

GARRETT, P.
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Proceedings, Third International Coral Reef Symposium
Rosenstiel School of Marine and Atmospheric Science
University of Miami
Miami, Florida 33149, U.S.A.
May 1977

SEDIMENTATION ON BERMUDA'S ATOLL RIM

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ABSTRACT

Bermuda is an atoll with growing reefs surrounding a lagoon. Like other atolls its living corals are most prolific outside its rim. The rim itself shows many signs of being a deposit of particulate carbonate sediment built during the Pleistocene. The SE rim consists of high Pleistocene eolianite islands which clearly derived their sediment from reefs on the "main terrace" outside the rim. The rest of the rim was probably also supplied with sediment from the "main terrace" during the Pleistocene. Longshore drift propelled by westerly winds and waves is believed to have moved sediment from the 6 km-wide SW main terrace around to the SE and NW rims, where the largest sand-bodies occur. S winds blew sand up into eolianites on the SE rim. Winter frontal storms from the NW drove sediment through breaches in the NW rim into lobes in the adjacent lagoon. There is also some evidence favoring progradation of the SW rim during the Pleistocene.

Karst solution during glacial low sea levels deepened the lagoonal basins and increased the relative elevations of rim sand bodies.

Contribution No. 702 from the Bermuda Biological Station

KEY WORDS: Atoll, Atoll Rim, Reef, Sand-bodies, Eolianite, Storm Deposits, Pleistocene.

SEDIMENTATION ON BERMUDA'S ATOLL RIM

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Introduction

Bermuda is an elliptical atoll about 1000 sq. km in area. It is situated at latitude 32°20'N in the North Atlantic, and is bathed by eddies of the Gulf Stream which keep mean sea surface temperatures within the range 19.3-27.3°C (1), i.e. near the tolerance limit for hermatypic coral reef building. Only 23 hermatypic coral species belonging to 14 genera are known from Bermuda's reefs.

Physical Features (Fig. 1)

The atoll rim almost completely encircles the lagoon and is mostly a terrace 1 km wide and 1-4 m deep, encrusted with living coral reefs. The outer edge of the rim is characterized in places by algal-vermetid reefs (3), presumably diminutive representatives of the algal ridge of more typical atolls.

The rim differs markedly in its 4 quadrants. On the SW, it curves sharply, and is at its shallowest. On the NW it is marked by several lobate extensions into the lagoon. On the NE it is poorly defined and relatively deep. On the SE, the south shore of the Bermuda islands occupies most of the rim, with a narrow reefal terrace to seaward.

The islands consist of Pleistocene eolianites interbedded with paleosols (4,5). The eolianites show evidence of deposition at high sea levels (interglacials) because they grade into marine deposits. Most paleosols are thought to represent periods of low sea level (glacials). Detailed stratigraphic knowledge only extends back two interglacials, which are represented by the Paget and Belmont Formations. Below the Belmont, the Walsingham and probably a sub-Walsingham unit extend the exposed record back another two interglacials. The islands can be conveniently divided into two geomorphic provinces. The south shore, with dunes facing the open ocean, and the north shore, with dunes facing the lagoon.

The lagoon is not a simple depression within the rim, but consists of many depressions separated from each other to varying degrees by arcuate portions of the north shore of the islands or by arcuate and irregular banks, capped in many instances by patch reefs (1).

Outside the rim, the outer slope consists mostly of a gently sloping terrace at about 18 m depth. Narrow and less regular lower terraces occur above a very steep platform margin (6). The 18 m terrace, because it is a major physiographic feature, we call the main terrace. It is 1/2-6 km wide, being widest on the SW and NE and narrowest on the SE. To call it the reef front

terrace as do Stanley and Swift (6) seems to us something of a misrepresentation, since it is actually the site of Bermuda's most flourishing reefs. The main terrace has notable accumulations of sand along its inner margin against the rim.

History of Research

From the above it can be seen that Bermuda's morphology resembles that of typical Pacific atolls, but with differences. Darwin (7), though he never went there, has given us a perspicacious account of the differences, namely:

- 1) the rim is submerged with no exposed reef flat;
- 2) the 18 m "main" terrace is much wider than on most atolls;
- 3) the islands are extraordinary in their size, height and lack of resemblance to the narrow islets of other atolls.

Agassiz (2) and Verrill (8) were impressed by the insignificance of coral growth as compared to the Bahamas and Florida. They believed that coral reefs only form a thin veneer on Pleistocene eolian deposits all around the platform even including the patch reefs. Agassiz denied significant reef building anywhere, and Verrill labeled Bermuda a "pseudoatoll."

Stanley and Swift (9) supported the arguments of Agassiz and Verrill by describing outcrops of eolianite, and caves attributed to solution, among the reefs off the south shore of the islands.

Purdy (10) noted that the geomorphic similarity of Bermuda and other atolls is probably caused by both being basin-and-rim features caused by karst solution.

Our chief purposes in this paper are to briefly describe the processes of sedimentation in the present, use them to hypothesize likely processes and products in the Pleistocene, and try to explain what is the cause of the dissimilarities between Bermuda and other atolls, as first noted by Darwin.

Winds and Waves

Bermuda lies in the belt of westerlies (Fig. 2A). Most atolls are in the easterly trade wind belt.

Bermuda is also battered by winter storms and hurricanes. Gale force winds (Fig. 2B) mostly blow during winter frontal storms which cross the Bermuda area from the NW: gales can blow

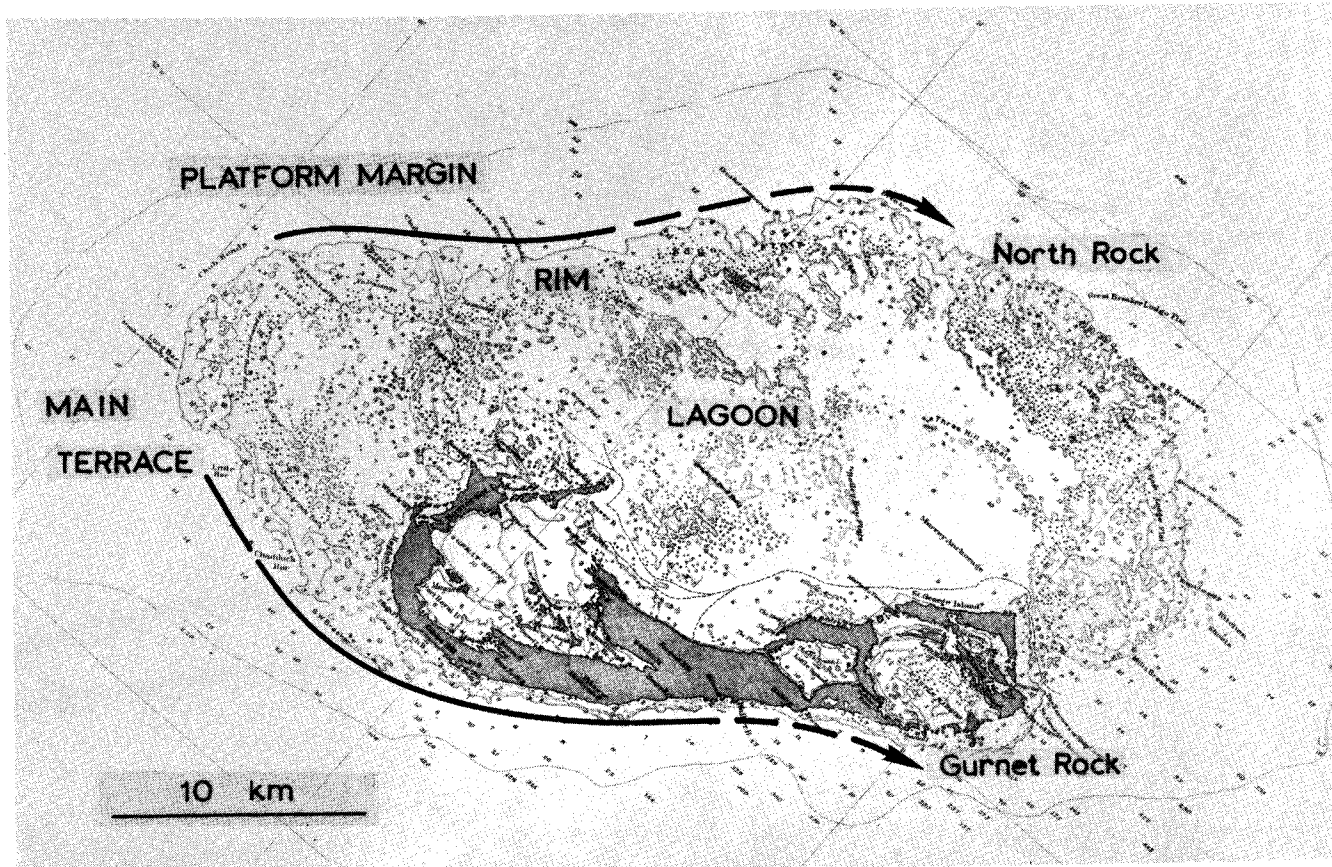


Fig. 1: Bermuda bathymetry, from U.S.H.O. Chart #27 (2). Labeled features use our terminology. Probable Pleistocene longshore drift shown by arrows. (We use this pre-1895 chart because it shows the outlines of the reefal shoals better than any chart since!)

Fig. 2: Wind patterns. A. Strong winds (>18.5 kph) (11) - these blow for 51% of the time. B. Gale force winds (>63 kph) (12). C. Hurricane force winds (>121 kph) (12). Periods: A. 1939-71; B. 1932-47; C. 1932-55. North points upwards. Scale bar = 10% of total duration in A and B.

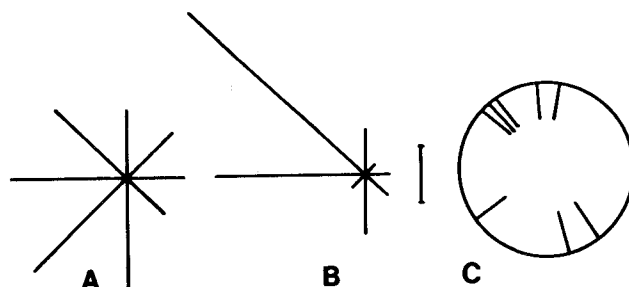
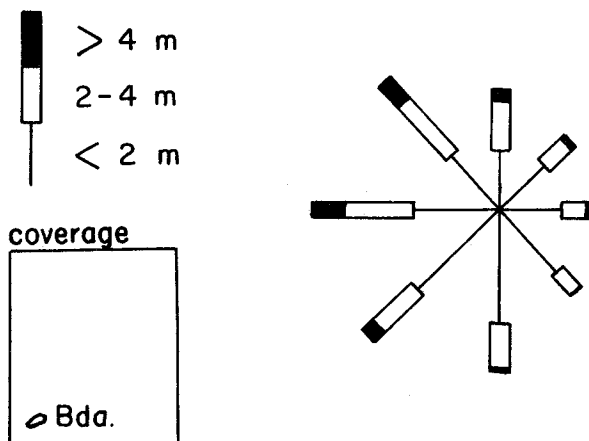


Fig. 3: Wave pattern for sea area including Bermuda. Data for the period 1946-71 (13).

continuously for 30 or 40 hours (12). Hurricane force winds are less frequent: only eight were recorded for the period 1932-55 (Fig. 2C), two of which occurred during winter storms not hurricanes.

The wave pattern (Fig. 3), like the winds, is characteristically westerly. Notice however that winter conditions (with W and NW winds) exert a strong influence on the wave pattern, despite the "fair weather bias" of the data, which was derived from ships' logs.



Wind and Wave Patterns and Sedimentation

We believe that a careful analysis of wind and wave patterns can help in predicting and explaining Pleistocene sedimentation patterns. But two cautions are timely.

First, our relatively short period records may not be entirely applicable for explaining sedimentation that took place over periods of thousands of years.

Secondly, present day conditions may not have prevailed during Pleistocene interglacials. We believe that they did, however, on the grounds that similar world sea levels during interglacial and postglacial times were probably associated with similar icecap sizes, and therefore similar locations of climatic belts.

Processes and Products

South Shore Dunes and the Sand Supply Problem

Bermuda's islands are eolianite sand hills, reaching elevations exceeding 50 m, and including practically no gravel deposits. No reef deposits have been penetrated by boring and excavating below the exposed Pleistocene eolianites (8,14). In fact, more sandy deposits were found, suggesting that the islands are not built on a reef flat, but rather that the SE rim has always been maintained as a sand body.

Questions that arise concerning Bermuda's islands are the following:

- a) What is the sand source for these islands?
- b) Why do high eolianite islands occur only on the SE rim?

Both Pleistocene and Recent south shore sands share a common reefal source, as is clear from their constituent composition (5,15). But the exact location of the source is in question.

At first inspection it seems that the sand for the Pleistocene dunes was derived from reefs on the seaward margin of the rim (5). But that this is unlikely is illustrated by Gurnet Rock (Fig. 4). Its upper strata consist entirely of foresets, yet it stands on the seaward edge of the rim. Thus the beach supplying sand to the Gurnet dune must have been located where the main terrace now is.

Even modern south shore beaches are probably supplied from a main terrace source. Large quantities of sand on the rim are not associated with conspicuous reef growth, but with aprons of sediment which bank up from the main terrace onto the rim.

At the present time there is relatively little sand supplied to the south shore. Probably the reason is twofold: (1) there has been relatively little time for sand production from

main terrace reefs since the last rise in sea level, and (2) although sand is accumulating at most places on the inner main terrace, it is relatively difficult for it to pass up onto the rim because of a submarine cliff (possibly cut in interstadial times) which acts as a barrier between the two.

For these reasons, Holocene dunes are relatively small, and much of the south coast is, in fact, still erosional. Given more time, sand deposition should increase until the south shore progrades seaward as it did during previous interglacial periods.

The Presently-Submerged Rim

If reefs on the main terrace provided sand for the south shore dunes during the Pleistocene, then main terrace reefs around the entire platform could have provided sand for the entire rim, at least during part of its geological history. The rim is actually only slightly submerged below sea level (less than 4 m in most places). At a slightly lower sea level this rim would be exposed, and if sand were available, sand islands would probably form along it. During parts of the last interglacial, sea level apparently did stand a few meters below present sea level (4,5), so it is more than likely that a ring of islands did form all around the rim.

One such island remains. It is North Rock, the last remnant of a probably eolian Pleistocene island. We have no direct evidence of any other islands around the rest of the submerged rim. If present, however, other islands were probably relatively small and/or low lying, and were either eroded away or encrusted by reefs during earlier high sea level stands and/or during the Recent sea level rise. North Rock is presently only one projection about 4 m above sea level, so recent marine erosion has been rapid judging from the size of the feature photographed in 1876 (Fig. 5).

Longshore Drift in the Pleistocene

The chief consequence of the rim bearing a ring of islands is that the seaward beaches of such islands could provide a "road" along which sand could move by longshore drift. The question is then, in what direction would it move the sand? The answer is to be found in an analysis of the wind and wave patterns (Figs. 2 and 3). One would expect a longshore drift away from the SW rim and around to the adjacent rims (Fig. 1, arrows), with the largest sandbodies developing on the SE and NW rims. This presupposes that there is an adequate means of removing sand from the longshore drift on the SE and NW rims. This problem is dealt with below.

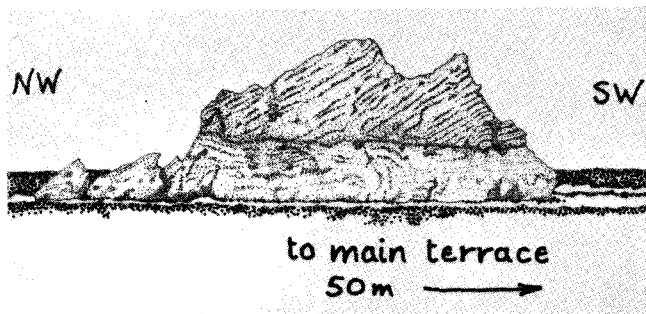


Fig. 4: Gurnet Rock, eroded remnant of a south shore eolianite whose beach must have been supplied with sand from the main terrace. Drawing by Ms. E. Hoffman, from a photograph.



Fig. 5: North Rock, last remnant of the only extant island on the northern rim. Photo by J.B. Heyl in 1876, courtesy Bermuda Book Store.

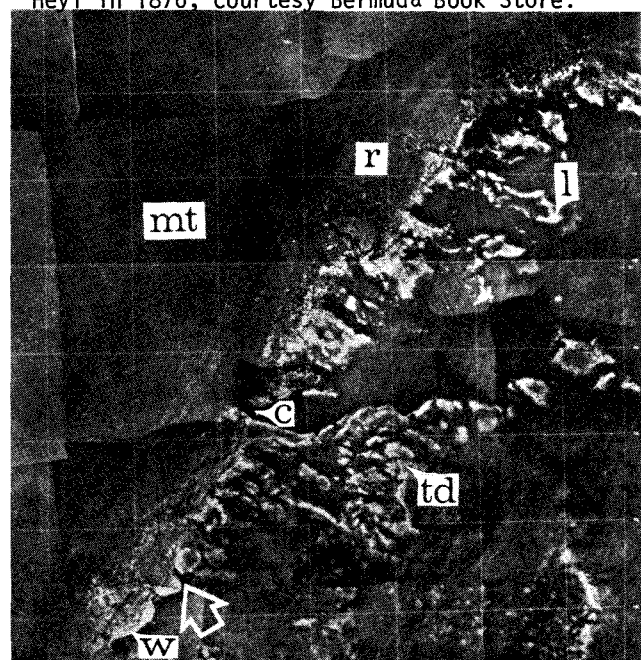


Fig. 6: Air photo mosaic (16) of NW rim. Grid squares are 2 km on a side. c: channel, l: lobe, mt: main terrace, r: rim, td: tidal delta, w: washover, arrow: Fig. 9.

South Shore Eolianites as "Sink" Sandbodies on the SE Rim

During Paget time, eolianites were developed along at least 2/3 of the length of the south shore of the islands (Fig. 10). Two thirds is

probably an underestimate since much of the seaward portions have been eroded away. Of these Paget dunes, the largest volume of sand and the highest dunes are those nearest the SW main terrace, which was probably the chief source area for sand, since it is 2 or 3 times as wide as the main terrace on the SE. Thus the dunes of the western portion of the south shore functioned as a very considerable and efficient sink. It is possible that they took almost all the sand from the longshore drift, leaving very little for the eastern portion of the south shore which has poorly developed Paget eolianites situated in-shore from a relatively narrow main terrace.

The vector of eolianite depositing winds can be determined from the long axes of foreset lobes (5). Most vectors are oriented S→N, oblique to the trend of the south shore. This indicates that S winds rather than SE winds are responsible for transporting beach sand into neighboring dunes. Such a conclusion is backed up by the present-day wind pattern (Fig. 2A,B) which shows that all significant winds are more frequent from the S than from the SE. It is probably the strong winds that are chiefly responsible for "sinking" the sand into the south shore dunes.

The NW Rim - A Pleistocene Storm-Modified Barrier Island Chain

The NW rim is peculiar in having an almost straight ocean-facing side, but many irregular extensions into the lagoon (Fig. 6). The most prominent of these extensions are lobes which are up to 6 km long and between 100 m and 2000 m wide. They consist of many banks rising from lagoon depths of 12-17 m, on which reefs grow nearly to sea level.

The pattern of a straight ridge with lobes extending back at high angles into a lagoon is similar to some storm-modified barrier-island features described from the continental coast of the U.S.A. (17). Fig. 7 illustrates the process

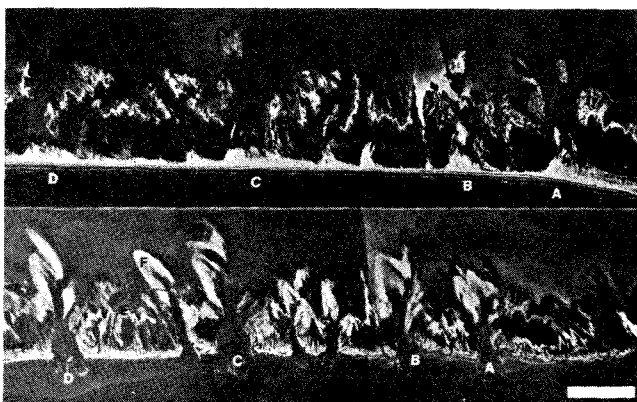


Fig. 7: Spillthrough lobes of a Texas barrier island (17). Top: between storms, bottom: 6 days after hurricane. Letters are in equivalent positions in both photographs. Scale 1 km.

of formation of such lobes. They are usually termed "washover deltas" (17), but it is apparent from the photograph that washthrough deltas or lobes would be more appropriate, since the barrier is breached by the storm, and sand is literally washed through the breaches and deposited in lobes in the lagoon. After each storm, the breaches are healed by longshore drift, and the morphology of the lobes becomes modified by the growth of vegetation and the lapping of small lagoonal waves.

We believe that similar processes operated on Bermuda's NW rim during the Pleistocene, but with some differences. One of the chief differences is the greater size and especially length of the Bermuda spillthrough lobes. This may have two causes: (1) their formation during winter frontal storms, rather than hurricanes; (2) the possibility that some cross-barrier breaches were semi-permanent features.

First, let us consider frontal versus hurricane storms. Fig. 2B shows that the NW rim is without doubt the side most prone to gales. Most of Bermuda's gale-force-and-greater winds occur during winter frontal storms. The remaining gales are generated by hurricanes, which approach Bermuda mostly from the S and SW, but due to their tight cyclonic circulation, can produce winds from a variety of different directions depending upon their path and whether they approach to the right or left of Bermuda. Table 1 compares frontal storms and hurricanes affecting Bermuda. It is clear that though frontal storms may be less intense, they have a longer duration and a much greater fetch, which combine to generate waves as large as hurricane waves. In addition frontal storms are more frequent and the direction of their winds is more consistent between and during storms.

Secondly, we believe that cross-barrier breaches of Bermuda's NW rim could have been more permanent features than similar channels across terrigenous barrier islands. Stability could have been achieved by (a) growth of reefs along channel banks, (b) early cementation in zones of rapid water flux, and (c) Pleistocene "basement" control in consolidated rock rather than loose sand.

Both the consistent direction of frontal storm winds, and the more stable location of carbonate channels would tend to favor the growth through repeated storms, of existing spillthrough lobes, until they could conceivably enlarge to the size of the Bermuda lobes.

Though probably formed and chiefly fed by storm deposition, the lobes were no doubt modified by tidal currents setting in and out of the channels, especially if the channels were restricted between islands. Similar channels between islands today experience tidal current velocities of up to 28 cm/sec (20). Such modifi-

TABLE 1. Comparison of Frontal Storms and Hurricanes Affecting Bermuda

	Frontal Storms	Hurricanes
Frequency:	Several per year	Average: 1 per 4 years touching platform
Duration:	1-2 days	Less than 1 day (12)
Wind Strength:	60-120 kph	60-200 kph
Wind Direction:	Consistently from NW quadrant	Can be from any quadrant depending on path of hurricane. Directions reverse during passage.
Size:	1000 km wide	100 km wide
Fetch:	1100 km	? usually <100 km
Wave Height:	7-20 m*	Up to 20 m† (or waves may break into spray with such high winds (18))
Surge:	? 1 m	1-2 m, exceptionally 3 m, on open atolls (18)

*These are "significant deep water wave heights" as calculated from curves (19), using wind speed 34-65 knots, duration 30 hrs., fetch 600 miles. Due to decreasing depth, wave heights should increase up on to the rim.

†Calculated for Hurricane Hattie, an unusually strong hurricane (18).

cation would have made the lobes more closely resemble tidal deltas, which one of them does (Fig. 6td).

The channels which presumably fed the lobes are now completely closed, though small incomplete channels through the rim do occur on the NE side of several prominent lobes (Fig. 6c). The inference from this is that longshore drift from SW to NE eventually closed the cross-barrier channels leaving the NW rim entire. It might have done this at a slightly lower sea level.

Other related features on the NW rim resemble washover fans (Fig. 6w). They are similar to features formed by transport of material by storms, over and across low points on a barrier, without the barrier being breached (Fig. 8).

Between washover fans, lagoonward drainage and tidal ebb and flow causes dead-end tidal creeks to develop from the lagoon side (see left portion of Fig. 8). Similar creeks are present on the lagoonside of Bermuda's NW rim (Fig. 9).

At present the NW rim is encrusted by reefs and shows other evidence of its frequent exposure to storm activity: the reef surface is relatively barren, with only scattered well-attached coral growth and little loose sand. Elsewhere in the world, reefs which are periodically exposed

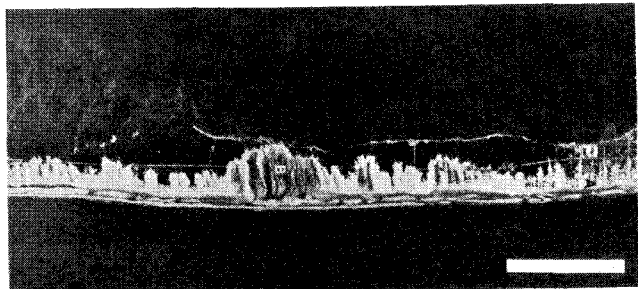


Fig. 8: Washover fans developed on a Delaware barrier island by storm sedimentation (17). Older washover fan deposits to upper left. Scale 1 km. North to right.



Fig. 9: Lagoonside tidal channel now encrusted with reefs. Oblique air photo, view to N. See arrow on Fig. 6.

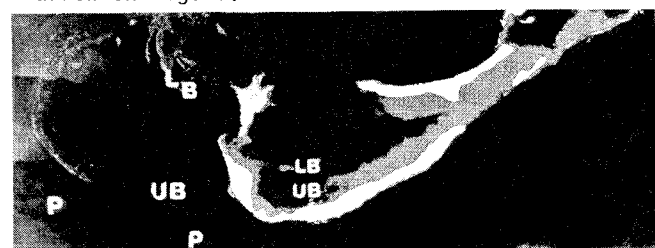


Fig. 10: Air photo mosaic (16) of southern Bermuda platform with geological map (26) superimposed. LB: Lower Belmont, UB: Upper Belmont, P: Paget. Patterns: white = Paget, stippled = Belmont.

to hurricanes probably follow a cycle of luxuriant growth under "normal" conditions followed by catastrophic destruction, regrowth back to normal taking years or decades (21,22). Bermuda's NW rim, because it is annually subjected to conditions approaching those in hurricane seas, is thus kept in a relatively barren state.

The effects of hurricanes on barrier reefs are distinct from their effects on barrier islands. Hurricanes destroy reefs producing quantities of rubble and sand, some of which is carried into deep water, while much is carried across the reef to be deposited as ridges on the reef top or as aprons on the lagoon side (23,24).

In contrast, where hurricanes attack barrier islands, sediment is funnelled through channels to build leeward lobes (25). Thus the pattern of Bermuda's NW rim lobes does suggest the earlier existence of barrier islands along this margin.

The SW Rim and Progradation

Neither the SW nor the NE rim have any particularly distinctive morphology suggesting what the sub-reef formations might be.

There is, however, some evidence to suggest that the SW rim has prograded in steps towards the SW. The evidence is summarized in Fig. 10. In brief, the main arc of the SW rim is not strictly continuous with the line of Paget dunes along the south shore. Instead it abuts against the island and is more closely continuous with a line of Upper Belmont dunes (right UB in Fig. 10) (Vacher, pers. comm., 1975). It is therefore reasonable to suppose that the main SW rim is an Upper Belmont feature. A Lower Belmont SW rim may be Ely's Flat (left LB in Fig. 10), because it is continuous with a Lower Belmont line of dunes among the islands of the Great Sound (right LB). Paget islands along the SW rim are probably represented by a line of shoals ["Chubb Heads," "Long Bar," "Little Bar," "Chaddock Bar" and "SW Breaker" (P on Fig. 10)], which lie outside the main SW rim and are continuous with Paget dunes and the edge of the rim on the SE. Late in Paget time the rims were overtopped, and sand was transported from the lagoon floor to build the present west-facing Paget dunes.

In a similar fashion, both the NE and NW rims could have prograded, though the evidence is not strong. The SE rim has prograded too, but only slightly: Paget dunes sit on the backs of Belmont dunes and Belmont on Walsingham (4,26).

Karst Solution During Glacial Low Sea Levels

Some of the major features of Bermuda's (and other atolls') morphology can be explained by karst solution during glacial low sea levels (10). For instance: (a) lagoonal basins owe their great depth to increased solution in topographic lows (where water collects, vegetation is lusher, and thus humic acids are more concentrated); (b) elevated topography such as the rim, becomes relatively more elevated by increased solution around it; and (c) reef growth and island building take place preferentially on elevated substrates. Thus solution during glacial periods and deposition during interglacials tend to cooperate in an accentuation of topography.

Such a scheme helps to explain why the lagoon is not at present a source of sediment for lagoon-shore dune-building. The lagoon was overdeepened during the last glacial period, and requires a time period longer than the Recent to build up its sediment level.

This scheme also explains the sharp definition of the lobate extensions of the NW rim (Fig. 6). These features, though initially probably only slightly elevated above the surrounding lagoon floor, were relatively elevated by glacial period solution around them, and absolutely elevated by Recent reef growth on them.

Discussion

An annular organic reef surrounds the lagoon of all atolls (27). But it is not usually located on the rim, for the rim reef flat of most atolls is largely a dead cemented rubble surface (28). The most actively growing zone of atolls actually lies between the rim and platform margin (29). The same is true for Bermuda. Coral growth is lusher and more widespread on the main terrace reefs than anywhere else on the platform.

On Pacific atolls most of the gravel debris deposited on the reef flat during storms is derived by the ripping up and transport of corals from the reefs outside the rim (7,29,30). Presumably most of the sand fraction of sediment supplied to the reef flat shares a similar original source. Thus the rim can be said to be largely built and maintained by sediment contributed from reefs outside the rim. Again the same can be said for Bermuda. We have shown in this paper how the main terrace has provided large quantities of sand for the south shore dunes of the SE rim. And we have suggested that the rest of the rim was similarly supplied with sediment during the Pleistocene. Thus Bermuda emerges as more like an atoll in both form and process than had previously been suspected.

Two of the chief differences between Bermuda and other atolls include the submerged rim and the wide main terrace. The rim is probably submerged because it was drowned by the recent rise of sea level, and is barely able or unable to grow up to sea level due to the absence of fast-growing *Acropora* corals. The great width of the main terrace may be correlated with the probability that progradation of the rim is still active. If this is so, it illustrates that a balance between the rate of supply of main terrace sediment, and the position of the rim has only recently been, or has yet to be found. Presumably progradation will continue until the main terrace is narrow enough to only provide sediment for maintenance but not for building out of the rim. This would probably still leave a relatively wide main terrace, because of the slower growth rate of Bermuda's corals and reefs. That the growth rate is slower is due to Bermuda's position as the world's most northerly atoll.

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