

**PROCEEDINGS OF THE
EIGHTH SYMPOSIUM
ON THE GEOLOGY
OF THE BAHAMAS AND
OTHER CARBONATE REGIONS**

Edited by
James L. Carew

Production Editors
Daniel R. Suchy
Nicole G. Suchy

**Bahamian Field Station, Ltd.
San Salvador, Bahamas
1997**

Front Cover: View to the SSE on White Cay in Grahams Harbour off the north coast of San Salvador, Bahamas. At this spectacularly scenic site one can see that marine erosion has removed the entire windward portion of these early Holocene eolianites (North Point Member, with an alochem age of ~5000 radiocarbon years B.P.) that were deposited when sea level was at least 2 meters below its present position.

Back Cover: Stephen Jay Gould, keynote speaker for this symposium, holds a *Cerion rodregoi* at the Chicago Herald Tribune's 1891 monument to the landfall of Christopher Columbus, which is located on the windward coast of Crab Cay on the eastern side of San Salvador Island, Bahamas. The monument consists of an obelisk constructed from local limestone which houses a carved rock sphere depicting the globe with the continents. The inscription carved in a marble slab, reads: "On this spot, Christopher Columbus first set foot upon the soil of the New World."

© Copyright 1997 by Bahamian Field Station, Ltd.

All Rights Reserved

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in written form.

Printed in USA by Don Heuer

ISBN 0-935909-63-X

INFLUENCE OF SEA LEVEL ON THE ORIGIN AND DIAGENESIS OF THE SHALLOW AQUIFER OF ANDROS ISLAND, BAHAMAS

Mark R. Boardman
Department of Geology
Miami University
Oxford, OH 45056

Cindy K. Carney
Department of Geological Sciences
Wright State University
Dayton, OH 45435

ABSTRACT

The Pleistocene aquifer of Andros Island, Bahamas, contains a fresh-water lens that is thick and extensive compared to other Bahamian islands. Petrographic and geochemical examinations of core samples (upper 12 m) and chemical evaluation of water samples indicate that the origin and diagenesis of this aquifer are directly linked to Quaternary fluctuations of sea level, and that the process of diagenesis is punctuated, rather than gradual and continuous.

Late Pleistocene rocks of Andros Island contain a vertical sequence of lithologies which is the result of a depositional succession of subtidal sediments (burrowed packstones with corals, and skeletal wackestones) followed by a paleosol. Above the paleosol is a skeletal packstone overlain by a burrow-mottled oolitic grainstone. The subtidal lithologies include restricted lagoon, open lagoon, and stabilized sand flat deposits. A paleosol separates the restricted and open lagoon lithologies. These lithologies clearly reflect fluctuations of Quaternary sea level.

There is an overprint of diagenesis on the lithologies resulting from the changing position of the perched fresh-water lens and mixing zone during late Quaternary sea-level fluctuations. The current fresh-water lens and mixing zone were delineated by resistivity surveys and verified by conductivity profiles and chemical analyses of water in several wells.

The burrow-mottled oolitic grainstone (upper lithology) has retained a significant portion of its original carbonate. These rocks

are 60% aragonite, and the geochemistry of the water samples indicates that they are presently undergoing diagenetic stabilization (Sr/Ca values are high). The units below the paleosol (in the mixing zone) contain very little original carbonate (0% aragonite), and the water chemistry suggests that they are experiencing dissolution and are not now undergoing any substantial diagenetic alteration.

We suggest that the sediment above the paleosol was accumulated during the last highstand of sea level (substage 5e). Diagenesis during the subsequent lowstand of sea level (~120 ka to ~3.5 ka ago) was nearly absent. Only when sea level rose high enough to perch a phreatic fresh-water lens in the laminated sediments (during the last few thousand years) have these oolitic sediments experienced rapid diagenetic stabilization.

Andros Island's late Pleistocene rocks appear to be in a stage of diagenesis that is intermediate between that seen at Joulter Cays (Holocene) and the Yucatan Peninsula (Miocene).

INTRODUCTION

Sedimentary rocks, and carbonate rocks in particular, are products of deposition and diagenesis. Using comparisons to modern environments, sedimentologists have convincingly demonstrated that sea level, both absolute sea level and rates and magnitudes of fluctuations of sea level, are master variables in determining the depositional facies of carbonate sediments and rocks (Wilson, 1975; James, 1984; Walker and James, 1992). Many carbonate rocks are derived from sediments

deposited within 10 m of sea level, and stacked sequences of carbonate rocks result from changes in relative sea level.

The depositional process can occur during relatively short time intervals. For example, during the Quaternary, shallow marine carbonates of relatively stable regions (e. g., the Bahamas, Florida, and the Yucatan) were deposited predominantly during high, stillstands of sea level. Such periods usually lasted a few thousand years and are separated by tens of thousands of years of lowstands of sea level (Shackleton and Opdyke, 1973; Schlager, 1981; Kendall and Schlager, 1981; Boardman et al., 1986, 1993, 1995; Carew and Mylroie, 1995). Rates of shallow-marine deposition are typically 1 m/1000 years; so each highstand deposit is a few meters of sediment.

In contrast, the diagenetic process occurs over a long time period. Diagenesis can start immediately following deposition and can proceed indefinitely. Diagenesis is usually imagined as an overlapping or coincident set of relatively continuous processes of dissolution, cementation, mineralogic stabilization, trace-element and isotope equilibration, etc. (Land, 1967, 1986; Land et al., 1967; Friedman, 1964, 1969, 1975; Brand and Veizer, 1980; Pingitore, 1976, 1978). Terms related to diagenesis, such as "progressive" (Gavish and Friedman, 1969), and concepts such as the "half-life of aragonite" (Budd, 1988a; Budd and Land, 1990; Vacher et al., 1990) suggest that diagenesis is uniform and continuous.

Studies from Bermuda on lithologies of distinctly different ages have been used to support the idea of progressive and continuous (ongoing) diagenesis (Land et al., 1964; Vacher, 1978; Vacher et al., 1990). However, Vacher et al. (1995) have recently modified this concept of ongoing diagenesis. Their figure 10 (p. 286) can be interpreted to indicate that, although diagenesis is progressive, it is not continuously occurring, but is punctuated.

If diagenesis is punctuated, rather than continuous, other questions arise. Such as, why it is episodic? What causes or controls episodic diagenesis? How often do diagenetic episodes occur? How fast does diagenesis occur? The purpose of this paper is to discuss the idea of punctuated diagenesis by linking

diagenesis to fluctuations of sea level, in addition to primary lithology.

Diagenesis and Lithology

Evolution of a carbonate rock starts with the deposition of carbonate sediments, whose mineralogy and trace-element geochemistry are unstable. Therefore, their mineralogic and trace-element signatures differ from those of rocks that are examined in cores or in outcrops. Following deposition, the sediments are diagenetically altered in a stabilization process that includes a mineralogic change from predominantly aragonite and high-Mg calcite to a greater proportion of low-Mg calcite, and/or dolomite; and a change in the trace element composition toward a more pure CaCO_3 or $\text{CaMg}(\text{CO}_3)_2$. That is, loss of strontium, and increase of calcium (Katz et al., 1972; Machel, 1988; Morrow and Meyers, 1978). These diagenetic processes are accomplished in an aqueous medium which is almost always accelerated by meteoric fresh water. Thus, the evolution of a carbonate rock can be monitored by measuring the geochemical properties of the rock and its associated fluids.

Mineralogic stabilization requires dissolution followed by precipitation (Pingitore, 1976, 1978, 1982). If the precipitation occurs in large voids, we call the process cementation. If the precipitation occurs in sub-microscopic regions, and retains pre-existing structures, we call the process mineralogic alteration. Both processes result in a more stable mineralogy (e.g., low-Mg calcite), and both processes result in a carbonate minerals with fewer foreign ions such as Sr^{2+} .

In this paper we show that: 1) diagenesis of the Pleistocene rocks of Andros Island is linked to primary lithologic characteristics and to the position of the fresh-water lens, 2) those rocks have experienced multiple episodes of diagenesis linked to fluctuations of sea level, and 3) they are at an intermediate stage of diagenesis relative to Joulter Cays, Bahamas (Holocene) and the Yucatan Peninsula, Mexico (Miocene).

METHODS

To evaluate the lithology of the aquifer, several rock cores 5 cm in diameter and up to 12 m in length were recovered from a 2 km by 5 km area of North Andros Island, Bahamas (Figure 1). The cores were described megascopically, and thin sections were made and examined from selected portions of the cores.

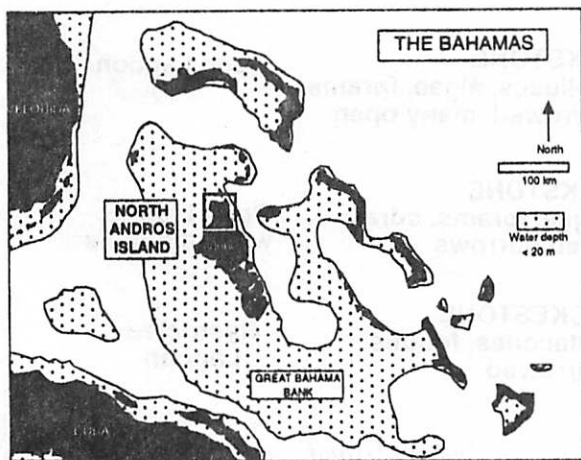


Figure 1. Map showing the study area on North Andros Island.

To examine the hydrology and hydrogeochemistry of the region, several bore holes (approximately 8 cm in diameter) were created by augering. Vertical profiles of conductivity and temperature were taken from these bore holes, the core holes, and the upper 20 m of a 40 m-deep blue hole (Charlie's Blue Hole) in order to determine the thickness and salinity of the fresh-water lens and the vertical salinity gradient of the mixing zone. Water samples were collected from 10 isolated depths from the deepest core hole (CH 69). These water samples include the fresh-water lens and the upper portion of the mixing zone. Water samples were returned to the lab and analyzed for major and minor elements using a Dionex liquid chromatograph. X-ray diffraction was used to determine the mineralogy of 26 subsamples from core CH 69. The relative proportions of aragonite and calcite were determined by measuring peak areas of the principal peaks of calcite and aragonite and comparing the peak-area ratios to a standard curve derived from X-ray diffraction of

natural carbonate standards.

Resistivity measurements were used to better define the thickness of the fresh-water lens and the mixing zone, and to link the results from conductivity at these specific holes. Tidally induced changes of the depth to the water table were determined in several well holes, the blue hole, and the ocean. A topographic survey was conducted, and sea level was determined from the lower limit of leaves on red mangrove trees. Some more detailed data can be found in Barton (1995) and Bukowski (1996).

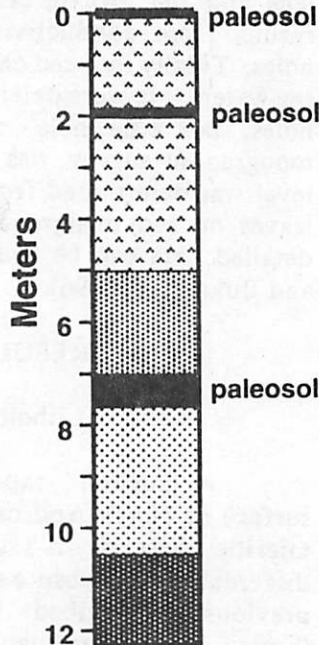
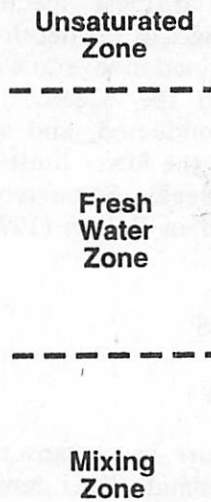
RESULTS

Lithology

A paleosol exposure crust caps the surface of North Andros Island. This dense, micritic crust is ~1-3 cm thick and is not different from exposure surfaces and paleosols previously described from the Bahamas (Sealey, 1985; Boardman et al., 1995). Below this cap is a vertical sequence of shallow-water carbonate lithologies and paleosols. A composite vertical sequence is presented in Figure 2, and the principal lithologies are described below.

The upper 5 m of core CH 69 from Andros Island includes a mottled ooid / peloid grainstone (Figure 3). The ooids are 0.5 to 0.8 mm in diameter, and usually have a peloid nucleus and several laminae. Dissolution features (i. e., dissolved laminae) and micritization are commonly seen in thin section (Figure 4). Up to 70% of the grains in this section of the core are ooids. Studies of modern ooids from Joulter Cays suggest that there is a range of micritization seen in Holocene ooids (Carney and Boardman, 1993). We suspect that greater micritization of many ooids in the North Andros rocks has obliterated the diagnostic criteria used to identify ooids, and that they have therefore been identified as peloids; together, peloids and ooids comprise 80% to 90% of the grains (Figure 4). The remaining grains are skeletal fragments of forams, molluscs, and green algae. The grains are well rounded, moderately well sorted, and there is little lime mud matrix. Cement occurs at grain contacts and as void fillings. The distinguishing feature

LENS CHARACTERISTICS



LITHOLOGY

GRAINSTONE
oolitic / peloidal
open burrows

PACKSTONE
molluscs, algae, forams
burrowed, many open

PACKSTONE
algae, forams, corals
filled burrows

WACKESTONE
ostacodes, forams
burrowed

ENVIRONMENT OF DEPOSITION

Stabilized
Sand Flat

Open Lagoon

Open Lagoon
w / patch reefs

Restricted
Lagoon

Figure 2. Composite vertical sequence of lithologies of northern Andros Island.

of this lithology is that it is riddled with 1 cm diameter holes, and there are numerous ~1 cm-diameter oval-shaped mottles. We interpret the holes in these rocks as relict burrows, and the mottles as filled burrows. Core recovery of the burrowed and mottled grainstone was sometimes less than 25% because the rock was so friable due to the abundance of holes. This lithology probably originated in a subtidal region (stabilized sand flat), or in regions of the mobile fringe of an ooid sand shoal. The lack of significant amounts of lime mud, the rather good sorting and rounding of grains, and the presence of skeletal grains is compatible with an origin as a mature stabilized sand flat (a major area of burrows in modern ooid sand shoal complexes).

In this core, a 2 cm thick, brownish-red, micritic zone with wavy laminations that occurs 2 m below the top of the mottled/burrowed grainstone may be a paleosol/exposure surface, but there is no evidence of roots or clasts which are expected to accompany a paleosol. Petrologic evidence indicates that the mottled/burrowed grainstone lithologies above and below this presumed

paleosol are identical. On the other hand, it is possible that this zone is not a paleosol, but rather is a recent diagenetic product of the upper water table (i. e., the vadose-phreatic interface) which partially mimics a paleosol (Braithwaite, 1983).

A mottled skeletal packstone ~2 m thick is found below the mottled grainstone. These mottles are irregular in shape, up to 4 cm in cross-section, and often stained reddish-brown. There are a few holes, both round and irregularly shaped, up to 1 cm in diameter. Skeletal grains of foraminifera, green algae, and molluscs are recognized in thin section (Figure 5). Peloids are common, and ooids are rare. The grains are poorly sorted and not rounded. Cement occurs at grain contacts, and commonly as equant void-fillings. There is no evidence of an exposure surface separating this facies from the facies above it. This layer appears to have originated in a normal-marine lagoon.

At 7 m below the surface an approximately 50 cm thick paleosol occurs below the mottled skeletal packstone. Blackened clasts, red-stained clasts, and

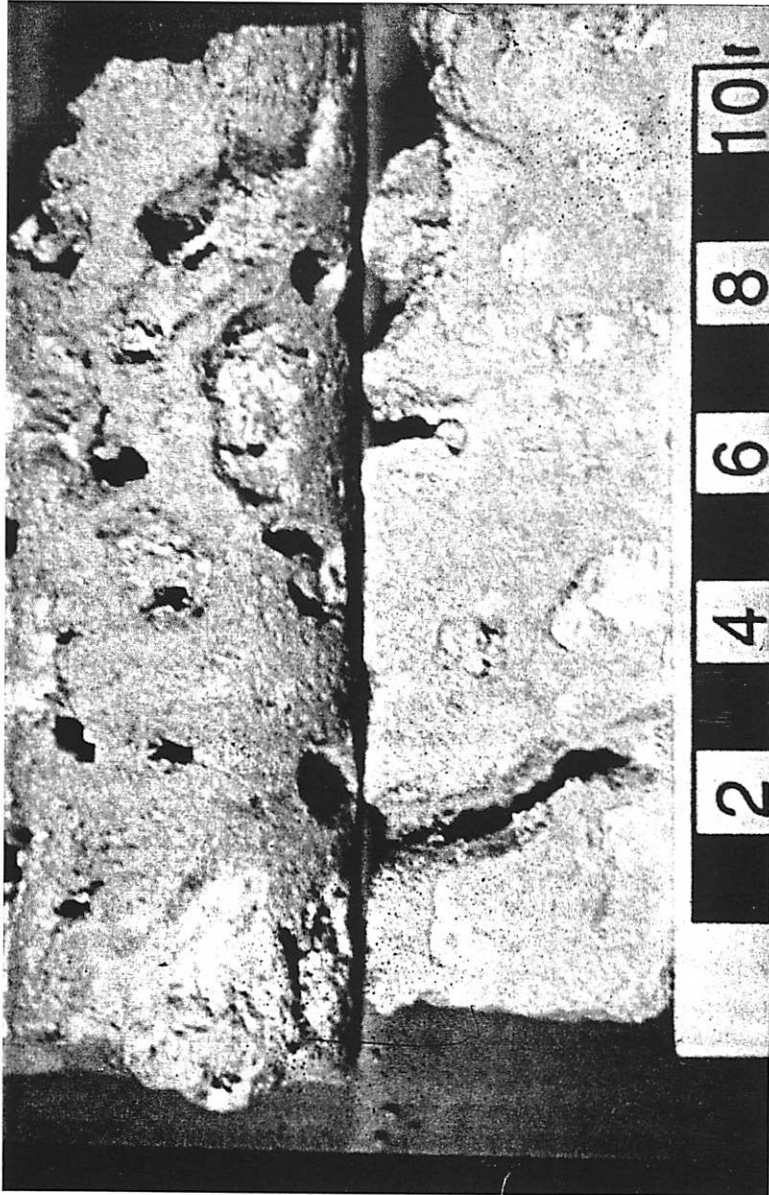


Figure 3. Burrows and burrow-mottled grainstone is composed of ooids, peloids, and bioclasts in CH 69. This facies is rarely found at elevations higher than 3 m above sea level. It is interpreted as a stabilized sand flat formed when sea level was about 5 m higher than present, during oxygen isotope substage 5e.

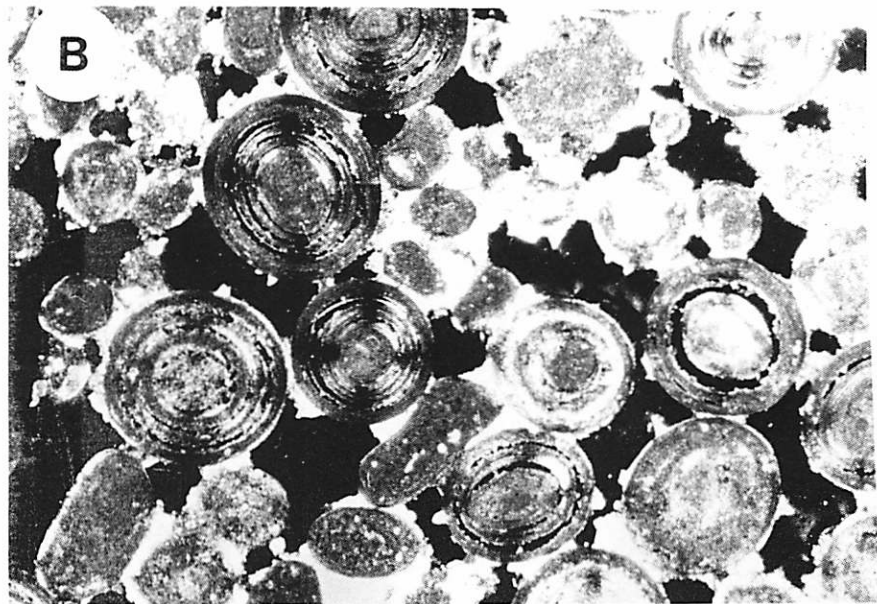
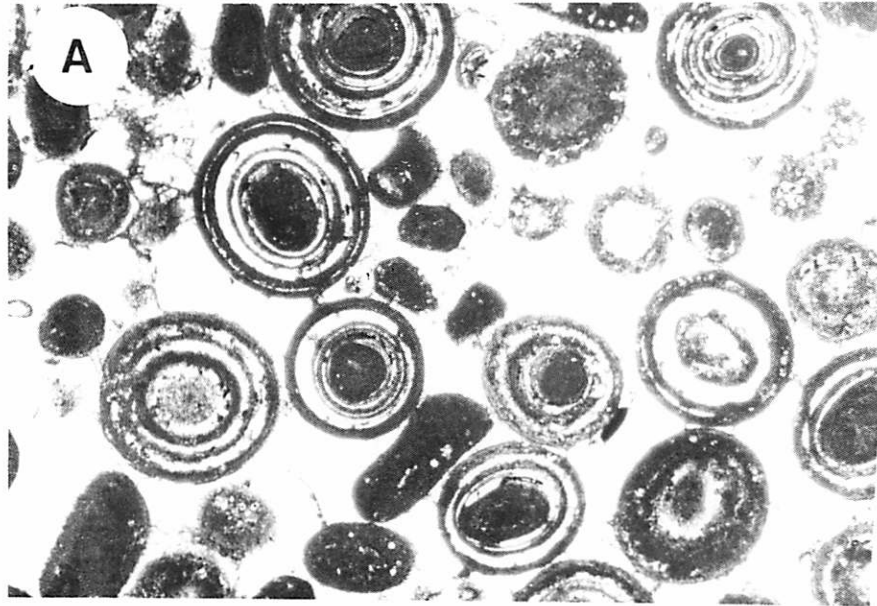


Figure 4. Photomicrographs of burrow-mottled oolitic grainstone from CH- 69 clearly show extensive selective dissolution of laminae of the ooid cortices. Cements are mostly at grain contacts. Both meniscus cement and phreatic cement are common. A) with plane-polarized light, B) with cross-polarized light. Field of view for both images is 4 mm across.

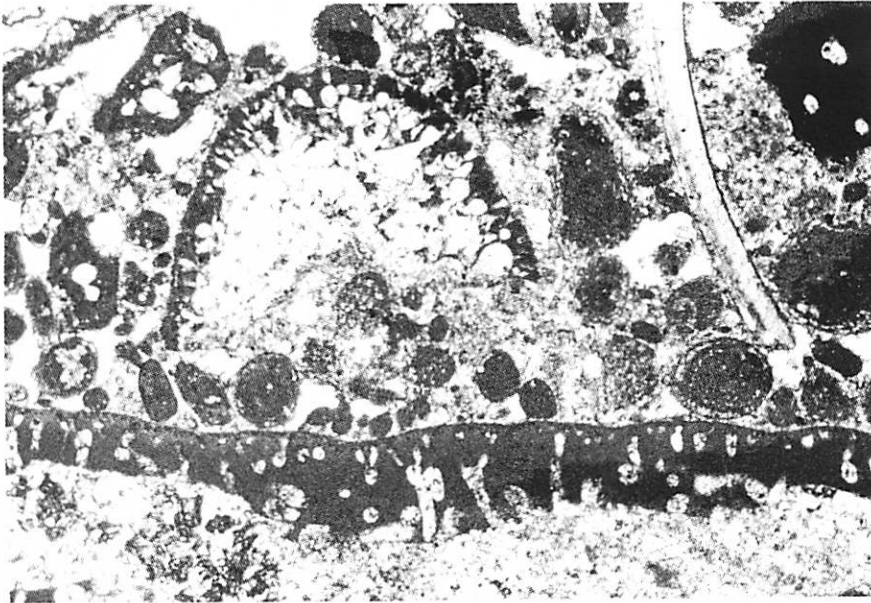


Figure 5. Photomicrograph, in plane-polarized light, of mottled skeletal packstone from CH 69. This lithology is interpreted to have originated as sediments deposited in a normal-marine lagoon. Field of view is 4 mm across.

unstained clasts embedded in a dense, micritic matrix (Figure 6) typify this lithology. Tiny calcified rootlets are seen in many voids.

A 3 m-thick skeletal packstone containing branching corals, molluscs, algae and forams (Figure 7) is present below the paleosol. Voids in this facies are filled with large calcite crystals. The most distinguishing feature of this section is that it is solid rather than friable. Core recovery in this section was nearly 100%. The presence of corals in this packstone suggests that this lithology originated in a well-ventilated lagoon.

The lowest section recovered is 1.5 m of a mottled, skeletal wackestone / packstone (Figure 8). Skeletal fragments include ostracodes and small forams. Lime mud matrix is abundant. Cement is mainly micritic, and difficult to distinguish from deposited lime mud. Based on the abundance of matrix and the skeletal allochems, we suggest this lithology originated in a restricted lagoon (perhaps stressed by salinity or temperature excursions from normal-marine conditions).

Hydrology

The fresh-water lens in the study area

is located at the seaward edge of the lens covering the north-central portion of North Andros Island (Figure 9). The island lens is up to 15 m thick. Resistivity studies in the region of our study area (Cowles, 1992; Wolfe, 1994) confirm a fresh-water lens thickness of up to 15 m which thins to the east (seaward). Resistivity studies were ground-truthed to conductivity profiles within boreholes and the blue hole. The thickest fresh-water lens recorded by conductivity data from any borehole or the blue hole in the area was 9 m.

At the site of CH 69, the fresh-water lens was determined to be approximately 7 m thick using conductivity measurements (Figure 10)

The depth to the water table at this site is 1 to 2 m below the ground surface (Figure 10), and about 1 m above present sea level. Tidal fluctuation in this corehole is closely linked to the tidal fluctuations of the ocean located approximately 2 km to the east. Maximum tidal fluctuations measured in CH 69 were 70 cm when the oceanic tidal range was 90 cm (Bukowski, 1996), and the tidal fluctuations are in phase.

The flow of groundwater in this region of North Andros Island is from the west to the east (toward the ocean), as expected from the

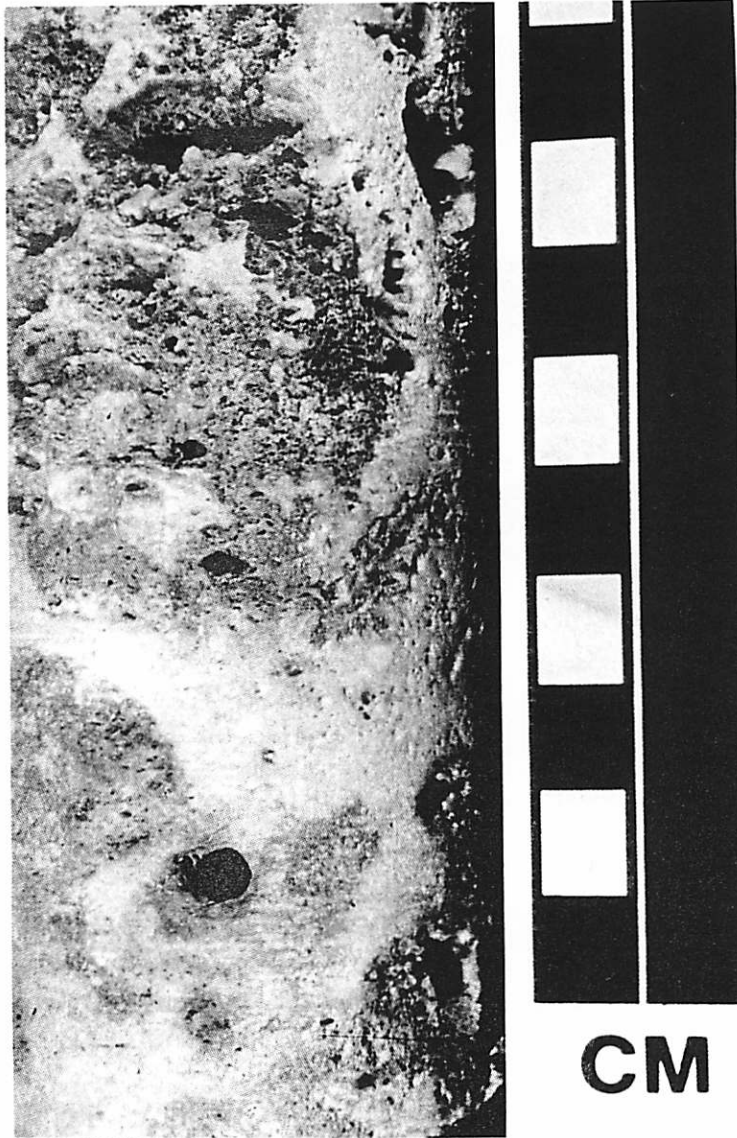
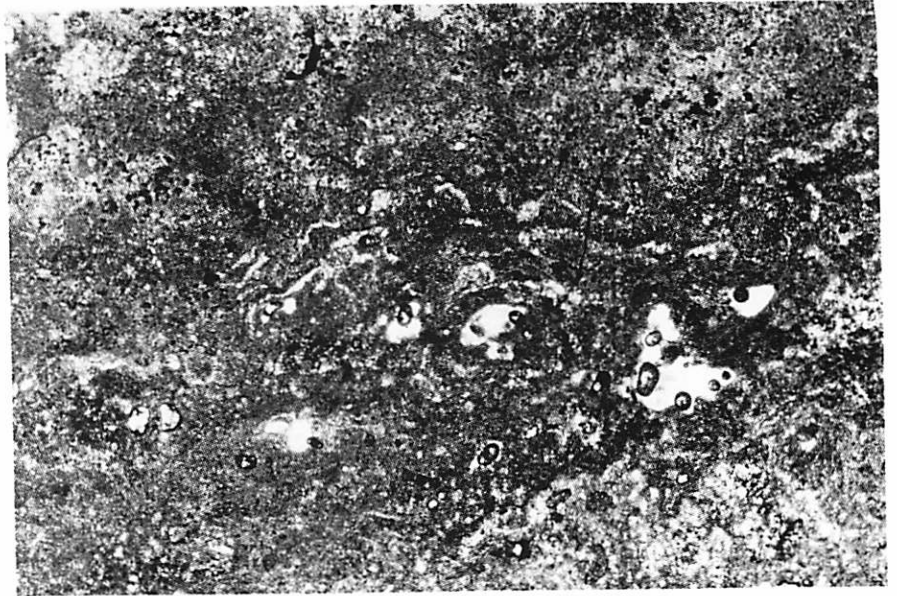


Figure 6. Photomicrograph of micritic matrix of 50 cm thick paleosol located below the mottled skeletal packstone, and at 7 m below the surface in CH 69.

Figure 7. Skeletal packstone with corals lies beneath the paleosol in CH 69. This lithology is ~3 m thick, and is interpreted to have originated in a normal marine lagoon with sufficient water movement to promote the growth of corals.

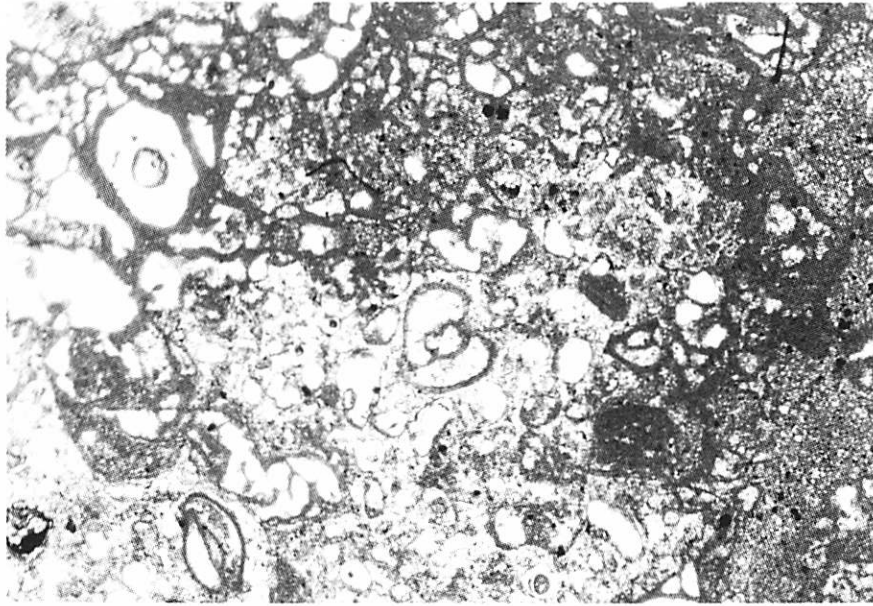


Figure 8. Photomicrograph, in plane-polarized light, of skeletal wackestone/packstone from CH 69. The presence of ostracodes and numerous small foraminifera suggest that this wackestone originated in a restricted lagoon. Field of view is 4 mm across.

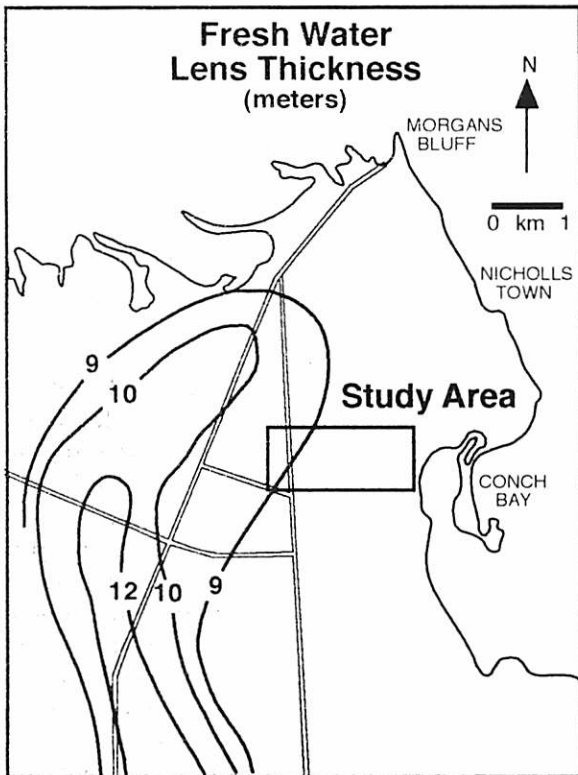


Figure 9. Thickness of the fresh-water lens on North Andros Island attains 15 m. The focus of our study is a portion of the eastern flank of the lens.

shape of the island-wide lens (Barton, 1995; Bukowski, 1996). The flow is greatest near the top of the fresh-water lens, and diminishes with depth. Flow rates and recharge considerations suggest that the residence time of groundwater near the surface is a few years.

Mineralogy

X-ray diffraction detected only aragonite and calcite in the samples of core CH 69 (Figure 10). No dolomite was detected. The upper portion of core CH 69 is dominated by aragonite (60%), but below the paleosol at 7 m, the relative amount of aragonite decreases to 0 %, (i. e., below the detection limit of the method, 2%), and the rock is 100% low-Mg calcite.

Geochemistry of the Water

Several elements were analyzed for, including Mg which showed no significant information, but the elements of interest to this study are calcium (Ca) and strontium (Sr). Ca and Sr can be derived from reactions with the rock, and from sea water. The amount of Ca added to the groundwater by dissolution of

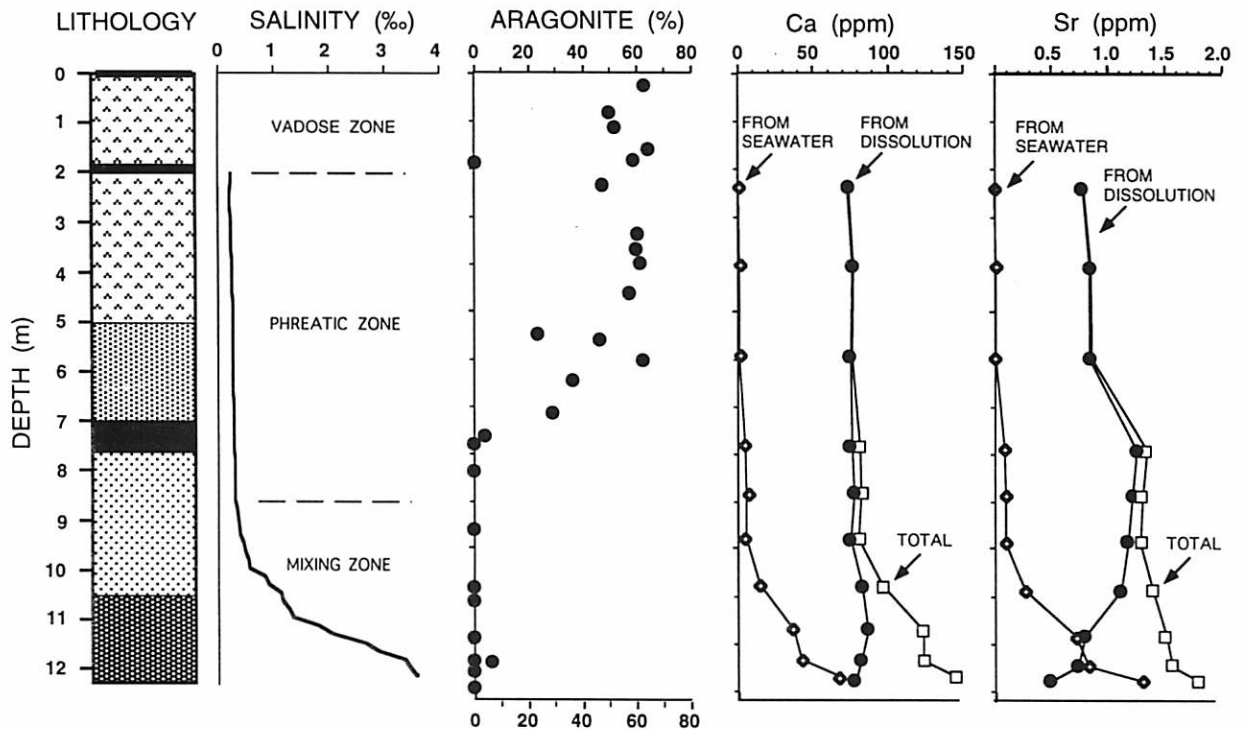


Figure 10. Vertical profiles of the geochemical characteristics of the aquifer system are compared to the lithologic profile. Conductivity was measured and recalculated as salinity. The conductivity profile (recalculated to salinity) at site CH 69 shows that the fresh-water lens (salinity < 1 ‰; Cl < 500 ppm) is ~7 m thick. Below the fresh water, the salinity increases rapidly. Aragonite is the dominant mineralogy in the upper portion of the core, while calcite comprises 100% of rock below the paleosol at 7 m depth. Ca and Sr profiles at site CH 69 show that some of the Ca and Sr comes from dissolution of aragonite and calcite, and some comes from sea water via rain or by mixing from below.

CaCO₃ is here termed excess Ca (Ca_{excess}). Ca_{excess} can be found by subtracting the Ca derived from sea water (Ca_{sw}) from the total Ca (Ca_{total}).

$$\begin{aligned} \text{Ca}_{\text{total}} &= \text{Ca}_{\text{sw}} + \text{Ca}_{\text{excess}} \\ \text{Ca}_{\text{excess}} &= \text{Ca}_{\text{total}} - \text{Ca}_{\text{sw}} \end{aligned}$$

As carbonate rocks and sediment have very little Cl, the only source of Cl in the groundwater is from sea water, either by mixing from below, or from rain. Rainwater gets its Ca, Sr, and Cl from aerosols derived from evaporation of sea spray. Thus, rainwater has the same Ca/Cl and Sr/Cl ratio as sea water. The amount of Ca derived from sea water can be calculated by multiplying the Cl concentration of the groundwater sample by the Ca/Cl ratio of sea water (= 400/19350). Similarly, the different sources of Sr can be determined.

$$\begin{aligned} \text{Ca}_{\text{from sw}} &= (\text{Ca}/\text{Cl})_{\text{sw}} \times \text{Cl}_{\text{groundwater}} \\ \text{Sr}_{\text{from sw}} &= (\text{Sr}/\text{Cl})_{\text{sw}} \times \text{Cl}_{\text{groundwater}} \end{aligned}$$

Calcium.

The total Ca in the groundwater is about 75 ppm in the fresh-water lens and increases in the mixing zone to about 150 ppm (Figure 10). There is almost no Cl in the upper portion of the ground water (fresh-water lens), thus all the Ca in this portion of the water profile (approximately 75 ppm) is in excess of that expected from a sea-water source. This "excess Ca" is derived from dissolution of CaCO₃. The vertical profile of excess Ca (i. e., from dissolution) is nearly uniform at ~75 ppm. The amount of Ca derived from a sea-water source is essentially 0 in the upper portion of the fresh-water lens and increases to 75 ppm in the upper portion of the mixing zone (i. e., doubling total Ca to 150 ppm).

Strontium.

The total Sr in the groundwater is about 1 ppm in the fresh-water lens, and increases to about 2 ppm in the mixing zone (Figure 10). There is almost no Cl in the upper portion of the groundwater (the fresh-water lens), thus all the Sr in this portion of the water profile (approximately 1 ppm) is in excess of that expected from a sea-water source. This "excess Sr" is derived from dissolution of CaCO_3 (aragonite). The vertical profile of excess Sr is not identical to that of Ca. The excess Sr rises from about 0.8 ppm in the upper portion of the fresh-water lens to about 1.2 ppm in the lower portion of the fresh-water lens. It then decreases with depth in the mixing zone to about 0.4 ppm. Excess Ca (i. e., Ca derived from dissolution of carbonates) remains nearly constant with depth in both zones. The amount of Sr derived from a sea-water source is essentially 0 in the upper portion of the fresh-water lens, and increases to 1.6 ppm in the mixing zone.

DISCUSSION

The purpose of this paper is to explore the correlations of diagenesis with composition, time of deposition, and fluctuations of sea level. Our results suggest that both primary lithology and fluctuations of sea level are significant controls on the pathway and rate of diagenesis. Because both deposition and fluctuations of sea level are episodic, diagenesis is episodic or punctuated at these time scales.

Diagenesis, Lithology, and Time

The most striking evidence of punctuated diagenesis is shown by the mineralogic distribution within core CH 69. The upper 5-6 m of the core is primarily aragonitic (~60%; Figure 10) and is composed mostly of burrow-mottled oolitic grainstone that is interpreted to have been a stabilized sand flat associated with an ooid sand shoal. This lithology lies beneath a thin paleosol surface and is presumed to have formed ~125 ka ago (oxygen isotope substage 5e) when sea level was approximately 5-6 m higher than present (Neumann and Moore, 1975; Boardman et al., 1993; Carew and Mylroie, 1995b). The portion

of the core below 7 m depth (below a thick paleosol) is 100% calcite. This duality of mineralogy suggests two stages of diagenesis. The separation of the two mineralogic units by a paleosol places the deposition of these units in at least two different time periods (Boardman et al., 1995).

In this discussion, the Joulter Cays area is used as a modern analog of the late Pleistocene rocks of Andros Island because Joulter Cays are adjacent (north) to Andros Island, and there has been substantial previous research comparing the two regions (Carney and Boardman, 1993; Boardman et al., 1993). The sediment from stabilized sand flats of Joulter Cays is 70-80% aragonite, but the Pleistocene Andros Island stabilized sand flat has approximately 60% aragonite (Figure 10); so, it has retained a high proportion of its original aragonite. These Pleistocene rocks have 10-20% less aragonite (or more calcite) than their modern counterpart, and petrologic evidence of this modification is seen in the dissolution of laminae of ooids (aragonite) and the precipitation of calcite cement (Figure 4). In the Bahamas, studies of islands of Joulter Cays (Halley and Harris, 1979) and a modern ooid sand-shoal island in Schooner Cays (Budd, 1988a, b) have suggested that there is a conservation of carbonate (stabilization) during early diagenesis (i. e., that the amount of cement is equal to the amount of carbonate dissolved from ooid laminae). Extending this idea to the petrologic features seen on Andros, we estimate that there has been a mineralogic stabilization of 14% to 25% of the available aragonite (20/80 to 10/70; aragonite loss/total aragonite) in approximately 125 ka of subaerial exposure. Is this reasonable?

Diagenesis is certainly occurring on both Andros and Joulter Cays, and rocks from Joulter Cays and Andros Island are today experiencing similar diagenetic forces (rainfall, rain chemistry, temperature, Holocene sea-level fluctuations). Rocks from the upper portion of Andros Island, as well as rocks from Joulter Cays, contain abundant petrologic evidence of dissolution of ooid laminae, and vadose and phreatic calcite cement. Also, in both areas, high Ca^{2+} concentrations in the groundwater (~70 ppm) and relatively low Ca/Sr ratios (~90 on Andros and <<20 on Joulter Cays; Figure 11) suggest dissolution of

a high-Sr aragonite, and/or selective dissolution of a higher-Sr carbonate accompanied by precipitation of a lower-Sr carbonate (Figure 12). It has been reported (Harris, 1979; Halley and Harris, 1979) that in the last 1000 years ~7% calcite has been added to the ooid sands of subaerially exposed portions of Joulter Cays, by dissolution of ooid laminae (aragonite) and re-precipitation of calcite as vadose and phreatic cements. Thus, during the past 1000 years, approximately 7% of the aragonite has been stabilized. This rate of stabilization fits exceptionally well with the aragonite stabilization curve of Budd (1988a) in which 7% stabilization is expected to occur in the fresh-water lens in approximately 600-700 years (Figure 13). According to that curve, the 125 ka old rocks of Andros Island should be completely altered to calcite; yet only 14% to 25% of the available aragonite has been converted to calcite (see above). Based on the Budd curve, stabilization of 14% to 25% is expected to take only 2000 to 3500 years

(Figure 13).

A partial resolution to this dilemma is suggested by considering the position of the fresh-water lens over time. Even though Andros Island has been subaerially exposed for approximately 125 ka longer than rocks at Joulter Cays, the rocks from the upper 5 m of Andros Island cores have contained a fresh-water lens only during the regression from the 5e highstand and again during the last ~2000-3500 years. The stabilized sand flat sediments of Andros Island are originally subtidal, and they probably did not experience subaerial exposure until sea level fell following the highstand ~125 ka ago. During that time it is likely that those rocks were within the fresh-water lens for several thousands of years, because most banana holes in the Bahamas are thought to have formed near the top of a past fresh-water lens contained in such rocks during the 5e regression (Harris et al., 1995). Although sea level fluctuated during oxygen isotope stages 5-2, there is little

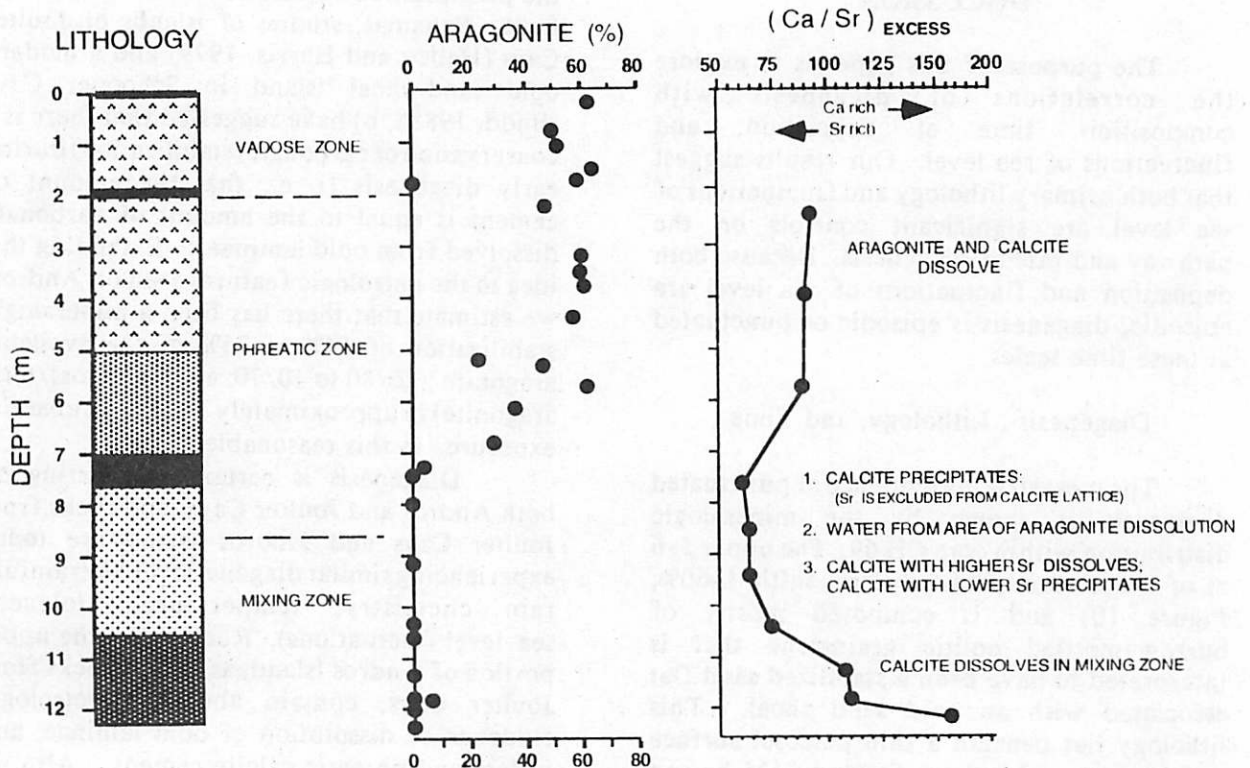


Figure 11. Vertical profiles of lithology, hydrology, mineralogy, and ratios of Ca/Sr.

ORIGINS OF Sr AND Ca IN LIMESTONE AQUIFERS

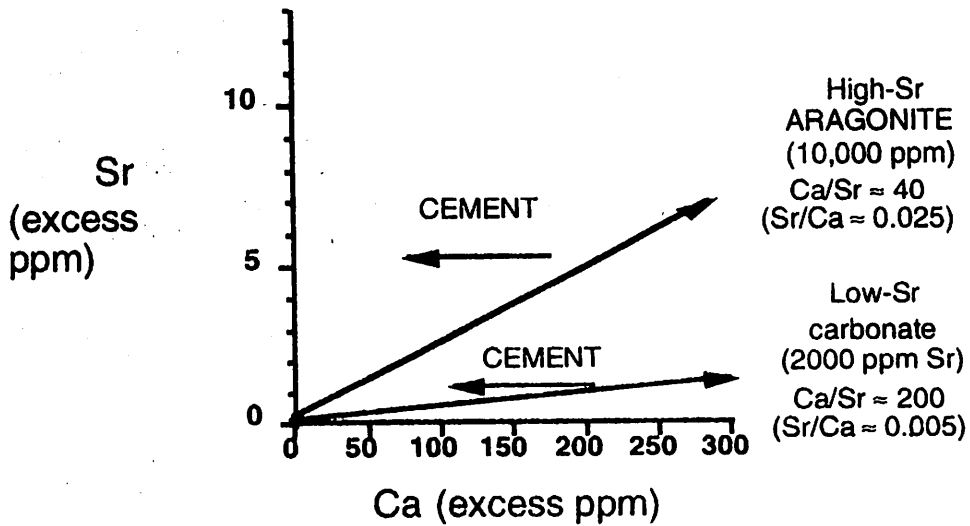


Figure 12. Origins and controls of the concentration of Ca and Sr in limestone aquifers is largely a result of the dissolution of limestone with some Sr and the precipitation of calcite with less Sr in it. Ooids, corals, and green algae have aragonite with nearly 10,000 ppm Sr. When these grains dissolve, a solution is produced with a Ca/Sr ratio of approximately 90 (or an Sr/Ca ratio of ~0.01). Dissolution of all other carbonates will produce a higher Ca/Sr ratio (lower Sr/Ca) because all other carbonates have lower concentrations of Sr in them. Typically, calcite and molluscan aragonite have <2000 ppm Sr. Precipitation of calcite excludes Sr; so, when lower ratios of Ca/Sr are found in the groundwater, it means that Ca has preferentially precipitated as CaCO_3 .

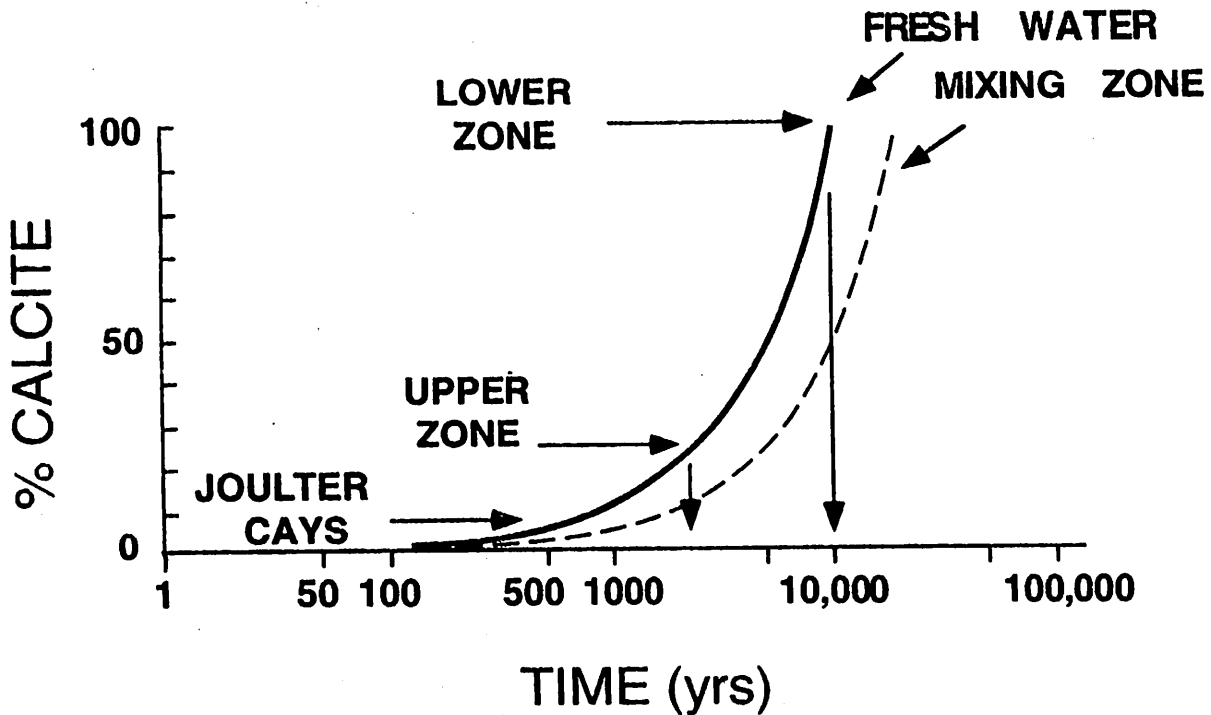


Figure 13. Alteration of aragonite to calcite (stabilization) versus time (modified from Budd, 1988). The solid line represents stabilization in a fresh-water lens. The dashed line represents stabilization in a mixing zone.

evidence to suggest that it was ever again near present level for an extended time until the Holocene (Shackleton and Opdyke, 1973; Boardman et al., 1986; but see Carew and Mylroie, 1987, for evidence of a possible short-term sea-level highstand at ~40-50 ka ago). The Holocene rise of sea level would have resulted in placement of a fresh-water lens into these upper 5 m of rock beginning about 3.5 ka ago (Fairbanks, 1989; Boardman et al., 1989). Thus, the diagenetic stage of the upper portion of this core from Andros Island suggests that it has experienced only two phreatic diagenetic events since its deposition, but it has been exposed for at least twice as long as the Buud curve would indicate is appropriate.

Using the stabilization versus time curve (Budd, 1988a), we estimate that the section of the Andros core below the paleosol, that is 100% calcite, has been in a fresh-water phreatic diagenetic system for a total of approximately 10 ka (Figure 13). Exactly when that 10 ka occurred is uncertain. We speculate that it did not include the bulk of substage-5e highstand, because at that time the area was accumulating marine sediments, and was completely submerged in marine water. However, it did experience fresh-water lens environments during the rise to, and fall from, that highstand. The sedimentary unit below the paleosol was not necessarily deposited during the stage 7 highstand, but could be much older, perhaps dating to stage 9 or 11.

Diagenesis Today

Evidence of dissolution is prevalent in all portions of the upper 12 m of the aquifer based on water samples (Figures 10, 11) and petrologic examination of the rocks. The excess Ca concentration of 75 ppm found in all water samples is many times supersaturated for both aragonite and calcite in equilibrium with atmospheric concentrations of CO₂. At atmospheric CO₂ concentrations (~350 ppm), the amount of Ca at equilibrium with calcite would be about 20 ppm. Equilibrium with respect to aragonite would be a bit higher. To dissolve 75 ppm Ca in equilibrium with calcite would require about 10,000 ppm CO₂, and in equilibrium with aragonite it would require a little less CO₂. A concentration of 10,000 ppm

CO₂ can be attained if the aquifer waters pass through an organic-rich soil zone where they pick up additional CO₂. Because of the uncertainty regarding the total CO₂, we cannot use the excess Ca concentration to indicate which carbonate phase (aragonite or calcite), if any, is in equilibrium with the aquifer solution. However, there is clear evidence that substantial dissolution is occurring.

Upper aquifer.

We can use additional details about the water chemistry and petrology to infer that aragonite is being selectively, but not exclusively, dissolved in the upper aquifer (i. e., above the paleosol that occurs at 7 m depth). Numerous investigators have observed that natural carbonates have either high Sr concentrations (~10,000 ppm) or low Sr concentrations (≤ 2000 ppm; Kinsman, 1969; Milliman, 1974; Land and Hoopes, 1973). The low-Sr carbonates include all calcite minerals plus aragonite formed by molluscs. The high-Sr carbonates include aragonite formed by corals and green algae, and in ooids. The exclusion of Sr from the calcite minerals occurs because Sr does not fit well in the lattice site reserved for a cation (Sr²⁺ has an ionic radius of 1.14 angstroms, whereas Ca²⁺ has an ionic radius of 0.99 angstroms), whereas Sr does fit well in the lattice site reserved for a cation in the aragonite structure. In high-Sr carbonates the Ca/Sr ratio is ~40, in low-Sr carbonates the ratio is ~200, and in sea water the ratio is ~50 (by convention, the trace element is the numerator and the carrier element is the denominator). If dissolution is the dominant process (i. e., cementation is negligible), we can use this difference in ratios to calculate the type of carbonate being dissolved, by the following balance:

$$\begin{aligned}
 (\text{Ca/Sr})_{\text{excess}} &= \\
 & (x) (\text{Ca/Sr from 10,000 ppm carbonate}) \\
 & + (1-x) (\text{Ca/Sr from 2000 ppm carbonate}) \\
 \\
 (\text{Ca/Sr})_{\text{excess}} &= x (40) + (1-x) (200) \\
 (\text{Ca/Sr})_{\text{excess}} &= x (40) + 200 - (200)x \\
 (\text{Ca/Sr})_{\text{excess}} - 200 &= x (40 - 200) \\
 (\text{Ca/Sr})_{\text{excess}} - 200 &= x (-160) \\
 ((\text{Ca/Sr})_{\text{excess}} - 200) &= x \\
 \hline
 & -160
 \end{aligned}$$

where x is the fraction of the sample that is the 10,000 ppm variety of carbonate with a Ca/Sr ratio of 40. These ideas are graphically displayed in Figure 12.

The Ca/Sr ratio in the upper portion of the aquifer is about 90 (Figure 11). From this ratio, we estimate that the type of carbonate being dissolved in the upper portion of the fresh-water zone is mostly the high-Sr variety ($\approx 70\%$), the rest being a low-Sr variety of carbonate (mollusc aragonite and/or calcite). As only 60% of the rock of the upper aquifer is aragonite (the more soluble polymorph of carbonate), there must be some selectivity of dissolution. Many of the ooids have missing laminae (Figure 4) which are interpreted to be the result of selective dissolution. Furthermore, although most of the aragonite can be petrologically accounted for in the form of ooids (high-Sr aragonite), some of the aragonite is molluscan (low-Sr aragonite), and some aragonite may be in the form of peloids. Clearly, ooids are selectively being dissolved, and it may be that the rest of the material being dissolved (the 30% of low-Sr carbonate) is all aragonite from molluscs (and perhaps peloids) or a combination of low-Sr aragonite and calcite.

Middle aquifer.

In the area immediately below the paleosol at 7 m depth, the Sr concentration increases to ~ 1 ppm (Figure 10) and the Ca/Sr ratio decreases to about 60 (Figure 11). In contrast to the overlying portion of the aquifer, this geochemical signature cannot be directly linked to dissolution of the local rock, because the local rock is 100% calcite, and when dissolved, calcite should produce a high Ca/Sr ratio (~ 200 or greater) and a low Sr value (~ 0.4 ppm). A logical way to get a lower Ca/Sr ratio is to selectively precipitate Ca, and selectively exclude Sr from the precipitated solid, which is the process expected for precipitation of calcite cement. The distribution coefficient for Sr precipitating into calcite is ~ 0.06 (Katz et al., 1972), which means that the ratio of Sr/Ca going into calcite will be 6% of the ratio of Sr/Ca in the water; so, Sr in the water will increase relative to Ca.

It is remarkable that the Sr in the solution is higher than in the aragonitic aquifer above it. There are two ways to get a high Sr

concentration: 1) dissolution of a rock with high Sr values, and/or 2) repeated/continuous dissolution of a low-Sr host rock and precipitation of an even lower-Sr carbonate cement. If dissolution alone caused the Sr values and Ca/Sr ratios, 87% of the material dissolved would have to have been high-Sr carbonate. Even dissolution of the upper aquifer would be unlikely to yield this signature. We suggest that precipitation of calcite is occurring, or has occurred, in order to have created this geochemical signature. Petrologically, this region is the best-cemented portion of the aquifer.

Lower Aquifer.

From the top of the mixing zone (~ 8.5 m from the surface) to the base of the cored interval, the amount of excess Sr decreases from 1 ppm to < 0.5 ppm; while excess Ca remains constant, and the Ca/Sr ratio increases to 170. This suggests that a low-Sr carbonate (calcite) is being dissolved within the mixing zone. The salinity in this region increases from 0.5 ‰ to ~ 3.5 ‰ (salinity of 3.5 ‰ corresponds to a mixture of 10% sea water and 90% fresh water). Several studies have demonstrated that there is increased dissolution in the fresh-water/marine mixing zone (Back and Hanshaw, 1970; Hanshaw and Back, 1979; Back et al., 1986; Mylroie and Carew, 1988, 1990). Quantitative geochemical studies indicate that calcite should dissolve in a mixture of 10% sea water and 90% fresh water. Even though the fluids may be saturated with respect to both aragonite and calcite in the fresh water, when fresh water is mixed with sea water, the resulting fluid can be under saturated with respect to both calcite and aragonite. As there is no aragonite in the region of the mixing zone, calcite dissolves. The Ca/Sr ratio of calcite is often ≥ 200 ; hence the Ca/Sr ratio in the water that dissolves this limestone goes up. In the mixing zone, the Ca/Sr ratio increases from 70 (at a salinity of 1.5‰) to 156 (at a salinity of 3.5‰).

Summary of Diagenetic Processes.

What the petrologic, geochemical, hydrologic, and geotechnical data suggest is that rain enters the aquifer and selectively dissolves high-Sr aragonite in the upper portion of the fresh-water lens (above the

paleosol at 7 m depth). Some precipitation of calcite may be occurring, but the geochemical evidence suggests only selective dissolution of aragonite. Water below the paleosol is derived from above, but moves more slowly. Cementation by calcite occurs below the paleosol causing the Ca/Sr ratio to decrease. In the current mixing zone, dissolution of calcite appears to be occurring.

Diagenesis and Age

The upper 12 m of Andros Island consists of rocks that exhibit two distinct stages of diagenesis, with a small intermediate zone separating them. The lower zone is 100% calcite, and the upper zone is approximately 40% calcite (60% aragonite). Clearly, the older (lower) limestone unit has undergone greater diagenesis than the upper limestone unit. The water chemistry indicates that several processes are presently occurring which are causing an overall decrease in aragonite and an increase in calcite. These diagenetic processes are linked to the position and thickness of the modern fresh-water lens and mixing zone.

The geochemistry of the groundwater in these two units from Andros (Pleistocene) can be compared to Joulter Cays, a modern ooid sand shoal (~1000 years old), and to data from

the Yucatan Peninsula, a Miocene limestone. A plot of Sr vs Ca shows that the groundwater of each of these limestones has a distinct Ca and Sr concentration (Figure 14). The solutions contain Ca concentrations of 20 to 80 ppm, which is what is expected from a limestone in equilibrium with CO₂ concentrations ranging from atmospheric values (PCO₂ = 10^{-3.5}) to ones which have been increased by reaction within soils (e. g., PCO₂ = 10⁻²).

The Joulter Cays samples have relatively high concentrations of Sr because the Joulter Cays rock is composed primarily of high-Sr aragonite ooids. The low Ca/Sr ratio suggests that substantial dissolution is occurring, followed by precipitation of calcite cement. Thus, the Sr concentration rises; yet the Ca concentration remains at values near saturation with respect to calcite.

Andros samples have much lower concentrations of Sr than Joulter's samples. Dissolution of these rocks in the fresh-water phreatic zone adds Sr, and the Ca/Sr ratios suggest precipitation of calcite in the lower portion of the fresh-water lens and the upper portion of the mixing zone. Thus, mineralogic stabilization is occurring at the present time, and it is incomplete.

The water samples from the Yucatan

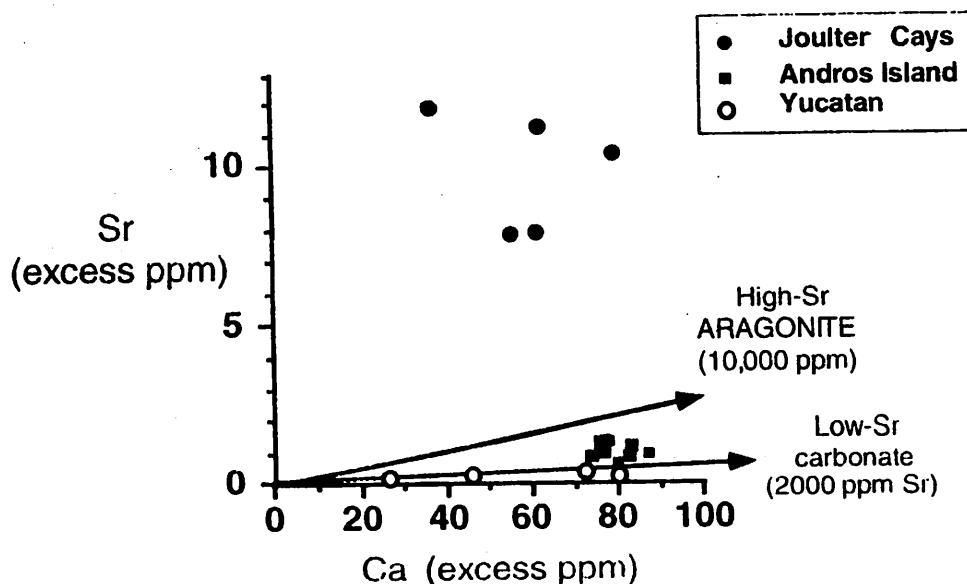


Figure 14. Sr versus Ca for water samples from three regions with carbonate rocks of different ages. The Ca/Sr ratio increases from a low of ~5-10 for Joulter Cays (Holocene) to a high of >200 for the Yucatan Peninsula (Miocene).

have slightly lower concentrations of Sr than those from Andros. The Yucatan rocks are entirely calcite, and the water chemistry resulting from their dissolution has a Ca/Sr ratio which is what would be expected for samples of water from a rock that is all calcite.

The decrease of Sr, and increase of the Ca/Sr ratio of diagenetic solutions reflects the diagenetic stabilization of the rocks. The clumping of the groundwater geochemistry is correlated with age of the rock, and suggests that diagenetic stabilization is a step-wise process.

SUMMARY

The principle mechanism controlling both the mineralogic stabilization and trace-element diagenesis of the carbonates studied is the intensity and duration of diagenetic processes in the fresh-water vadose, fresh-water phreatic, and mixing-zone environments. As the fresh-water lens rises and falls with sea level fluctuations, the duration of fresh-water diagenesis depends on the rates of sea-level change and the duration of sea-level stillstands. Likewise, the duration of vadose diagenesis is linked to sea-level fluctuations.

Although the difference in age between Joulter Cay rocks and the upper portion of the Andros aquifer is ~125 ka, there is a much smaller difference in the duration of fresh-water diagenesis, because the upper part of Andros Island did not experience fresh-water phreatic diagenesis during most of the time between deposition and today, because sea level, and the fresh-water lens, was below these rocks during this time. Only during the last few thousand years has a fresh-water lens been situated near its present position; so, the upper section of Andros Island has experienced fresh-water phreatic diagenesis for only the past 2000-3500 years. Apparently, the rocks below the paleosol at 7 m depth have experienced greater diagenesis (more steps) than the rocks above this thick paleosol, most likely indicating that those rocks are older than 125 ka.

REFERENCES

- Back, W. and Hanshaw, B. B., 1970, Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatan: *Journal of Hydrology*, v. 10, p. 330-368.
- Back, W., Hanshaw, B. B., Herman, J. S. and Vandriel, J. N., 1986, Differential dissolution of a Pleistocene reef in the ground-water mixing zone of coastal Yucatan, Mexico: *Geology*, v. 14, p. 137-140.
- Barton, D. H., 1995, Aquifer characteristics and ground water flow in a Pleistocene karst terrain, Andros Island, Bahamas: M.S. Thesis, Wright State University, Dayton, OH. 159p.
- Boardman, M. R., Carney, C. K. and Bergstrand, P. M., 1993, A Quaternary analog for interpretation of Mississippian oolites: *American Association of Petroleum Geologists, Studies in Geology #35, Mississippian oolites and modern analogs*, p. 227-241.
- Boardman, M. R.; McCartney, R. F. and Eaton, M. R., 1995, Bahamian paleosols: origin, relation to paleoclimate, and stratigraphic significance, in Curran, H. A. and White, B., eds., *Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300*, p. 33-49.
- Boardman, M. R., Neumann, A. C., Baker, P. A., Dulin, L. A., Kenter, R. J., Hunter, G. E. and Keifer, K. B., 1986, Banktop responses to Quaternary fluctuations of sea level recorded in periplatform sediments: *Geology*, v. 14, p. 28-31.
- Boardman, M. R.; Neumann, A. C. and Rasmussen, K. A., 1989, Holocene sea level in the Bahamas, in Mylroie, J. E., ed., *Proceedings of the Fourth Symposium on the Geology of the Bahamas: San Salvador, Bahamian Field Station*, p. 45-52.
- Back, W. and Hanshaw, B. B., 1970,

- Braithwaite, C. J. R., 1983, Calcrete and other soils in Quaternary limestones: structures, processes and applications: *Journal of the Geological Society of London*, v. 140, p. 351-163.
- Brand, U. and Veizer, J., 1980, Chemical diagenesis of a multicomponent carbonate system - I: Trace elements: *Journal of Sedimentary Petrology*, v. 50, p. 1219-1236.
- Budd, D. A., 1988a, Aragonite-to-calcite transformation during fresh-water diagenesis of carbonates: Insights from pore-water chemistry: *Geological Society of America Bulletin*, v. 100, p. 1260-1270.
- Budd, D. A., 1988b, Petrographic products of freshwater diagenesis in Holocene ooid sands, Schooner Cays, Bahamas: *Carbonates and Evaporites*, v. 3, p. 143-163.
- Budd, D. A. and Land, L. S., 1990, Geochemical imprint of meteoric diagenesis in Holocene ooid sands, Schooner Cays, Bahamas: correlation of calcite cement geochemistry with extant groundwaters: *Journal of Sedimentary Petrology*, v. 60, p. 361-378.
- Bukowski, J. M., 1996, Modeling the fresh water - salt water interface in the Pleistocene aquifer on Andros Island, Bahamas: M.S. Thesis, Wright State University, Dayton, OH. 106p.
- Carew, J. L. and Mylroie, J. E., 1987, A refined geochronology for San Salvador Island, Bahamas, *in* Curran, H. A., ed., *Proceedings of the Third Symposium on the Geology of the Bahamas: San Salvador, Bahamian Field Station*, p. 31-60.
- Carew, J. L. and Mylroie, J. E., 1995a, Depositional model and stratigraphy for the Quaternary geology of the Bahama islands, *in* Curran, H. A. and White, B., eds., *Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300*, p. 5-31.
- Carew, J. L. and Mylroie, J. E., 1995b, Quaternary tectonic stability of the Bahamian archipelago: Evidence from fossil coral reefs and flank margin caves: *Quaternary Science Reviews*, v. 14 (2), p. 145-153.
- Carney, C. K. and Boardman, M. R., 1993, Trends of sedimentary microfabrics of ooid tidal channels and deltas, *in* Rezak, R. and Lavoie, D., eds., *Carbonate Microfabrics: Frontiers in Sedimentary Geology: Amsterdam, Springer-Verlag*, p. 29-39.
- Cowles R. M., 1992, Resistivity of Andros Island, Bahamas: M.S. Thesis, Wright State University, Dayton, OH. 129p.
- Fairbanks, R. G., 1989, A 17,000 year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation: *Nature*, v. 342, p. 637-642.
- Friedman, G. M., 1964, Early diagenesis and lithification in carbonate sediments: *Journal of Sedimentary Petrology*, v. 34, p. 777-813.
- Friedman, G. M., 1969, Trace elements as possible environmental indicators in carbonate sediments, *in* Friedman, G. M., ed., *Depositional Environments in Carbonate Rocks: Society of Economic Paleontologists and Mineralogists Special Publication 14*, p. 193-200.
- Friedman, G. M., 1975, The making and unmaking of limestones or the downs and ups of porosity: *Journal of Sedimentary Petrology*, v. 45, p. 379-398.
- Gavish, E. and Friedman, G. M., 1969, Progressive diagenesis in Quaternary to late Tertiary carbonate sediment - sequence and time scale: *Journal of*

- Sedimentary Petrology, v. 39, p. 980-1006.
- Halley, R. B. and Harris, P. M., 1979, Fresh-water cementation of a 1,000-year-old oolite: *Journal of Sedimentary Petrology*, v. 49, p. 969-988.
- Hanshaw, B. B. and Back, W., 1979, Chemical mass wasting of the northern Yucatan Peninsula by groundwater dissolution: *Geology*, v. 8, p. 222-224.
- Harris, J. G., Mylroie, J. E. and Carew, J. L., 1995, Banana holes: Unique karst features of the Bahamas: *Carbonates and Evaporites*, v. 10, n. 2, p.215-224.
- Harris, P. M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal: *Sedimenta VII, The Comparative Sedimentology Laboratory, University of Miami*, 163 p.
- James, N. P., 1984, Shallowing-upward sequences in carbonates, *in* Walker, R. G., ed., *Facies Models (2nd Ed.): Geoscience Canada Reprint Series*, v. 1, Geological Society of Canada, p. 213-228.
- Katz, A., Sass, E., Starinsky, A. and Holland, H. D., 1972, Strontium behavior in the aragonite-calcite transformation: An experimental study at 40-98° C: *Geochimica et Cosmochimica Acta*, v. 36, p. 481-496.
- Kendall, G. St. C., and Schlager, W., 1981, Carbonates and relative changes in sea level: *Marine Geology*, v. 44, p. 181-212.
- Kinsman, D. J. J., 1969, Interpretation of Sr⁺² concentrations in carbonate minerals and rocks: *Journal of Sedimentary Petrology*, v. 39, p. 486-508.
- Land, L. S., 1967, Diagenesis of skeletal carbonates: *Journal of Sedimentary Petrology*, v. 39, p. 980-1006.
- Land, L. S., 1986, Environments of limestone and dolomite diagenesis: some geochemical considerations: *Colorado School of Mines Quarterly*, v. 81, p. 26-41.
- Land, L. S. and Hoops, G. K., 1973, Sodium in carbonate sediments and rocks: a possible indicator to the salinity of diagenetic solutions: *Journal of Sedimentary Petrology*, v. 43, p. 614-617.
- Land, L. S., Mackenzie, F. T. and Gould, S. J., 1967, The Pleistocene history of Bermuda: *Geological Society of America Bulletin*, v. 78, p. 993-1006.
- Machel, H. G., 1988, Fluid flow direction during dolomite formation as deduced from trace-element trends: *Sedimentary and Geochemistry of Dolostones*, v. 43, p. 115-125.
- Milliman, J. D., 1974, *Marine carbonates*: New York, Springer-Verlag, 375 p.
- Morrow, D. W. and Meyers, I. R., 1978, Simulation of limestone diagenesis - a model based on strontium depletion: *Canadian Journal of Earth Sciences*, v. 15, p. 376-396.
- Mylroie, J. E., and Carew, J. L., 1988, Solution conduits as indicators of late Quaternary sea level position: *Quaternary Science Reviews*, v. 7, p. 55-64.
- Mylroie, J. E. and Carew, J. L., 1990, The flank margin model for dissolution cave development in carbonate platforms: *Earth Surface Processes and Landforms*, v. 15, p. 413-424.
- Neumann, A. C. and Moore, W. S., 1975, Sea level events and Pleistocene coral ages in the northern Bahamas: *Quaternary Research*, v. 5, p. 215-224.
- Pingitore N. E., Jr., 1976, Vadose and phreatic diagenesis: processes, products and

- their recognition in corals: *Journal of Sedimentary Petrology*, v. 46, p. 985-1006.
- Pingitore, N. E., Jr., 1978, The behavior of Zn^{2+} and Mn^{2+} during carbonate diagenesis: theory and applications: *Journal of Sedimentary Petrology*, v. 48, p. 799-814.
- Pingitore, N. E., Jr., 1982, The role of diffusion during carbonate diagenesis: *Journal of Sedimentary Petrology*, v. 52, p. 27-39.
- Schlager, W., 1981, The paradox of drowned reefs and carbonate platforms: *Geological Society of America Bulletin*, v.
- Sealey, N. E., 1985, Bahamian Landscapes: London, Collins Caribbean, 96 p.
- Shackleton, N. J. and Opdyke, N. D., 1973, Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperature and ice volumes on a 10^5 year time scale: *Quaternary Research*, v. 3, p. 39-55.
- Vacher, H. L., 1978, Hydrogeology of Bermuda - Significance of an across-the-island variation in permeability: *Journal of Hydrology*, v. 39, p. 207-226.
- Vacher, H. L., Bengtsson, T. O. and Plummer, L. N., 1990, Hydrology of meteoric diagenesis - Residence time of meteoric ground water in island fresh-water lenses with application to aragonite-calcite stabilization rate in Bermuda: *Geological Society of America Bulletin*, v. 102, p. 223-232.
- Vacher, H. L.; Hearty, P. J., and Rowe, M. P., 1995, Stratigraphy of Bermuda: Nomenclature, concepts, and status of multiple systems of classification., *in* Curran, H. A. and White, B., eds., *Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300*, p. 271-294.
- Walker, R. G. and James, N. P., 1992, Facies models: response to sea level change: *Geological Association of Canada*, 409 p.
- Wilson, J. L., 1975, Carbonate facies in geologic history: New York, Springer-Verlag, 471 p.
- Wolfe, B. L., 1994, A geoelectric interpretation of groundwater near Charlie's Blue Hole, North Andros Island, Bahamas: M.S. Thesis, Wright State University, Dayton, OH. 141p.