Journal of Coastal Research	4	3	381–394	Charlottesville, Virginia	Summer 1988

Bioerosion of Rocky Carbonate Coastlines on Andros Island, Bahamas

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ABSTRACT

DONN, T.F. and BOARDMAN, M.F., 1988. Bioerosion of rocky carbonate coastlines on Andros Island, Bahamas. *Journal of Coastal Research*, 4(3), 381–394. Charlottesville (Virginia), ISSN 0749-0208.

Erosion of rocky carbonate coastlines has been measured and described at intertidal and supratidal locations on Andros Island, Bahamas. Rates of intertidal erosion vary from 1.8 to 2.6 m/1000 years. Supratidal erosion is measured at 0.4 m/1000 years.

Intertidal erosion creates terraces and nips which lie near low-tide level. The width of the terraces, combined with the erosion rates, suggests that sea level has been within 0.5 meters of present level for the past 1400 to 3700 years. Degradation of this coastline results in coastal retreat and an annual sediment production of 2.98 kg/m^2 which accounts for less than 1 percent of the nearby lagoon sediment.

Erosion occurs in an irregular pattern with no preferential lowering of pinnacles or pits. The activity of organisms (endolithic algae, chitons, snails, limpets, barnacles and sponges) is sufficient to account for the majority of the erosion.

ADDITIONAL INDEX WORDS: *Bioerosion; sea level; karst; limestone weathering; coastal erosion; Andros Island, Bahamas.*

INTRODUCTION

Rocky carbonate coastlines are common to many low-latitude regions of the world and are sites of mechanical, chemical and biological erosion. The combination of these processes not only produces an erosional coastal morphology, but also is the source of an undetermined quantity of carbonate sediment. The purpose of this research is to measure the rate of coastal erosion and to evaluate the relative importance of bioerosion to coastal erosion.

The morphology and processes of erosion of carbonate coastlines have been studied by many people and reviewed by FAIRBRIDGE (1968). In Bermuda, the importance of subtidal notches formed by bioerosion was stressed (NEUMANN, 1966); while intertidal terraces, nips and escarpments are apparently more common in Barbados (McLEAN, 1964), the Florida Keys (GINSBURG, 1953), Guam (EMERY, 1962), Puerto Rico (KAYE, 1959), and the coasts of Yugoslavia (SCHNEIDER and TORUNSKI, 1983). The erosional morphology of these intertidal environments is clear, but the relative importance of biological, mechanical and chemical factors controlling intertidal erosion is not clearly understood.

Biological Erosion

Bioerosion can be divided into grazing activity and boring activity. Grazing organisms rasp, bite and scrape away a thin layer of rock in order to obtain nutrition from endolithic algae. The removal of rock and algae is achieved by specialized feeding structures such as radulas in chitons, snails and limpets (LOWENSTAM, 1962a; 1962b; HICKMAN and MORRIS, 1985), beaklike jaws in parrotfish (OGDEN and BUCKMAN, 1973; OGDEN, 1977) and radially-arranged teeth in sea urchins (OGDEN *et al.*, 1973; WARME, 1977).

Boring organisms bore into the rock for stability and protection, rather than for food. Important intertidal boring organisms include sponges (NEUMANN, 1966; COBB, 1969; RUTZLER and RIEGER, 1973; FUTTERER, 1974; RUTZLER, 1975), barnacles (AHR and STANTON, 1973), endolithic algae (GOLUBIC, 1969; PERKINS and TSENTAS, 1976), and fungi

87001 received 5 February 1987; accepted in revision 10 March 1988.

(PERKINS and HALSEY, 1971; PERKINS and TSENTAS, 1976).

Bioerosion produces sediment which may be a significant contribution to the nearshore sediment budget (FUTTERER, 1974; NEUMANN and LAND, 1975; OGDEN, 1977; SCHNEIDER and TORUNSKI, 1983). In addition to the direct removal of rock and production of sediment, bioerosion also enhances the effects of mechanical erosion. This is accomplished by creating weakened sections of rock which may be easily dislodged by mechanical action (GINSBURG, 1953; AHR and STANTON, 1973).

Mechanical Erosion

Physical processes, such as wave impact and sand abrasion, should also contribute to erosion of many rocky coasts. Although this seems logical, very few field investigations have attempted to assess the effect of these factors on coastal rocks. Most studies have centered on the mechanical breakdown of sediment and skeletal grains (CHAVE, 1964; FORCE, 1969). In high-energy areas, the impact of waves alone may remove pieces of rock, but even relatively low-amplitude waves may release grains which were previously weakened by biological processes.

Chemical Erosion

Bahamian waters are supersaturated with respect to aragonite (324-494 percent) and calcite (480-745 percent; MORSE *et al.*, 1985); thus solution of continually wetted intertidal rocks is not expected. However, mixing of freshwater (40-50 percent) with sea water can cause dissolution (BACK *et al.*, 1986). Several investigators conclude that chemical solution is the dominant process of erosion in certain intertidal areas. REVELLE and EMERY (1957) suggest that in tidal pools of Bikini Atoll, nocturnal cooling of water and biological respiration cause a drop in pH which results in dissolution. FAIRBRIDGE (1968) concludes that dissolution occurs at night when respiration causes undersaturation, and precipitation occurs during the day creating a densely cemented surface. GINSBURG (1953) argues that the morphology of tidal pools is inconsistent with the idea that chemical erosion is the dominant process. Because the bottom of the pools are soaked with seawater more continuously than the walls, tidal pools should be proportionally deeper, not wider. Also, Ginsburg points out that no selective solution of aragonite takes place as would be expected because aragonite is about twice as soluble as calcite.

Purpose

The purpose of this investigation is to determine the extent and nature of erosion along the rocky shores of Andros Island, Bahamas. Specifically, the following questions are posed. What is the overall rate of erosion on intertidal rocks? What is the importance of bioerosion relative to mechanical and chemical erosion? How can excavations and sediments produced by grazing and boring organisms be recognized? What is the sequence of colonization and rate of early erosion which occurs on fresh rock surfaces? Does coastal erosion contribute significant amounts of sediment to lagoons?

METHODS

Location

Study sites were selected on Pigeon Cay and Calabash Cay, which lie along the windward shore of Andros Island, Bahamas (Figure 1). These cays are primarily rimmed by rocky shores, with interspersed beaches of foraminifera-rich sand. Although located on the windward margin of Andros Island, the water in this area is generally calm because of a well-developed barrier reef lying approximately 3 kilometers offshore. Tidal range is approximately one meter.

Measurement of Erosion

A surface profiler (DONN and BOARDMAN, 1986) was used to directly measure the rock surface in order to determine erosion rates, surface irregularity and patterns of erosion development. Most measurement sites were positioned in the middle intertidal zone and were exposed to direct wave approach. The system is designed to measure a grid of points 1.5 cm apart covering an area of approximately 2300 cm^2 (approximately 50 cm $\times$ 50 cm). A description of this apparatus and its operation can be found in DONN and BOARDMAN (1986).

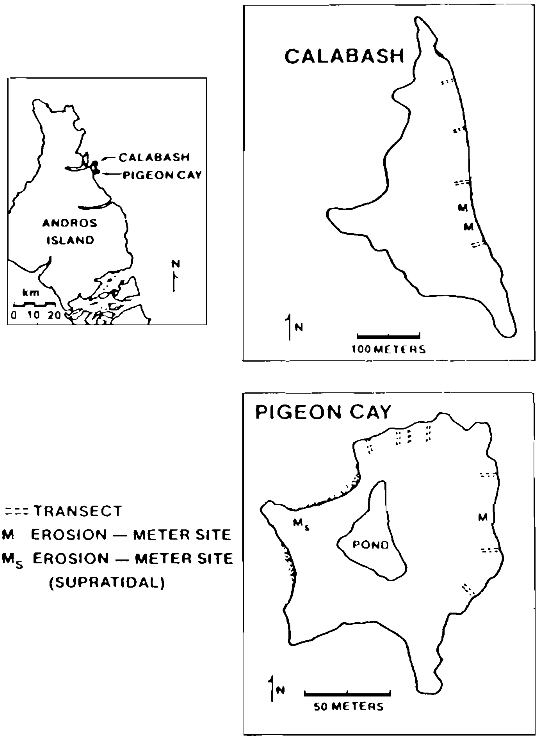


Figure 1. Location map. Pigeon Cay and Calabash are small islands on the eastern margin of Andros Island.

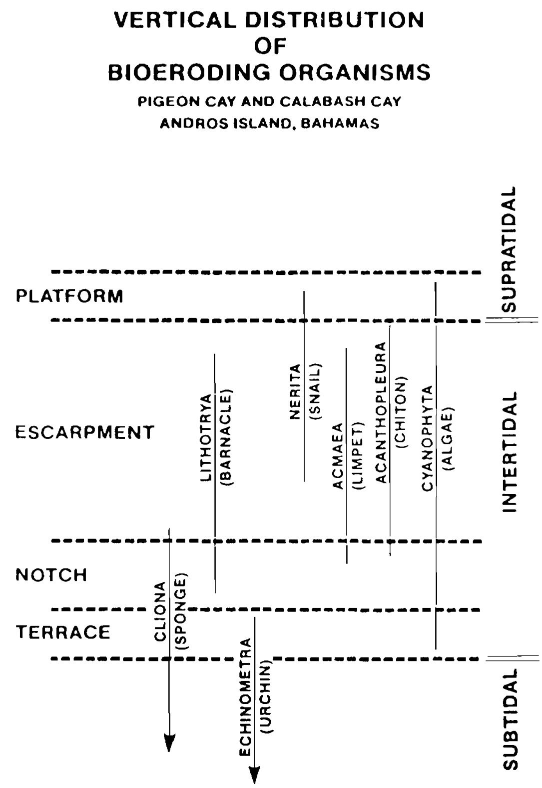


Figure 2. Vertical distribution of organisms responsible for bioerosion. Only ranges are shown here. The population densities of selected organisms are shown in Table 2.

At each site, 1020 measurements were made in May, 1984, January, 1985 and May, 1985. The differences between initial and subsequent measurements were used to obtain the overall erosion rate at each site. Computer-generated contour maps of the difference between initial and subsequent measurements were produced for each site (termed "erosion pattern" maps) to determine areas of preferential erosion.

Petrography

Microscopic examination of rock samples by light and scanning electron microscopy was used to examine and describe the detailed morphology of biological excavations.

Organism Density

The abundance and distribution of bioeroding organisms were recorded along 3 transects on Pigeon Cay. Each transect was one meter wide and included the entire surface from low to high tide level. Individual organisms were counted, and visual estimates of the percent of rock surface infested with sponges and algae were made. These data allowed computation of organism densities and distributions (Figure 2).

Cemented and Smoothed Surfaces

Sawed pieces of native limestone (porous, moderately-sorted peloidal grainstone) and Salem Limestone (Mississippian of Indiana; low porosity, moderately-sorted, foraminiferal grainstone) were cemented onto the intertidal area with quick-setting hydraulic cement in May, 1984. They were sampled in January, 1985, and May, 1985, to observe how initial erosion and colonization occurs on rock surfaces during the first year of exposure. Also, *in-situ* limestone surfaces were smoothed with a por-

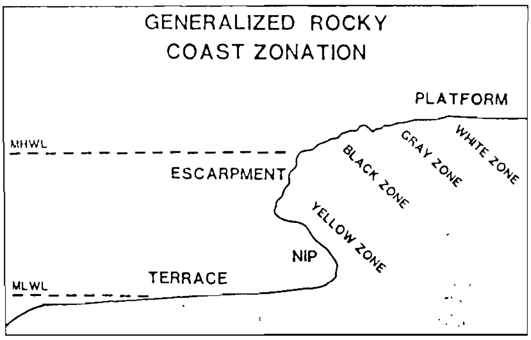


Figure 3. Coastal morphology of a typical rocky coastline in the study area.

table saw to observe erosional development and colonization.

RESULTS

Coastal Morphology

The coastal morphology of the study area is similar to that of many low-latitude carbonate regions (FAIRBRIDGE, 1968). A typical morphology includes a well-developed terrace, nip, escarpment and supratidal platform (Figure 3). The low-tide terrace is up to eight meters wide and is commonly covered by the red alga *Goniolithon*, and riddled with the interconnected borings of the sea urchin *Echinometra lucunter*. An intertidal nip exists along most of the coast and is most pronounced between low and middle tide level. It is usually incised one meter or less. The escarpment measures approximately one meter in height and consists of sharp, irregularly-shaped depressions and pinnacles. A yellowish-gray color is characteristic of the lower and middle portion of the escarpment, while the upper 20-30 centimeters is a blackened surface. This black color extends into the supratidal platform as far landward as the limit of seawater splash and spray. The supratidal platform is relatively flat, with a width ranging from 1-2 meters in protected areas, to over 7 meters in areas of higher wave energy.

Erosion Rates

The overall rate of coastal erosion was measured at 3 intertidal and 1 supratidal locations. The average erosion rate for the intertidal sites is 2.2 mm/yr (Table 1). The supratidal site underwent a markedly lower rate of erosion (0.4 mm/yr) than the intertidal sites (Figure 4b). Erosion pattern maps (Figure 4a and 4b) show that an appreciable irregularity or spatial variation of erosion takes place on each surface.

Biological Traces

Traces of the chiton *Acanthopleura granulata* are short, subparallel furrows measuring approximately 130 microns wide, 450 microns long and a few tens of microns deep (Figure 5). On a larger scale, chiton traces appear as light colored homing pits which measure up to 10 cm deep, but are commonly 1 to 2 cm. Because chitons are mobile during the night and remain in their pit during the day (GLYNN, 1970; MOOK, 1983), the pit's surface is rasped and deepened to a greater extent than surrounding surfaces. The chiton's erosive activity also creates sediment in the form of fecal pellets which are primarily comprised of carbonate rock grains (Figure 6a), the material which remains after algal tissue has been digested. Individual grains within the fecal pellets are tiny blocks 3 to 10 microns in diameter with slightly rounded edges (Figure 6).

The grazing snail *Nerita* is more abundant than the chiton; existing from the middle intertidal zone to the blackened, seaward portion of the supratidal platform (*cf* Figure 2). The rock particles comprising *Nerita*'s fecal pellets are similar in morphology and size to those of chitons.

The grazing limpet *Acmaea sp.* is found in the middle and upper intertidal zone and is common, but less abundant than *Acanthopleura* and *Nerita*. As with the chiton, *Acmaea* has a homing instinct which leads to the formation of shallow scars of less than 1 cm in depth. SEM examination of these scars reveals furrows similar to those of chitons (about 30 microns wide, 110 microns long and a few 10s of microns deep.

Endolithic cyanophyta bore into the upper surface of rock. The micro-borings measure from 5 to 15 microns in diameter (Figure 7a), and the density of algal boring decreases rapidly away from the surface of the rock, with maximum density observed in the upper 0.4 mm (Figure 7b). Some borings reach to depths of up

Table 1. *Results of surface profiling of four stations. Stations 1, 2 and 3 are intertidal, and station 4 is a supratidal station. Surfaces were measured 3 times (May, 1984; January, 1985; and May, 1985). The standard deviation of measurements is shown in parenthesis. The overall erosion rates are shown in the far right column.*

	SURFACE LOWERING (mm)		MEAN MEASUREMENT (cm) (STD. DEV. (cm))			EXPOSURE TIME (days)		EROSION RATE (mm/yr)		(OVERALL)
STN.	5/84-1/85	1/85-5/85	5/84	1/85	5/85	5/84-5/85	1/85-5/85	5/84-1/85	1/85-5/85	5/84-5/85
1	1.4	0.7	50.96 (4.88)	51.10 (4.88)	51.17 (4.85)	219	132	2.3	1.9	2.2
2	1.5	1.0	45.62 (2.92)	45.77 (2.94)	45.87 (2.93)	219	131	2.6	2.8	2.6
3	1.3	0.4	36.98 (3.48)	37.11 (3.48)	37.15 (3.44)	215	136	2.2	1.1	1.8
4	− 0.1	0.5	34.71 (1.93)	34.70 (1.92)	34.75 (1.93)	215	133	− 0.2	1.4	0.4

to 1.0 mm (based on thin-section and SEM observations).

The boring sponge *Cliona* thoroughly perforates much of the rock surface in the lower intertidal zone (*cf* Figure 2). Their excavations, which penetrate several centimeters, are individual galleries interconnected by narrow passageways (NEUMANN, 1968). The walls of each gallery are sculpted by many rounded, pitted surfaces which represent the sites where individual grains or "chips" were excavated (RUTZLER and RIEGER, 1973). Sponge chips are easily identified by their characteristic shape (FUTTERER, 1974), possessing one large convex surface and several smaller concave surfaces.

The final bioeroder investigated in this study is the barnacle *Lithotrya dorsalis*. This organism has a patchy distribution and is found in the lower and middle intertidal zones (*cf* Figure 2). Their borings are ellipsoidal and elongate, measuring 0.2 to 0.8 cm in maximum cross-sectional diameter and 1 to 4 cm deep. The walls are comprised of abraded grains and often possess a strip of carbonaceous plates or discs which were secreted by the peduncle (AHR and STANTON, 1973) and served as holdfasts. Sediment resulting from the creation of these excavations was not obtained; however based upon wall smoothness and the method of boring, it is expected that clay-sized grains are being produced (AHR and STANTON, 1973).

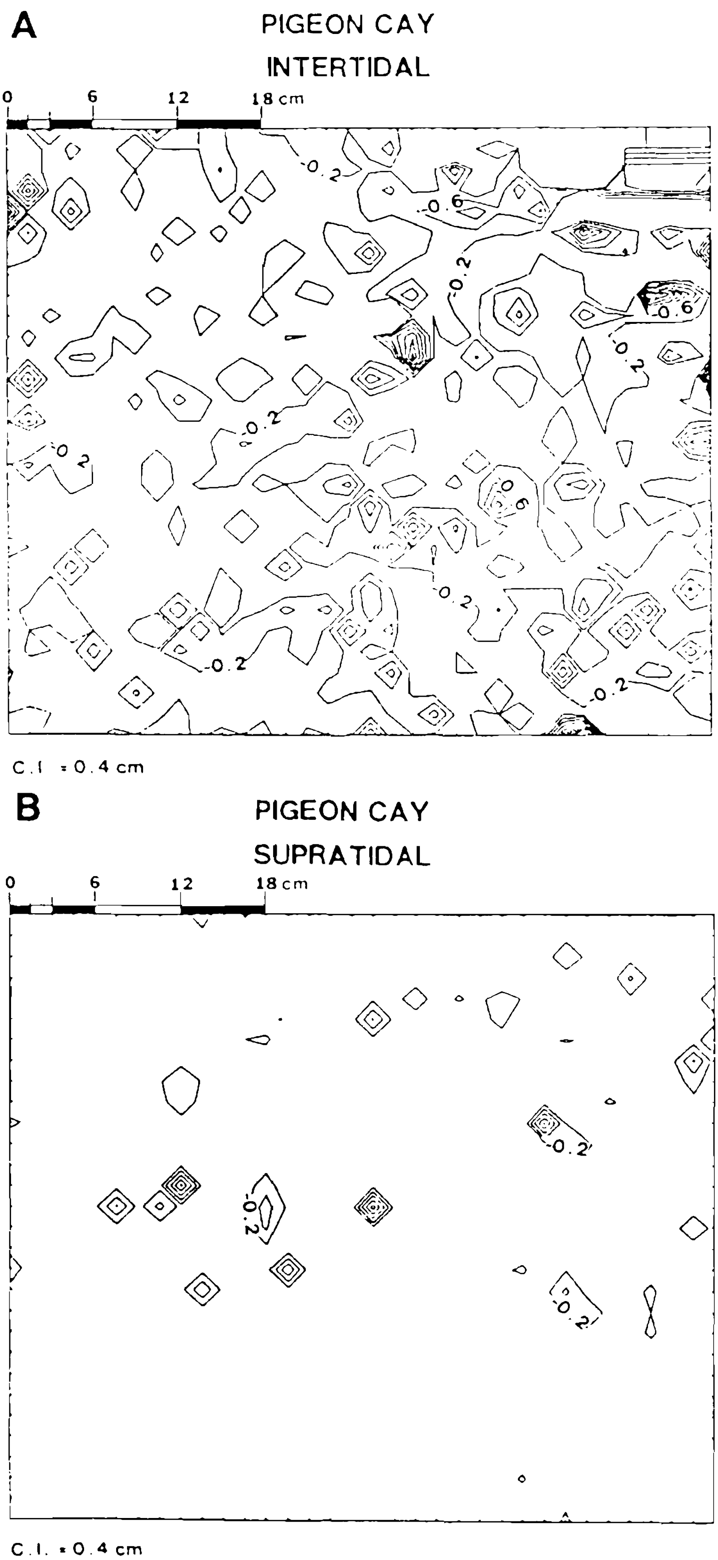
Initial Erosion

After a full year of exposure, the cemented blocks of native limestone and Salem Limestone displayed only minor boring activity by endolithic algae, and no grazing marks were found on any of the blocks. The smoothed, *in-situ* surfaces were also colonized by endolithic cyanophyta, and similarly showed no animal-produced scrapings or macroscopic borings. The only appreciable erosion was mechanical erosion found in a single locality where the sharp corners on a block of Salem Limestone were thoroughly rounded.

DISCUSSION

Erosion Rates

Retreat of the three intertidal escarpment surfaces is occurring at an average rate of 2.2 mm/yr (range = 1.8 to 2.6 mm/yr) which is comparable with results obtained by workers in other areas. A micro erosion-meter, described by HIGH and HANNA (1970), was used by TRUDGILL (1972) to measure coastal erosion on Aldabra Atoll, Indian Ocean. He recorded rates of intertidal erosion of 1.0-1.5 mm/yr on sheltered shores and 2.0-4.0 mm/yr on more exposed shores. SCHNEIDER and TORUNSKI (1983) used a modified version of the micro erosion-meter and measured rates of intertidal erosion of 0.1-1.1 mm/yr on limestone coasts of the northern Adriatic. The highest rates were near mean low-tide level, with decreasing rates of erosion toward the upper intertidal zone. HODGKIN (1964) reports that intertidal notch formation occurs at 1 mm/yr in eolian calcarenites. Massive, better-cemented limestone used as building material in Tripoli displays minor erosion after being exposed to intertidal


A
PIGEON CAY
INTERTIDAL
0
6
12
18 cm
-0.2
-0.6
-0.2
-0.6
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-0.2
C.I = 0.4 cm
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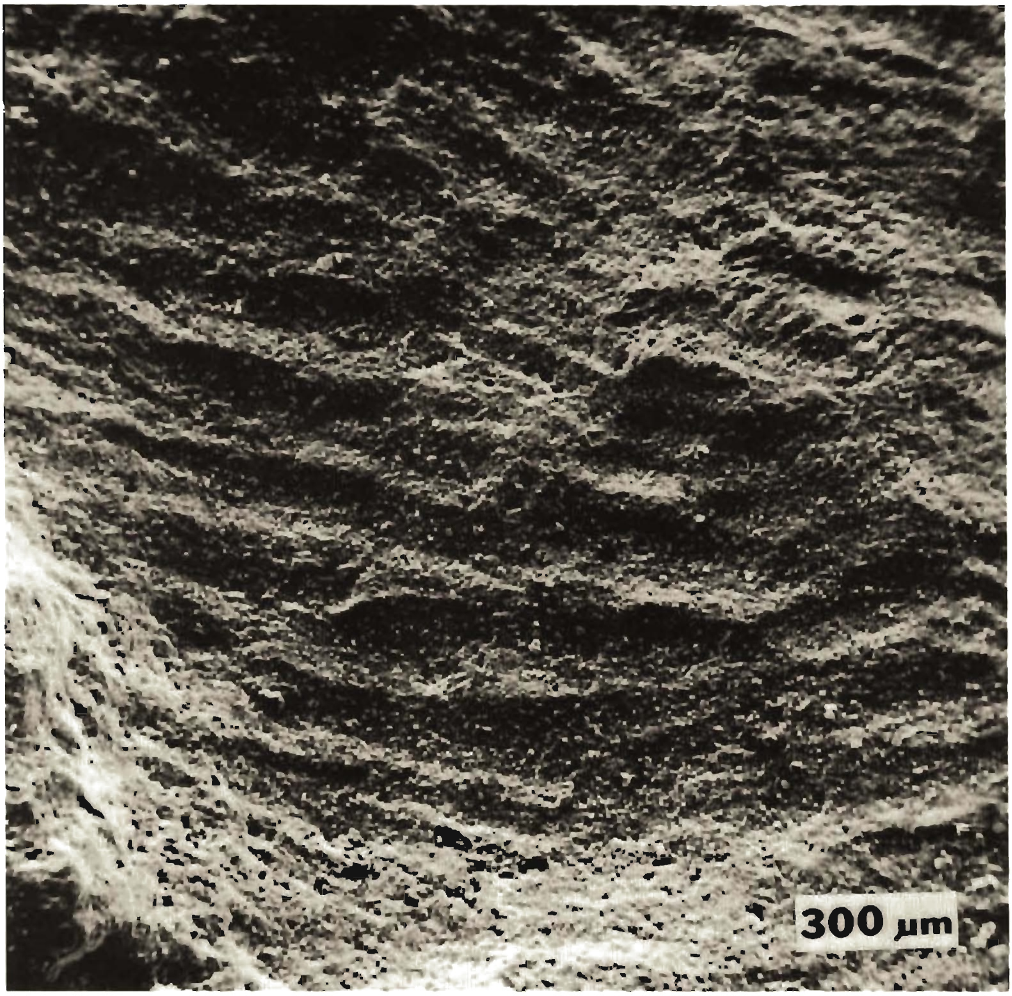

Figure 5. SEM photo of grazing furrows produced by the chiton, *Acanthopleura sp.* This surface is from a homing site of the chiton.

conditions for over 1000 years (FAIRBRIDGE, 1968). Thus, the results from Andros Island's shores appear to correspond well with the rates of intertidal erosion that have been determined in these other studies.

Terraces and Sea Level

The widths of low-tide level terraces along with the measured rate of escarpment retreat provide a means to estimate the duration of present sea level. The terraces found along the shores of Calabash Cay and Pigeon Cay measure from 3 to 8 meters wide. By dividing the terrace width by the erosion rate (2.2 mm/yr = 2.2 m/1000 yr) we estimate that sea level has been at its present position for the last 1400 to 3700 years. Basal peat from a 1.5 m core of the lagoon surrounding the study area yields a C-14 date of 3750 years BP and marine shells 10 cm above this peat yields a C-14 date of 3210

Figure 4. Erosion pattern maps. Contour interval is 0.4 mm. Contours are the differences between measurements made in May, 1984, and May, 1985. All values are negative indicating erosion. (A) Intertidal erosion pattern from Pigeon Cay. (B) Supratidal erosion pattern from Pigeon Cay. (*Facing page*).

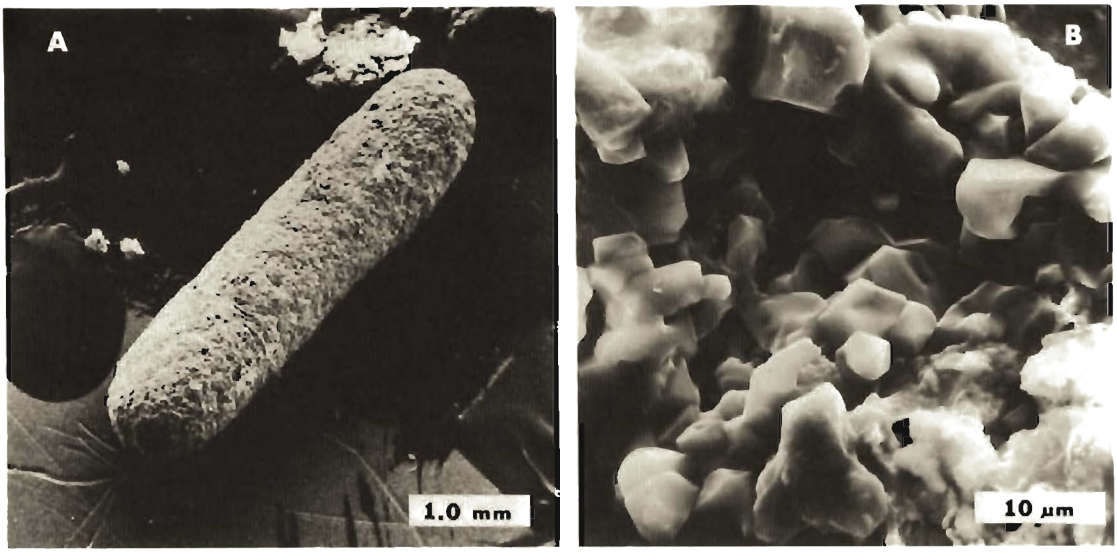

Figure 6. SEM photo of a fecal pellet of the chiton, *Acanthopleura sp.* (A) illustrates the regular, elongate nature of the pellets. (B) illustrates that the composition of the pellets is comprised of blocky grains with slightly rounded edges.

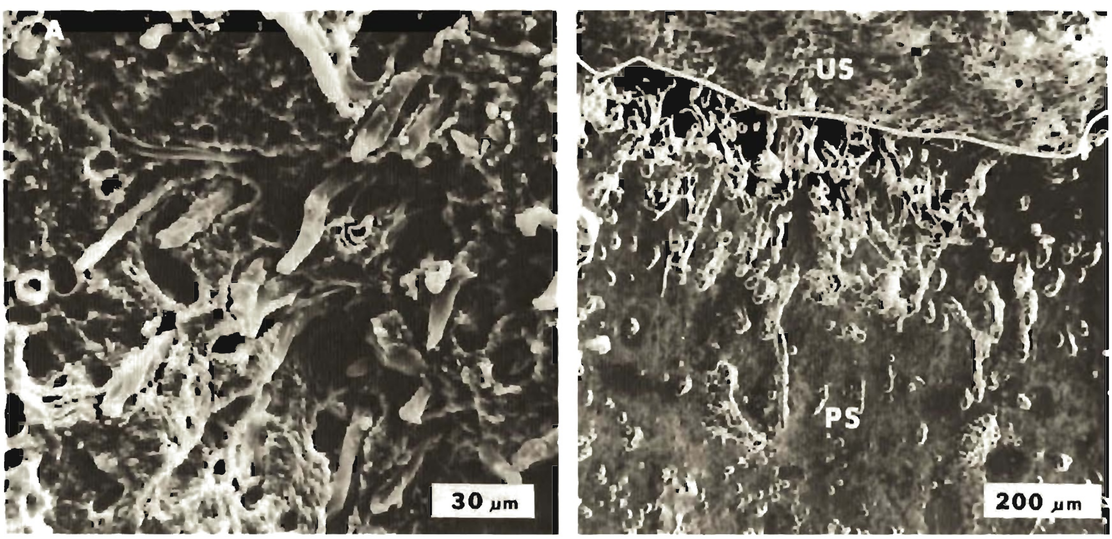

Figure 7. SEM photos of boring traces of endolithic algae. (A) shows desiccated filaments within borings. (B) illustrates the depth zonation of boring. This sample from the intertidal region was cut and polished. The upper surface of the rock "US" is densely pitted. The polished surface of the rock "PS" shows that the upper 400 µm contains vertical and horizontal borings; whereas the lower section displays mostly horizontal borings. The porosity of the upper surface is greatly enhanced by boring.

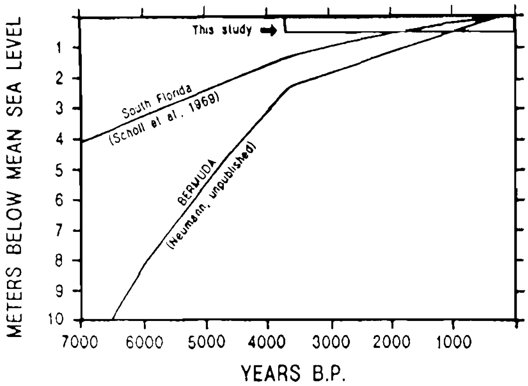

Figure 8. Comparison of two sea-level curves with data from eastern Andros. Terrace formation could have begun within 0.5 meters of present sea level 3700 years ago, and was certainly occuring 1400 years ago. A typical sedimentary sequence from a nearby lagoon suggests sea level was at −1.5 meters between 3750 and 3210 years BP.

years BP indicating that sea level was within 1.5 meters of its present position 3210 to 3750 years BP on this part of Great Bahama Bank (Figure 8). Our estimate of the duration of present sea level (1400-3700 years) derived from terrace development and C-14 dates of lagoonal material is compatible with smoothed sea-level curves recorded for southern Florida (SCHOLL *et al.*, 1969) and for Jamaica (DIGERFELDT and HENDRY, 1987). The rapidly oscillating interpretation of late Holocene sea level for Florida (FAIRBRIDGE, 1974) is also compatible with intertidal terrace development measured in this study. The Bermuda sea-level curve (NEUMANN, 1972) is not compatible with our data (Figure 8).

Significance of Bioerosion

Bioerosion is an important processes of coastal limestone degradation (GINSBURG, 1953; NEUMANN, 1968; FAIRBRIDGE, 1968). Pits, borings and scratches (furrows) occupy virtually every rock surface, and fecal pellets are readily apparent in the upper intertidal zone. Occasional storm waves, as well as the normal low amplitude waves of the region dislodge and remove various-sized particles which were previously weakened by biochemical or biomechanical processes.

Endolithic cyanophytes occupy all intertidal surfaces and contribute significantly to intertidal erosion. Our SEM studies suggest that approximately 50 percent of the outer 400 μm may be removed by endolithic algal boring (*cf* Figure 7).

Feeding on endolithic algae are grazers, and studies of molluscan grazing patterns show that considerable distances can be traveled while feeding. Chitons in moderate-energy zones traveled significantly farther (6-65 cm) from their home than chitons in lower energy zones (2-30 cm; MOOK, 1983). The distance of nighttime excursions by limpets is as great as 1.5 meters from homesites (STEPHENSON, 1936).

The amount of substrate removed by grazing organisms has been monitored through several studies. GLYNN (1973) reports that erosion by the chiton *A. granulata* results in a surficial planation of approximately 0.18 mm/yr. This is 8.2 percent of the average total planation of 2.2 mm/yr measured by us. McLEAN (1964; 1967) measured annual erosion rates of beach rock by *Nerita versicolor* (2.4 g/yr), *N. peloronta* (8.0 g/yr), *Acmaea* (2.4 g/yr), and *Acanthopleura* (22.0 g/yr). If we apply our estimate of 50 percent porosity in the grazed layer of rock and our estimates of the density of organisms (Table 2), *Acanthopleura* accounts for 9.6 percent of the annual planation; while *Nerita* and *Acmaea* combined cause less than 5 percent (Table 2). The agreement between GLYNN (1973) and McLEAN (1964) is excellent if our data is used in the conversion.

This erosion is only the final stage of intertidal erosion. Prior to grazing, extensive boring has usually occurred. Boring organisms, including *Cliona* and *Lithotrya* bore extensively in the lower intertidal zone. *Lithotrya* borings are non-existent in some locations, while in other, apparently identical settings, their abundance (greater than 70/m^2) greatly reduces the structural integrity of the substrate. *Cliona* perforations cover about 38 percent of the lowermost portion of the intertidal zone and extend up onto the escarpment in shaded areas which experience less desiccation (Figure 2). The profound effect which these sponges have upon limestone erosion was documented by NEUMANN (1966) in a description of subtidal notches of a wave-protected lagoon in Bermuda. Through laboratory experiments, he measured removal rates by *Cliona lampa* of up to 6.5 kg/m^2/100 days (23.7 kg/m^2/yr) of material from

Table 2: *The relative contribution of three intertidal molluscs to erosion of the rocky coastline. The contribution of each organism to the total surface planation (erosion) is estimated using data from McLean (1964) and data from this study.*

ORGANISM	ORGANISM DENSITY[1] no./m^2	ORGANISM (2) g/yr/org	EROSION (3) $g/m^2/yr$	VOLUME OF EROSION[4] $cm^3/yr/org$	SURFACE PLANATION[5] mm/yr	PERCENTAGE OF TOTAL[6] %
ACANTHOPLEURA (chiton)	13	22.0	286	16.24	.21	9.6
NERITA	15	2.4	36	1.77	.03	1.4
(snail)		8.0	120	5.90	.09	4.1
ACMAEA (limpet)	8	2.4	19.2	1.77	.01	0.6

1. transects; this study
2. McLean (1964)
3. (column 1) * (column 2)
4. (column 3) / (density of surface rock: 50% of 2.71)
5. (column 4) * (column 1) * (0.0001 m^2/cm^2)
6. (column 5) / (average plantation: 2.2 mm/yr)

carbonate substrates. Thus, in the lower intertidal area where sponges occupy approximately 38 percent of the surface, approximately 9.0 kg/m^2/yr will be removed. This rate is 20 times greater than the rate of bioerosion by chitons, snails and limpets combined (Table 2). This comparison is reported with a caution. The results of NEUMANN (1966) are not directly applicable to the intertidal zone because they were carried out in the laboratory under conditions which most nearly duplicated the subtidal environment. However, these best estimates suggest that bioerosion alone can account for all of the surface planation.

Contribution of Sediment to Lagoons

An estimate of the contribution of sediment derived from intertidal erosion to the lagoon adjacent to the study area can be made from the measurements of coastal retreat. It is important to remember that these measurements record surface planation, and the rock at the surface has already experienced significant bioerosion from sponges, barnacles and endolithic algae. Based on SEM examination, the outer 400 microns of the rock surface has 50 percent porosity (*cf* Figure 7). The intertidal escarpment with a surface porosity of 50 percent and eroding at 2.2 mm/yr would annually provide 2.98 kg of calcite sediment per m^2. With a tidal range of 1 m, 2980 kg of sediment could be produced each year for each linear kilometer of rocky coastline which borders the lagoon. Using air photos, field observations and information from the literature we estimate that this production contributes 0.05 to 0.5 percent of the nearby lagoonal sediment supply (Table 3). Thus, the surficial erosion of these limestone shores contributes little sediment to the adjacent lagoon.

This estimate of sediment contribution to the lagoon is minimal; since sponge chips are not included. Sponge excavation commonly occurs more deeply in the rock substrate than 2 mm, and their contribution to lagoonal sediment is not included in the calculations described above. Our measurements show that sponges contribute 9 kg/m^2/yr (see previous section) which is 3 times the amount produced by surficial erosion (2.98 kg/m^2/yr; Table 3). Thus sponges contribute up to 1.5 percent (3 times the surficial contribution of 0.05 to 0.5 percent) of the total sediment supply of the lagoon. This is much lower than the sponge contribution reported for Fanning Lagoon where 30 percent of the sediment was found to be sponge chips (FUTTERER, 1974). Our upper estimate of 1.5 percent contribution of sponge chips agrees with the qualitative examination of lagoonal sediment samples in which all lagoonal sediment samples examined by us have sponge chips, but in low concentrations.

Patterns of Erosion

A measure of the overall relief (roughness) of intertidal surfaces is the standard deviation of profile measurement sets (Table 1). Based upon the nearly constant standard deviation of

Table 3: *Sediment contribution to lagoons by erosion of the rocky intertidal coast. Using highest and lowest estimates of lagoon sediment mass and rates of coastal erosion, the relative contribution of coastal erosion to the total mass of lagoon sediment is very small.*

	PARAMETER	VALUE	SOURCE
A	DENSITY OF LAGOON SEDIMENT	1.15 g/cm^3	Neumann and Land (1975)
B	AREA OF LAGOON	11.3 x 10^6 m^2	air photos
C	SEDIMENT DEPTH IN LAGOON	C_1 0.5 m (low) C_2 2.0 m (high)	field observations
D	LENGTH OF ROCK COASTLINE	3000 m	air photos, field obs.
E	TIDAL RANGE	1 m	field observations
F	DURATION OF PRESENT SEA LEVEL	F_1 1400 yr (low) F_2 3700 yr (high)	terrace retreat, C-14
G	ESCARPMENT EROSION	2.98 $kg/m^2/yr$	this study

CALCULATIONS

MASS OF SEDIMENT FROM EROSION DURING PRESENT SEA LEVEL
Y_1 low estimate: G x D x E x F_1 = 12.51 x 10^6 kg
Y_2 high estimate: G x D x E x F_2 = 33.08 x 10^6 kg

MASS OF SEDIMENT IN LAGOON
Z_1 low estimate: B x C_1 x A = 6.50 x 10^9 kg
Z_2 high estimate: B x C_2 x A = 25.99 x 10^9 kg

PERCENTAGE OF LAGOONAL SEDIMENT
low estimate: (Y_1 / Z_2) x 100 = 0.05 %
high estimate: (Y_2 / Z_1) x 100 = 0.5 %

sequential sets of measurements (May, 1984, January, 1985 and May, 1985) at each erosion monitoring site, it appears that these surfaces have reached a mature or climax condition with respect to surface irregularity.

A visual comparison of surface relief maps and erosion pattern maps from each monitored site (DONN, 1986) shows no correlation between areas of maximum and minimum erosion with high and low points on the rocks. Instead, erosion is taking place in an apparently random manner. GINSBURG (1953) speculated that projections of the rock may be preserved by both surface hardening and their rapid drying during low water which would make projections less desirable for habitation by rock-destroying organisms. Behavioral studies of chitons and limpets (CHELAZZI *et al.*, 1983; STEPHENSON, 1936) show that homing depressions are created and deepened, and it was expected that depressions would appear as areas of preferential erosion on erosion pattern maps. Our data show that neither projections nor depressions are sites of preferential erosion. It may be that projections erode by 'episodic' mechanical erosion; whereas depressions erode by bioerosion. Our data do not clarify this; however we do record essentially equal erosion of projections and depressions.

Preservation Potential

Bioerosion traces have been reported in rocks of Cambrian age (JAMES *et al.*, 1977) and in many cases are similar to their recent counterparts. VOIGT (1977) describes gastropod and chiton grazing traces on formerly algal-coated bivalves from Jurassic, Cretaceous and Tertiary deposits. During the examination of intertidal rock samples, many grazing traces were found which were blurred or remained as only a vague imprint on the surface. The preservation potential of these traces is probaby very low; a result of their shallow form combined with their rapid destruction by endolithic cyanophyta.

An account of boring sponges from the Middle Ordovician (Chazy Group) recognizes the scalloped walls of borings in thin section, along with chips and spicules on the roof and walls of chambers (KOBLUK, 1981). In comparison to the furrows produced by grazers, the borings of organisms such as sponges and barnacles experience less exposure to destructive algae and may be more readily infilled with sediment, increasing their likelihood of preservation. Algal borings have been recognized in many ancient rocks and may serve as useful paleoenvironmental indicators of water depth (SWINCHATT, 1969).

Initial Erosion

Studies of cemented blocks and smoothed surfaces show that the growth of epilithic algae and shallow boring by endolithic algae are the only major effects on these smooth surfaces during the first year of exposure. Caution should be exercised in extending these results from smoothed surfaces to natural rock surfaces. The major difference between the smoothed surfaces and natural rock is that the natural surfaces are more irregular and possess crevices and depressions which would retain moisture more effectively than the smooth surfaces which we monitored. A greater moisture content may enhance the rate of endolithic colonization and subsequently shorten the period which is required to attract grazers. NEUMANN (1966) found sponge infestation to be quite rapid, but those results were under subtidal conditions, and the sponges were artificially attached to the substrates.

CONCLUSIONS

By utilizing a method of direct surface profiling, the rate of intertidal rock erosion has been determined to be 2.2 mm/yr (range of 1.8 to 2.6 mm/yr). Erosion of supratidal rock surfaces is much slower (0.4 mm/yr). By combining the measured intertidal erosion rates with the width of low-tide level terraces, sea level is calculated to have been at its present position for the last 1400-3700 years.

From examination of surface relief maps and erosion pattern maps, intertidal erosion occurs in an irregular pattern. No preferential erosion of pits or pinnacles is detectable. Fresh, smoothed limestone surfaces are eroded only by the boring of endolithic algae over the first year of exposure, resulting in a very minor amount of surficial degradation.

Erosion is primarily carried out through biological processes by grazing (chitons, snails, limpets) and boring (algae, sponges, barnacles) organisms. Bioerosion traces occur as furrows, pits and borings on macroscopic and microscopic scales. The preservation potential of surficial grazing traces is low, in part, because of algal destruction. Borings, however, are more likely to become preserved because these traces are deeper in the rock and will more likely be infilled with sediment or cement.

Each year, surface planation produces 2.98 kg of sediment per square meter of intertidal rock. This sediment source comprises less than 1 percent of the total sediment in the lagoon. Sponge boring contributes up to 1.5 percent to the lagoon sediment of eastern Andros Island.

Sediments produced by bioerosion are primarily silt-sized; however a wide range of particle sizes are created. Of these sediments, only sponge chips may be readily recognized in nearshore sediment samples.

ACKNOWLEDGEMENTS

This study is part of a Masters of Science research project by T.F. Donn. We thank Matt Eaton and Dave Daugherty for their help in the field and Dr. Ben Bohl and the staff of the Forfar Field Station operated by International Field Studies for logistical support on Andros Island. John Morrow and Robin David helped design, modify and construct the surface profiler. Zak Lasemi performed the SEM analysis. Partial funding for this project was provided by grants from the National Science Foundation (OCE 83-15203 to Neumann, Boardman and Baker), Sigma Xi, the Tenneco Oil Corporation and Miami University.

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