements observed in Andros oolites formed in the freshwater phreatic zone, or in the vadose zone under phreatic conditions associated with locally perched water tables (Trudgill, 1985). Because sea level has been lower than present during most of the 125,000 years since its formation, the Andros oöid sand shoal has been dominated by vadose conditions (seen by vadose cements and karst features), not phreatic conditions, suggesting that either cementation occurred early in the diagenetic history of the rock, that is, before paleo-sea level fell, or that perched water tables are prevalent in the vadose zone on Andros Island.

The distribution of cement relative to sea level at the time of formation on Andros Island (3 m above present sea level) and Joulters Cays is represented in Figure 9.

On Andros, cement is most abundant 1-2 m below paleo-sea level (approximately equal to the paleo-water table) analogous to the distribution of cement on Joulters. In fact, T-tests and Chi-square tests of independence show that the cement in mottled rocks on Andros (interpreted as subtidal) is significantly greater (avg. = 26%) than cement in laminated rocks (interpreted as supratidal; avg. = 20%).

Porosity Development

In Holocene rocks from Joulters Cays, porosity averages 47% (range is 40 to 52%) based on bulk density measurements (Halley and Harris, 1979). Halley and Harris (1979) showed that no net porosity reduction is associated with cementation which suggests that the cement is derived from in situ dissolution of carbonate which is then reprecipitated in the immediate area. They noted that no discernable change in porosity occurs with depth or in relation to the water table. Thus, on Joulters Cays, sea level has no recognizable influence on porosity development.

In Pleistocene rocks from Andros Island, interparticle porosity averages 8% (range is 0 to 32%). T-tests and Chi-square tests of independence show that interparticle porosities of laminated rocks (avg. = 8.6%; most located above paleo-sea level) and mottled rocks (avg. = 7.7%; most located below paleo-sea level) are statistically similar. There is no significant change in interparticle porosities with respect to paleo-sea level.

Although interparticle porosity shows no relationship to sea level, the cement concentration is greater below paleo-sea level than above paleo-sea level. Either cement above paleo-sea level has been selectively removed, or there has been more cementation below paleo-sea level. It is unlikely that cement above paleo-sea level has been selectively removed. Not only is it comprised of the stable form of calcite, but there is no petrographic evidence for its selective removal.

A source for the additional calcite cement below paleo-sea level may be the dissolution of carbonate in the mottled rocks. In fact, T-tests and Chi-square tests of independence show that dissolution porosity is significantly greater in mottled rocks (avg. = 7%) than in laminated rocks (avg. = 2%). The percentage of dissolution porosity counted in thin section does not include vugs which are common in mottled rocks. It seems likely that the vugs have influenced the diagenesis of these mottled rocks. One possible scenario for the porosity development of mottled rocks on Andros Island is presented in Table 2.

CONCLUSIONS

Structural and textural data from Andros Island oolites may be utilized as paleo-sea-level indicators. Fine, well-sorted, laminated deposits are common in supratidal and upper intertidal environments; whereas coarse, poorly-sorted, mottled deposits are indicative of subtidal and lower intertidal regimes. Composition is not a useful criterion to differentiate supratidal versus subtidal facies. Massive (homogeneous) deposits may be indicative of low supratidal to shallow subtidal facies.

Diagenetic alteration (micritization) of grains is extensive. The proportion of cement (vadose and phreatic) has increased in the last 125,000 years, especially in mottled rocks (subtidal facies). Average interparticle porosity has decreased, but there is no relationship of interparticle porosity with sea level. Micritization is common in rocks from northern Andros Island, and there is no relation of micritization to subenvironments or to paleo-sea level. However, cementation and porosity development have a recognizable relationship to paleo-sea level. The cement concentration is greater below paleo-sea level than above paleo-sea level. Dissolution porosity is enhanced in rocks below paleo-sea level.

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