Coral Reefs (1993) 12:203–221

Coral Reefs

# The geological effects of hurricanes on coral reefs and the interpretation of storm deposits

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Accepted 25 March 1993

**Abstract.** Hurricanes occur in belts 7° to 25° north and south of the equator. Reefs growing in these belts suffer periodic damage from hurricane-generated waves and storm surge. Corals down to 20 m depth may be broken and removed, branching colonies being much more susceptible to breakage than upright massive forms. Sand cays may be washed away and former storm ridges may migrate to leeward across reef flats to link with islands. Reef crest and reef front coral debris accumulate as talus at the foot of the fore-reef slope, on submarine terraces and grooves, on the intertidal reef flat as storm ridges of shingle or boulders and isolated blocks of reef framework, as accreting beach ridges of leeward migrating shingle, as lobes and wedges of debris in back-reef lagoons, as drapes of carbonate sand and mud in deep off-reef locations in the fore-reef and lagoonal areas. In addition to the coarse debris deposited, other features may aid the recognition of former hurricane events, including the assemblage of reef biota, its species composition and the structure of the skeletons; graded internal sediments in framework cavities; characteristic sequences of encrusting organisms; characteristic shapes of reef flat microatoll corals; and submarine cement crusts over truncated reef surfaces. The abundance of reef flat storm deposits whose ages cluster around 3000–4000 y BP in certain parts of the world most likely relate to a slight fall in relative sea level rather than an increase in storminess during that period. A higher frequency of storms need not result in more reef flat storm deposits. The violence of the storm relative to normal fair-weather conditions influences the extent of damage; the length of time since the previous major storm influences the amount of coral debris created; the length of time after the hurricane, and before a subsequent storm influences the degree of stabilization of reef-top storm deposits and hence their chances of preservation.

## Introduction

This study is concerned with the geological record of physical disturbances on coral reefs and is based on a review of studies of the effects of such disturbances on modern reefs. The focus of attention here will be physical disturbance relating to violent storms (hurricanes, cyclones, typhoons), though catastrophic wave action may also be created on reefs by earth movements caused by earthquakes and volcanic eruptions. Firstly, the characteristics of hurricanes will be described, followed by a summary of their effects on the submarine and subaerial morphology of reefs. The final section discusses those geomorphological and petrographic features whose preservation may help the recognition of former hurricanes and indicates some of the problems of interpretation of reef-top storm deposits.

## Hurricane characteristics

Hurricanes are intense cells of low pressure with a central eye (20–30 km diameter) surrounded by a circular wind system which rotates clockwise in the Southern Hemisphere and anti-clockwise in the Northern Hemisphere. The systems travel at speeds between 10 and 25 km/h and follow tracks which generally curve away from the equator. Wind speeds are in excess of 120 km/h and gusts may reach 300 km/h. Locations crossed by the central eye of the hurricane experience violent winds from different directions separated by a period of calm. These winds generate waves which are commonly 5–15 m in height at the reef front, but may be over 20 m. The low atmospheric pressure and the force of the wind help to bank the sea water into a storm surge which may reach 5 m above normal tide level. These storm surges are generally higher on coastal shelf reefs than on islands that rise steeply from the deep ocean. Though the direction of the wind changes during the passing of a hurricane, and few areas of the reef surface escape its full force, the greatest waves are normally generated on the seaward side of reefs because of the deep water and large fetch; waves created by winds from off the land or off a lagoon are smaller, but they may interfere with earlier formed waves from the other direction to produce a confused sea. Unusual currents may be created by the storm surge and these may be enhanced at channels between islands. The configuration of islands, bays and lagoons, combined with the changing wind direction may be responsible for marked reversals in current directions during the passing of a hurricane. For example, the flow between the Florida Keys during Hurricane Donna, when the opposing directions of the wind on either side of the eye caused water levels to be low in Florida Bay and high on the shelf side of the Keys. This led to very strong currents through the gaps in the Keys. Later the water level in Florida Bay rose dramatically and there followed swift currents in the opposite direction (Ball et al. 1967). Hurricanes are frequently accompanied by heavy falls of rain.

### *Spatial distribution*

Frequent hurricanes occur in belts 7° to 25° N and S of the equator (Fig. 1). Outside these belts hurricanes are rare and of lower intensity. The major reef areas of the world suffering regular hurricanes are as follows: the northwest Pacific Ocean from the Marshalls and Marianas to the Caroline Islands, South China Sea and the Philippines; southwest Pacific Ocean, from Society, Cook and Samoan Islands, Tuvalu, to Fiji, New Hebrides, New Caledonia and the Great Barrier Reef of Australia; the north Indian Ocean, including the Andaman Islands, Sri Lanka and the Laccadives; south Indian Ocean, Cocos Keeling, Chagos Archipelago and the islands between Malagasy and the Mascarenes; the northwest Atlantic Ocean, including the Gulf of Mexico and the Caribbean Sea. Reefs outside these hurricane belts include those of the Maldives, the East African Coast, the Red Sea, the area from the Malaysian peninsula, through northern Indonesia, Papua New Guinea and the Solomon Islands, the Pacific atolls of Kiribati, the Phoenix group, many of the Line Islands together with the easternmost Tuamotus.

The width of the band of catastrophic damage caused by the hurricane varies according to one's definition of damage (See Simpson and Reihl 1981; Done 1992), but for major damage, such as small cays washed away, all branching corals in less than 10 m of water on the reef front broken, all coconut trees blown down, the zone extends to about 30 km on either side of the eye. Woodley (1992) maintained that the passage of a hurricane within 65 km north or south of Jamaica would destroy its stands of *Acropora* coral.

### *Frequency*

Figure 1 gives some indication of the relative frequency of hurricanes in different parts of the world. Not all hurricanes have the same force and though the annual average may be as much as five per year for a large region of seas with reefs such as the Great Barrier Reef or the Caribbean, any particular reef such as an atoll may be struck by a severe hurricane only four to eight times a century (Harmelin–Vivien 1985). Stoddart (1985) noted that storm surges of 1.28 m on the Texas coast have a recurrence interval of 3 y, but those of 3.36 m recur at intervals of 280 y. Cyclone Ivor struck the Great Barrier Reef in 1990 and was level 2 on the 5-point Saffir–Simpson Scale (Simpson and Riehl 1981). Done (1992) considered the return period for such a cyclone somewhere in the 1200 km central to southern section of the Great Barrier Reef to be around 8 y, or 96 y for any 100 km section. On the other hand Riddle (1988) estimated 5.4 cyclones per 100 km of coast of the Great Barrier Reef between July 1909 and June 1980. Ball et al. (1967) estimated 160,000 to 320,000 hurricanes hit Florida Keys during the course of the Pleistocene (about 2 million years).

The likelihood of any particular area being damaged is a function of both the general frequency of hurricanes in the region and the width of their maximum damage path.

### *Factors affecting the severity of damage*

The effective wave parameters are orbital velocity and acceleration of water particles in breaking waves, which in a hurricane are derivable from central pressure, range, direction, forward velocity, fetch, bathymetry and shelter (Done 1992). The plan and profile shape of the reef front are critical in influencing the nature of the waves at specific points and thus the geometry and grain size of the deposits

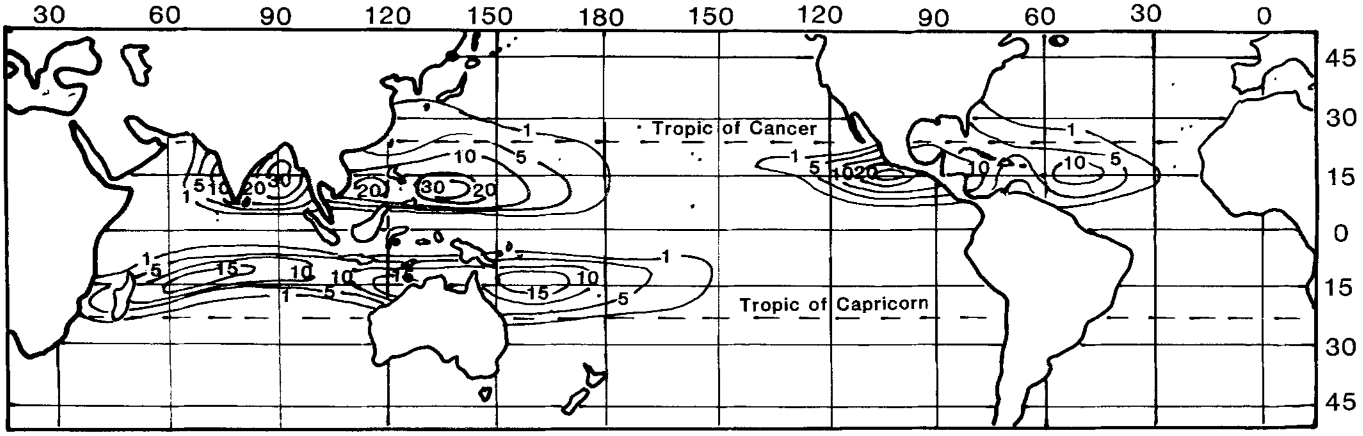

**Fig. 1.** Global sources of tropical cyclones and number generated during twenty tropical cyclone seasons (1958–1978). After Simpson and Reihl 1981

(Newell 1954; Baines et al. 1974). The vulnerability of a coral stand to wave impact is a function of age, species composition, strength of skeleton, tenacity of attachment, drag and mutual buttressing. Strength and tenacity are species specific variables affected by associated biota notably bioeroders, and drag is a species specific variable dependent on coral morphology and size (Done 1992). Several authors have recorded how branching corals such as *Acropora palmata* and *A. cervicornis* are much more vulnerable to damage than the upright massive colonies such as *Montastrea annularis* (Fig. 3) (Stoddart 1963; Woodley et al. 1981). Ball et al. (1967) noted that those colonies of *Acropora palmata* that were oriented leaning away from the incoming waves received less damage from waves created by Hurricane Donna in South Florida than unoriented colonies of the same species.

The state of the tide during the critical part of the storm can influence the location on the reef where the waves have most impact. It can also control the elevation above mean tide level that the storm surge may reach. The height of the storm surge is a function of the atmospheric pressure and the force of the wind. As a general rule, during hurricanes the processes of deposition predominate on the reef flat during low tides and the processes of erosion during high tides.

The availability of boulders, gravel and sand for reworking is important in governing the extent of damage by bombardment or abrasion caused by objects rolling or in suspension. The availability of boulders derived by the contemporaneous fragmentation of living branching corals is controlled by the size (age) of the corals. This, in turn, is a function of the time elapsed since the last hurricane (or other devastating event such as crown of thorns attack) and the rate of recovery of those species in that setting. Rates of recovery are significantly less where damage is slight (3–5 y) compared to where damage is severe (25 to 40 y). Stoddart (1974) suggested that there is a threshold of damage beyond which storm effects are likely to be prolonged.

## Geomorphological effects on reefs and islands

The following summary is based on a review of several published papers describing the effects of hurricanes on modern coral reefs and islands. Particular attention has been given to those areas where follow-up studies on reef recovery and the effects of subsequent hurricanes were conducted. These areas are as follows:

Jaluit Atoll in the Marshall Islands, Typhoon Ophelia in 1958 (Blumenstock 1958, 1961; Blumenstock et al. 1961; McKee 1959; Weins 1962; Curray et al. 1970). Funafuti Atoll, Tuvalu (Ellice Islands), Cyclone Bebe in 1972 (Maragos et al. 1973; Baines et al. 1974; Baines and McLean 1976; McLean 1993). Great Barrier Reef, Australia (Moorhouse 1936; Hopley 1982; Hopley and Isdale 1977; Flood and Jell 1977; Stoddart et al. 1978a, b; Scoffin et al. 1978; Scoffin and McLean 1978; Van Woesik et al. 1991; Done 1992). Discovery Bay, Jamaica, Hurricanes Allen and Gilbert in 1980 and 1988 respectively (Woodley et al. 1981; Kjerfve et al. 1986; Graus et al. 1984; Woodley 1989, 1992). Florida Keys, South Florida USA, Hurricanes Donna and Betsy in 1960 and 1965 respectively (Ball et al. 1967; Perkins and Enos 1968; Shinn 1972). Belize (British Honduras), Hurricane Hattie in 1961 (Stoddart 1963, 1969, 1971, 1974; Kjerfve and Dinnel 1983).

The main storm-related geomorphological features are illustrated for typical atoll rim and continental shelf platform reef setting in Fig. 2. Islands formed by coral reef debris can be split into two types "motus" and "sand cays" (Stoddart 1971). Motus are characteristic of Indo-Pacific atoll rims. They are long, narrow islands which in some cases may entirely encircle the atoll lagoon. The seaward beach may be formed of cobbles and gravel, the lagoon beach is normally sandy, and there may be swampy depressions between the two. In places aeolian dunes may form on the crest of the windward beach ridge. Sand cays are smaller and consist of gravel and sand rather than boulders and cobbles, and are formed at reef gaps and on the lee side of reef patches by wave refraction (Stoddart 1971). Not all of the effects described next will occur during each hurricane on each reef. Generally the more dramatic effects are associated with the more severe storms. However, there are exceptions to this, for example a storm may be so strong that all debris is washed over the reef and into the lagoon leaving no impressive intertidal storm ridge; and further, a hurricane may be strong, but if there is no source of debris (no loose blocks or branching corals) due, for example, to the activity of an earlier hurricane, then no storm deposit can be built and damage will be relatively less (e.g. Gilbert 1988 after Allen 1980 on Jamaica, Woodley 1989; and Betsy 1965 after Donna 1960 on Florida Keys, Perkins and Enos 1968).

### *Erosional effects*

*Subtidal.* Dissipation of wave energy depends on the aspect of the local reef profile, including depth, slope and shelf width. Though some authors (Woodley et al. 1981) found that sloping or level reef surfaces are more severely affected than vertical ones of comparable depths, other authors (Laboute 1985; Harmelin-Vivien 1985; Harmelin-Vivien and Laboute 1986) found the converse to be true. Hubbard et al. (1991), describing the effects of Hurricane Hugo on the reefs of the Virgin Islands, observed that downslope transport dominated steep areas, whereas landward movement of debris occurred in areas of gentler fore-reef slope.

Several reports note that surge channel and buttress topography, like spurs and grooves, act as a more effective baffle in dissipating wave energy with less structural reef damage and coral fragmentation than occurs in areas of smoother topographic relief. Nonetheless, severe hurricanes can demolish the spurs on reef fronts (Stoddart 1963, 1971) exposing a smooth truncated reef surface. Hurricane waves can break and remove all branching corals down to at least 12 m depth (Stoddart 1971; Hermandez-Avila et al. 1977; Harmelin-Vivien 1985; Van Woesik et al. 1991). The relative resistance to erosion

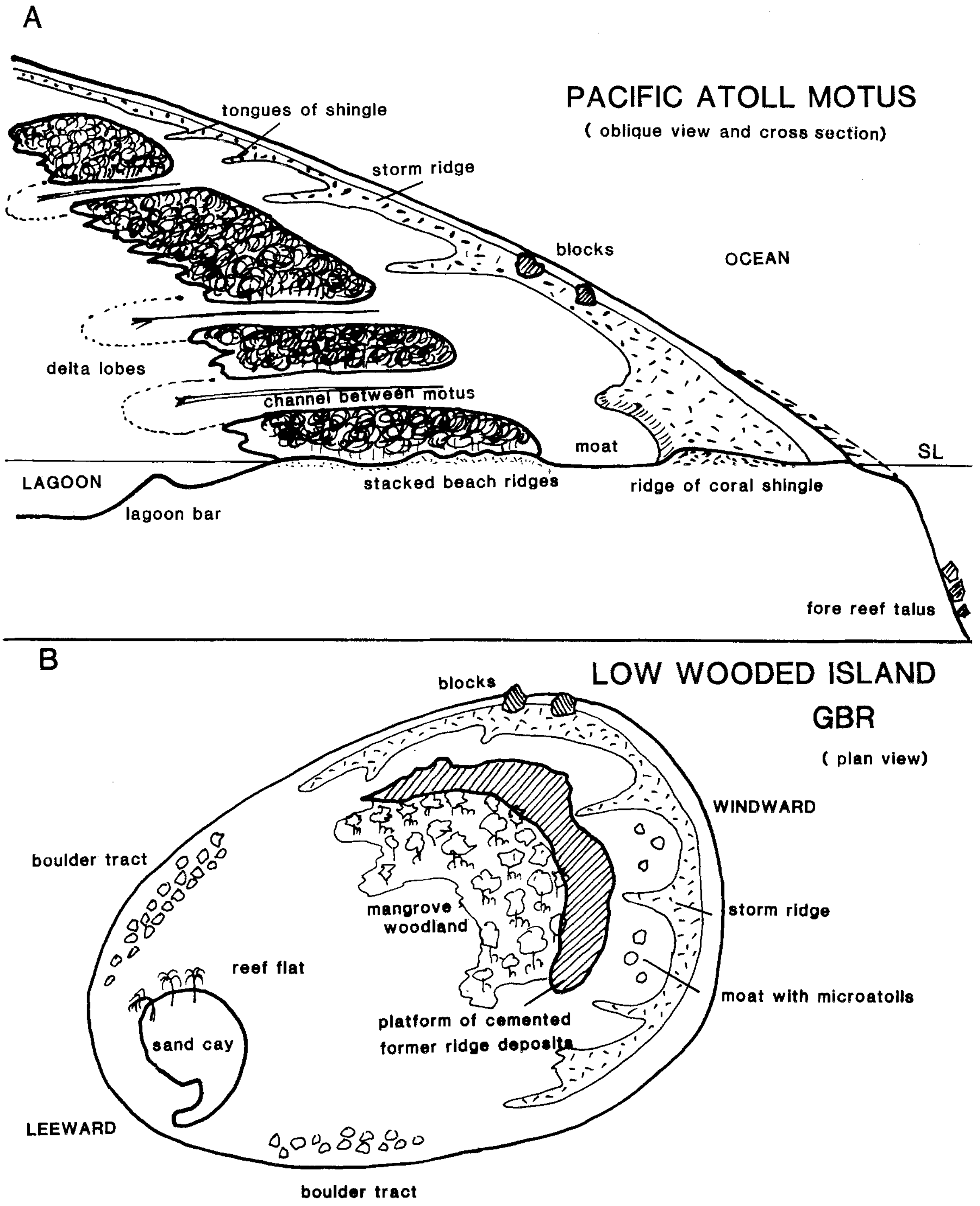

**Fig. 2.** A Sketch illustration of oblique view and cross section of typical motu development on a Pacific atoll rim indicating the major storm-induced geomorphological features. **B** Sketch illustration of plan view of a low wooded island type platform reef on the inner shelf of the northern Great Barrier Reef of Australia

of the dominant shallow water corals of Belize was recorded by Stoddart (1963). The spindly branched forms readily break, whereas the massive forms rarely break or move (Fig. 3). Hurricane Allen destroyed 99% of *Acropora* corals, 23% of the foliaceous and encrusting *Agaricia* corals and only 9% of the massive *Montastrea* colonies at 6 m depth at Discovery Bay (Woodley et al. 1981). The same hurricane removed 96% of the dominant coral, the branching *Porites porites*, on the fringing reefs of the west coast of Barbados, but the massive *Montastrea*, *Diploria* and *Siderastrea* were relatively unscathed (Mah and Stearn 1986). The factors that govern the ease with which coral colonies break are reviewed by Done (1992). A massive colony may provide shelter for delicate small corals in its lee, but it readily crushes such corals if it topples and rolls. Some foliaceous and platy growth forms are surprisingly resilient to breakage, especially the boxwork forms of *Millepora* and *Agaricia* (Stoddart 1985). However, many

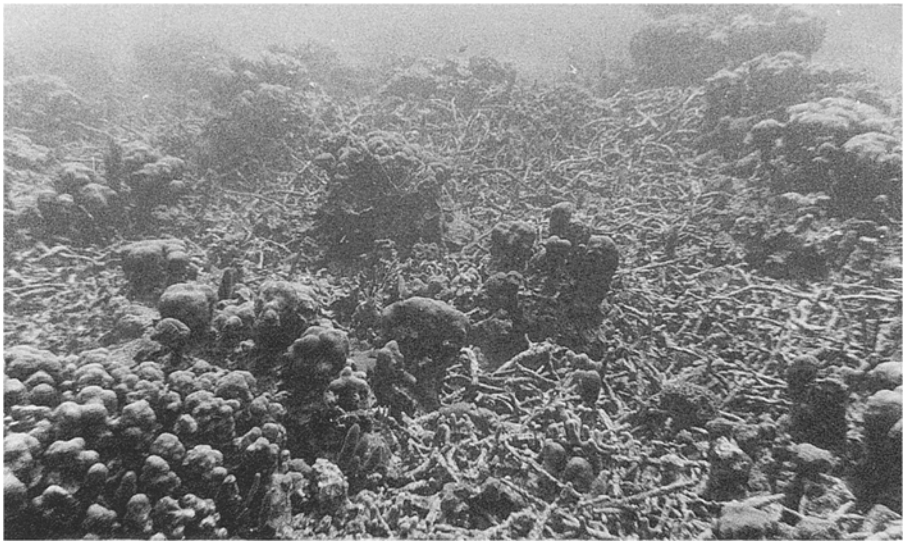

**Fig. 3.** Broken colonies of the branching coral *Acropora cervicornis* scattered among in situ colonies of *Montastrea annularis*. Water depth 8 m, West reef, Discovery Bay, Jamaica, 3 years after Hurricane Allen

platey colonies situated on the deep forereef slope (such as *Agaricia* and *Pachyseris*) are broken by large blocks falling from shallow zones (Woodley et al. 1981; Harmelin–Vivien 1985). The shallow-water corals that are adapted to high energy conditions may be sufficiently robust to avoid excessive breakage but those corals with delicate growth forms that live in water 10–20 m deep, well removed from damage by fair-weather waves, are commonly the worst affected by hurricane-generated waves.

In describing the effects of Typhoon Pamela on the coral reefs of Guam, Randall and Eldredge (1977) observed that normal trade wind surf breaks on the reef margin zone, but the increased height of typhoon-generated waves caused breakage further seaward in deeper water over the reef front and shallow submarine terraces where damage was excessive.

Most observers of the effects of hurricanes on reefs have pointed out how patchy the damage appears to be. The strength of the waves and currents must peak locally, like the wind gusts. Van Woesik et al. (1991) and Done (1992) reported a type of exfoliation on the reef crests of reefs on the seaward margin of the Great Barrier Reef of Australia, whereby a hole is first made into the coral covered substrate and then it is hollowed out. The reef crest is progressively peeled "chunk by chunk" and becomes a bare limestone pavement as slabs of reef up to several metres diameter are tossed down the fore-reef slope.

Sands may be stripped from submarine hollows and channels, and those corals sited seaward and shoreward of patches of sand are commonly scoured white by abrasion.

*Intertidal and supratidal.* Surface sand and soil is stripped from cays; the degree of this erosion is governed by the depth to which the island is submerged by the storm surge and also by the extent of cover by vegetation (Blumenstock 1961; Stoddart 1971). A major storm surge may remove small sand cays completely. The larger and wider cays show relatively less damage. Channels between motus are widened and deepened, and new channels may form, cutting part way or completely across motus. Shorelines retreat lagoonward with low vertical cliffs at their seaward margins, and spits may be eroded or dissected. Scour holes are produced by overtopping waves, especially at the margins of obstacles. Scour trenches are excavated in the lee of shingle ridges or beachrock (McKee 1959). Whole slabs of beachrock are plucked from the bedded outcrop, but they are normally not transported far. Plate-like microatoll growth forms of corals may also be snapped, tilted or even overturned on the reef flat. Ridges of coral shingle on the reef flat produced by earlier storm waves are transported to lee and commonly transformed from a steep elongate ridge into an evenly spread blanket of the coarser particles left as a lag deposit. Where the grain size distribution of reef flat sediments had been analysed before and after a hurricane event, it was found (Flood and Jell 1977; McKee 1959) that most remaining sediments show an increase in percentage of gravel size and above; and most sediments show a decrease in the percentage finer than 0.125 mm.

### *Depositional features*

*Subtidal.* The evidence from the Phanerozoic sedimentary record (e.g. Enos and Moore 1983) demonstrates that the majority of reef debris generated by physical disturbance events accumulates at the foot of the fore-reef slope in deep water. This wedge-shaped apron of talus may contain boulders several metres in diameter. The species composition of the component corals and their mutual orientations indicate that the blocks were derived from shallow water near the reef crest. The persistent surf at the seaward margins of reefs and the considerable depth of these deposits make them inaccessible to all but submersible studies. The nature of the reef front talus of the barrier reef at Belize has been described by James and Ginsburg (1979) from observations made from Alvin in 50–300 m of water. Blocks of individual massive coral colonies and composite reef framework are strewn on the sandy foot of the

**Fig. 4.** Oblique aerial photograph of reef rim of a lagoonal platform reef (Lady Musgrave, GBR, Australia) showing lobes of coral-covered sediment projecting into the lagoon. (Courtesy of P. G. Fiood)

fore-reef slope. Some show renewed encrustation by deep-water species. These boulders diminish in size and number away from the reef front. Blocks are also found perched on narrow ledges on the slope. This talus is enveloped in gravel-sized sediments rich in *Halimeda* plates which are supplied from the shallow and intermediate water depth framework surface. In some fossil reefs it is this fore-reef talus that is the sole evidence of the nature of the shallow-water reef composition, since the in situ shallow-water corals commonly are destroyed by physical erosion, exposure and solution, or their petrography obscured by meteoric and mixing-zone water diagenesis. For some days after a hurricane, plumes of turbid water are carried off the reef. Fine sediment settles in deep settings on terraces and on the muddy reef front floor. For example, a 15 cm thick layer of carbonate mud was deposited in 50 m of water 110 km to the north of Florida Keys as a direct result of hurricane Donna in 1960 (Ball et al. 1967). Much of this material was later reworked. In a study of the offshore effects of Cyclone Winifred in the central Great Barrier Reef area, Johnson et al. (1986) observed linear convex ridge bedforms 1 m high, 40–150 m wide, which had developed in 28–35 m water. The storm waves also caused widespread unmixing of bottom sediments, resulting in coarse lag deposits being later veneered by a mud drape. But the authors believed that within 3 months, bioturbation would homogenize the thin sedimentary units produced by the cyclone.

The deposits in shallow water near the seaward reef crest include gently sloping rubble ramparts where thickets of live branching corals once stood, and grooves partly or totally plugged by coral debris of boulder to sand size.

Those reefs with narrow rims have debris washed from the reef front and the reef top over to the leeward side to accumulate in the lagoon. These lagoonal deposits may take the form of regularly spaced wedged lobes extending from the rim towards the lagoon centre which may later be overgrown by corals (Fig. 4) or the configuration of deltas, or outwash fans, extending lagoonwards from the mouths of channels between motus (Fig. 2a). The coarse, angular fragments accumulate on steep submarine slopes (Fig. 5). Fine-grained sediments settle from storm-generated turbid waters to accumulate as a thin layered deposit on the lagoon floor. When sufficiently large waves are generated from a leeward direction, either by build-up in the lagoon or by refraction from the seaward side round the flank of an island, elongate submarine bars accumulate on the lagoon side of the reef rim (Blumenstock 1961).

*Intertidal and supratidal.* One of the most commonly reported features of storm-generated reef morphology is the storm ridge, or rampart, of coral shingle that accumulates near the seaward margin of the reef flat. The storm ridge created by Cyclone Bebe on Funafuti in 1972 was 19 km long, about 37 m wide and 4 m high. It had an estimated volume of $1.4 \times 10^6$ cubic metres and a mass of $2.8 \times 10^6$ tonnes (Maragos et al. 1973; Baines et al. 1974). This ridge was continuous across motus and gaps between motus but did not occur across the 20-m-deep passes into the lagoon. The storm ridges typical of the low wooded island type of platform reef on the inner shelf of the Great Barrier Reef of Australia are asymmetric ridges of coral shingle with steep inward faces locally reaching 80° and gentle seaward slopes of less than 10° with planar or convex profiles (Fig. 6). Their outer margins are feather edges of shingle on the reef flat and are often too indistinct to map; in plan they roughly parallel the seaward edge of the reef. The inner edge is arcuate with some narrow tongues of shingle extending leeward up to 300 m over the reef flat (Figs. 2, 6, 7) (Scoffin and McLean 1978; Stoddart et al. 1978). These shingle ridges may extend right round the platform reef, but usually occur just on the windward side, where they are 20–70 m in width and 1–4 m high. Trenches cut through storm ridges reveal indistinct layering, tens of centimeters thick, that dips to leeward paralleling the steep slope. The ridge itself may have coarse, cobble- and

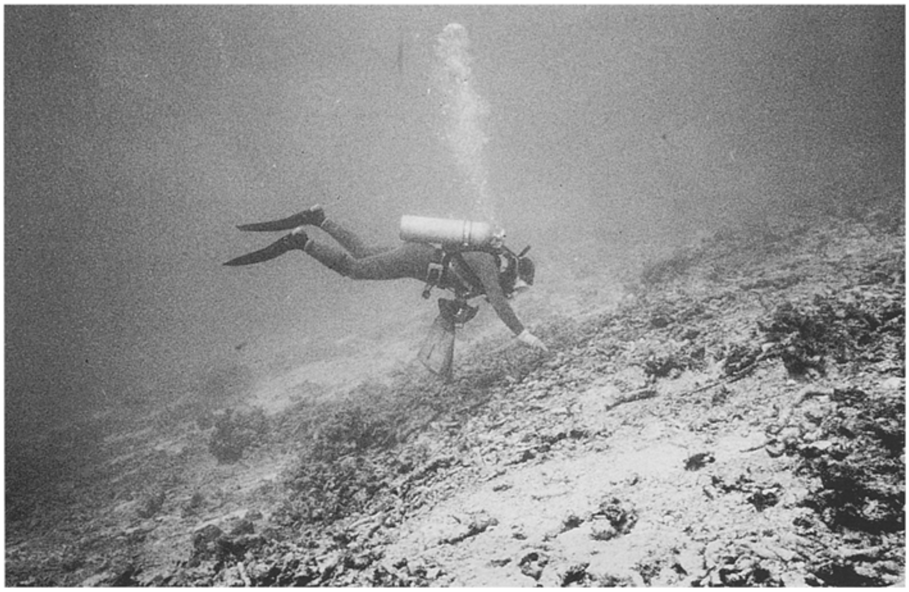

**Fig. 5.** Submarine wedge of storm generated rubble on the leeward margin of Davies Reef, GBR, Australia. Water depth 10 m. (Courtesy of A. W. Tudhope)

**Fig. 6.** Storm ridge (1 m high) consisting chiefly of rods of *Acropora* branches exposed at low tide, Windward margin, Three Isles, GBR, Australia

boulder-sized, regular and hemispherical shaped debris below and shingles of platy or stick-like coral rubble above. The platey and rod-shaped fragments may show an alignment normal to the wave front direction, and an imbrication of stacked fragments dipping to seaward. These storm ridges have been transported and deposited like large asymmetric waves of sediment; material picked up on the seaward side is rolled up the ridge and dropped down the advancing slope.

Pre-existing ridges of coral shingle may be breached or transported to leeward during hurricane events (Gleghorn 1947). On Raroia, ramparts of boulders become progressively higher and coarser where the coastline forms a high angle or an embayment directed toward the prevailing storm directions (Newell 1954).

The morphology of storm ridges is controlled in part by the orientation and nature of the waves. These, in turn, are governed by the physiography of the reef front. The motu islands on atoll rims owe their shape and permanence to additions from storm ridges. McLean (1993) estimated one third of the total land area of Funafuti Atoll is accounted for by storm deposits. Baines et al. (1974) noted that the island locations on Funafuti were characterized by broad reef platforms with convex seaward reef rims and well-developed spur and groove systems below which the reef drops steeply to a sloping terrace 7–8 m deep; whereas the gaps between islands have narrow reef flats and seaward reef rim concavities with no development of spurs and grooves and the reef slopes at angles of less than 10° to depths of 8 m some distance from the reef edge.

In his study of the coral reefs of the East Indies, Umbgrove (1947) noted a relationship between the direction of the dominant monsoon winds and the development and orientation of reef top shingle ridges and sand cays.

Fig. 7. Storm ridge with tongues of shingle. Windward margin. Three Isles, GBR, Australia

Hurricanes do not normally occur in this part of the world, but on occasion, the monsoon winds may be strong enough to break and transport coral branches to build windward storm ridges. In the Thousand Islands north of Java, the east monsoon blows stronger than the west and the storm ridges are located on the eastern margins of the small platform reefs. But in South Celebes the west monsoon is stronger (as the local mountains shelter the reefs from east winds) and ridges build on the west sides of reefs. Where there are no strong winds, ridges do not occur. The sand cays are located on the leeward sides of the reefs due to wave refraction and the confluence of the two opposing wave sets on the lee. So in the Thousand Islands these cays predominate on the west side of the reefs and in South Celebes they occur on the east sides. Whether the sand cay forms before or after storm ridges is probably not a question to which there is a general answer. Shingle ridges may influence the location of sand cays by affecting the patterns of wave refraction and water movement over the reef top and presumably the cays adjust to such changes (Stoddart et al. 1978c).

Verstappen (1954) studied the geomorphology of reefs in this same region. Like Umbgrove (1974), he plotted the wind effect (mean wind velocity × number of hours blowing) for each direction, and after examining 10-y running averages, he observed a significant variation in the direction of maximum wind effect since 1905. Verstappen (1954) studied old charts and compared the relative positions of storm ridges and noted that their movements could be correlated with these changing patterns of wind. In a similar study, Flood (1986) correlated the changing morphology of the sand cay on Heron Reef (GBR) with the records of changing patterns of wind.

Leeward migrating storm ridges may be stacked in series one against another, creating the main substance of windward islands and motus (Cloud 1952). The superimposition of ridges is most noted where the forward movement of shingle is checked by the presence of dense mangrove woodland (Stoddart et al. 1978a). Fairbridge and Teichert (1947, 1948) described four separate ridge systems on Low Isles of the Great Barrier Reefs.

The bulk of the debris in storm ridges on the windward reef flat is derived from the reef crest and reef front between 0 and 20 m depth. The large ridge created at the west reef of Discovery Bay, Jamaica, during hurricane Allen in 1980 originated mainly from stands of living *Acropora palmata* and *A. cervicornis* in the zone between the breakers and 10 m depth. Many fragments were alive immediately after the hurricane, but died within a few weeks. However, not all storm ridge material was necessarily growing at the time of the hurricane; Baines et al. (1974) found that only a small proportion of the vast Bebe storm ridge was recently living coral, most was probably debris on submarine ledges, terraces and in grooves.

The 'reworked' storm ridges usually form much steeper sided structures (Fig. 8) than those contemporaneous with the hurricane. They are sometimes described as beach or shore ridges, berms or breastwork and normally have a concave seaward margin. Gravel sheets are blanket deposits over islets which may be tens of centimetres thick, but generally contain finer debris than the storm ridges. They may have a vertical drop of 50 cm along a sinuous front.

The typical windward storm ridges are rich in platy and rod-shaped coral fragments with some rare blocks present. But, on the leeward flanks of some of the Great Barrier Reef inner shelf platform reefs, the ridges of coral debris consist essentially of fragments of massive coral colonies 10 cm to 2 m in diameter (Fig. 9) (Scoffin and McLean 1978). The dominant corals are *Porites*, and this same genus is especially abundant living on the leeward flanks of these reefs. On some reefs, two discrete boulder tracts are developed separated by a shallow moat (Fig. 9). The position, heights and attitudes of intertidal encrusting and endolithic organisms indicate that these boulders do not, in general, move once deposited.

Exceptionally large boulders of coral or blocks of reef framework are found perched near the windward margin of some reefs (Fig. 10). These blocks may be as much as 50 $m^3$ in volume. Bourrouilh-Le Jan and Talandier (1985) observed on Rangiroa in the Tuamotus reef-edge fractures with radii of curvature measuring 100–200 m from which

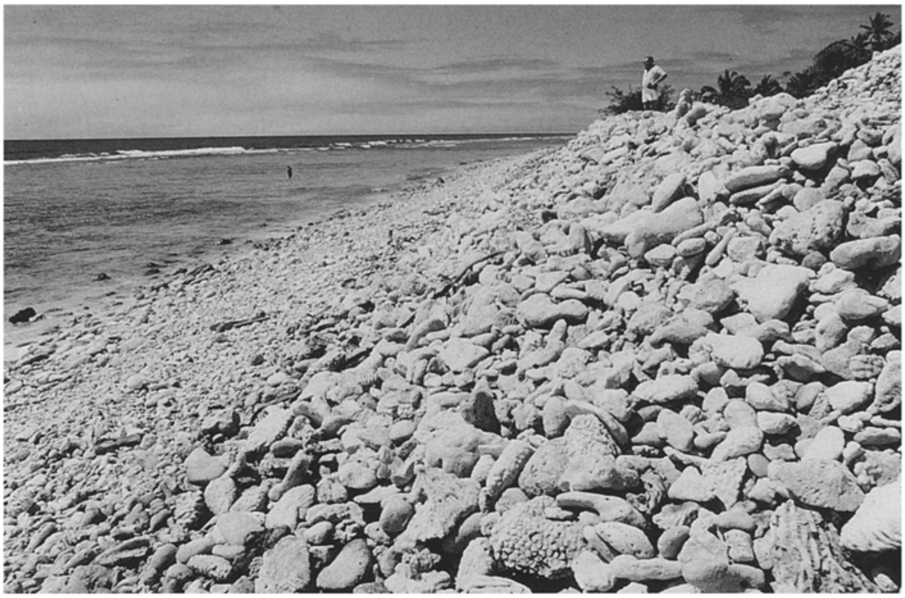

**Fig. 8.** Reworked ridge (breastwork) showing steep crest and concave windward profile. Rarotonga, Cook Islands

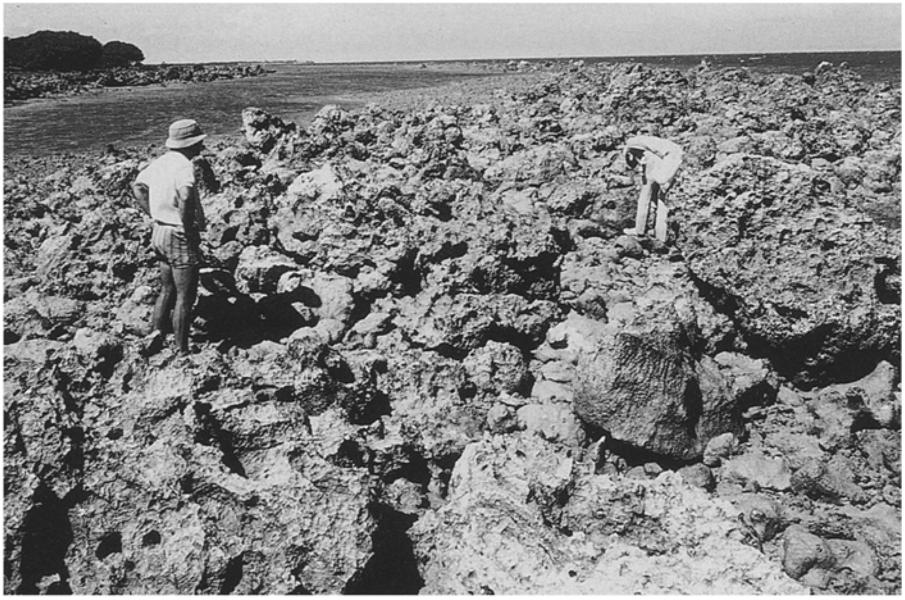

**Fig. 9.** Boulder tract of massive corals (mainly *Porites*) on the leeward flanks of Watson Reef, GBR, Australia. Photographed during low tide. Note an earlier boulder tract beyond the moat

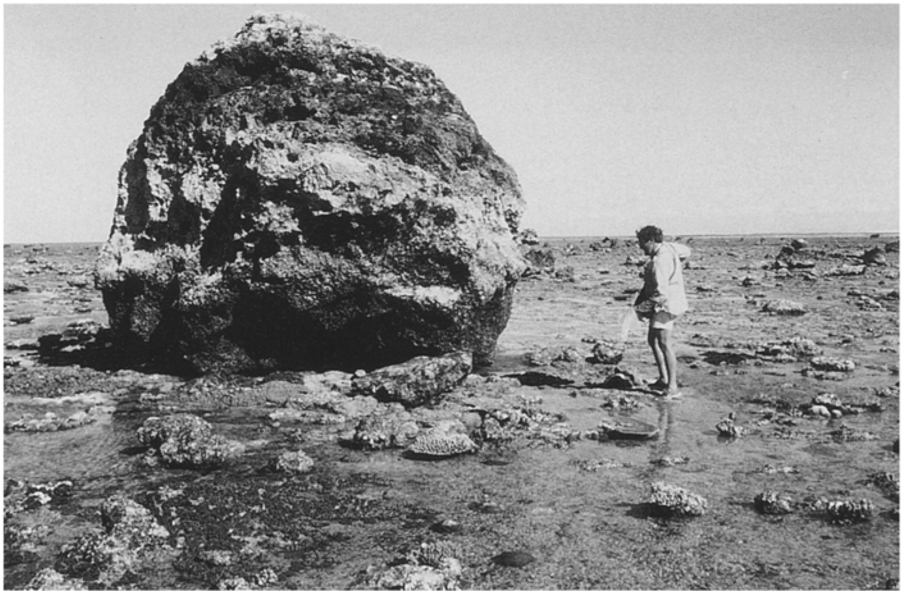

**Fig. 10.** Large block perched on the seaward side of the outer reef at Waterwich Pass, GBR, Australia. This block is approximately 4 × 4 × 3 m in size

blocks had been detached. Reef margin slumps or pulses of tectonic activity may be responsible for this fracturing of the reefs. Associated with these fractures are large blocks up to 20 m in diameter thrown up on the reef flat. The severe hurricanes of 1983 (6 hurricanes occurred in 5 months during the southern summer of 1982–83, which were probably related to the El Niño climatic event) coincided with the appearance of many of these blocks (Guilcher 1988) and were presumably responsible for their transport. Bourrouilh-Le Jan and Talandier considered some of the blocks too large to be lifted by storm waves and suggested it may take the force of a tsunami to produce a wave big enough to lift objects of such size (Bourrouilh-Le Jan and Talandier 1985; Talandier and Bourrouilh-Le Jan 1988).

The waves created during eruption of Krakatoa, Java, in 1883 lifted reef blocks up to 300 cubic metres in volume 100 m from the coast, and the eruption of Paloeweh volcano in 1928 was accompanied by 3 sea waves 5–10 m high on the coast of Flores Island, throwing coral boulders up to 10 $m^3$ in volume on to the beaches (Umbgrove 1947).

The combination of the extreme hydraulic energy conditions during the hurricane and the fracture of parts of the reef result in sediment-laden water flushing deep into the reef framework. During the ensuing calm, fine detrital particles will settle from suspension in the unsealed cavities within the framework. The resulting layer of sediments will contain grains of external and internal (framework) origin and be graded from coarse at the base to fine above. Several such layers in reef internal cavities indicates periodic storm action (Scoffin and Tudhope 1993).

### *Recovery*

The recovery period is the time taken for the reef to return to pre-hurricane conditions. During this period, fair-weather waves and tidal currents, plus seasonal storms of intermediate intensity, impinge upon the newly created substrates and geomorphological features. Biological processes of growth and destruction act in consort with these background physical conditions leading towards a new equilibrium. The greater the damage to the reef, the longer the recovery time, which may take anywhere between 5 and 40 y. The recovery may be punctuated by another hurricane.

*Subtidal.* Initially the shallow water zone exposes large areas of bare rock. These are covered fairly rapidly with green fleshy and filamentous algae (In Funafuti–*Chorodesmis* (Baines et al. 1974), in Jamaica *Trichosolen* (Woodley et al. 1981), in Puerto Rico *Bryopsis* (Glynn et al. 1964)). Surviving echinoids (such as *Diadema antillarum*) graze these algae-covered dead coral surfaces and may contribute a noticeable increase in silt-sized coral fragments to the fine particulate sediments of the reef. Eventually coral cover increases; the undisturbed massive forms continue as before, some of the partially dead branching corals recover and expand, and the bare rock surfaces are colonized by the opportunistic species. In the Barbados after Hurricane Allen, the first coral colonisers were *Millepora alcicornis*, *Porites astreoides* and *Agaricia agaricia* which had grown to about 10 cm diameter after 10 y and covered less than 10% of the formerly scoured surfaces (personal observation).

Punctuations in the growth of reef framework, such as that induced by a hurricane, may permit crusts of lithification to develop on the truncated reef surface. These submarine cemented crusts have distinctive petrography (Lighty 1985) and represent hiatuses in framework vertical development. They also critically influence the pathways of internal percolating fluids (Lighty 1985).

The new deposits of freshly dead coral plates and branches will be encrusted by coelobites (Choi and Ginsburg 1983) Those surfaces at the base of a pile of rubble will be overgrown by the encrusters, such as sclerosponges, that prefer the deep, dark cavities (Scoffin and Hendry 1984) and will not undergo the normal stages of encrustation from light to dark conditions that is reflected in the encrusting sequences on corals that were progressively buried (Martindale 1992).

Sand is gradually shifted back into the grooves and onto shallow ledges where it had been stripped during the heavy surf.

*Intertidal and supratidal moats and microatolls.* Storm ridges on reef flats may pond water at low tide. The level of the water at low tide is controlled by the permeability of the ridge and the lowest point (or sill) along its length. Commonly, reef flat moats are hundreds of metres long, tens of metres wide and 5–50 cm deep. Corals may grow in these moats up to a maximum level of daily replenishment throughout the monthly tidal cycle, i.e. to high water neap tide level (Scoffin and Stoddart 1978). The water is relatively still in moats during low tide and so massive corals will develop dead horizontal surfaces when they reach the air/water interface. Growth is then in the lateral direction only and massive corals build microatoll forms. The fate of these reef-flat, moated microatolls lies in the hands of the damming storm ridge. If the ridge is breached (by a later storm) and the moat is drained, the microatolls will be exposed to the atmosphere at low tide and die (Fig. 11). If the moat level is only lowered then the microatolls will continue growth at a new lower level developing a terraced or top hat morphology (Moorhouse 1936; Scoffin and Stoddart 1978). If seasonal bands can be detected in the internal structure of the coral (by, for example, X-radiography of slabs cut along the growth axis) then it will be possible to count the number of years since the new shape commenced and, thus, hindcast the ridge-breaching event (Hopley and Isdale 1977). If the water level during low tide in the moat is raised (by, for example, steepening of the ridge, or a reduction in its permeability due to interstital mud or cement) then the microatolls develop a taller rim and this annulus may eventually develop a new higher dead surface (Scoffin and Stoddart 1978).

Moated microatolls typically have the following characteristics:

1. Broad disc-like shapes less than 50 cm tall.
2. The stillness of the moat water results in planar dead upper surfaces.

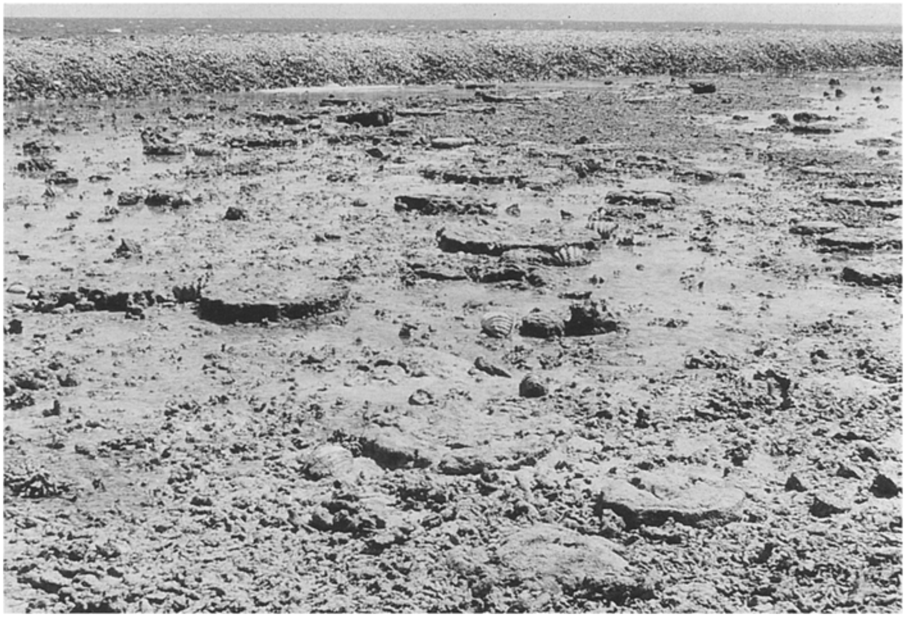

**Fig. 11.** Dead microatolls exposed in a drained moat. The storm ridge (at top of photograph) that formerly ponded water here has recently been breached. Windward margin Nymph Reef, GBR, Australia

3. As moat levels change periodically, terraced surfaces are common.
4. The microatolls are seated on, and ultimately surrounded by, storm produced coral shingle.

In contrast, open-water microatolls which grow roughly to a maximum height of low-water spring tide level are tall steep-sided colonies, with irregularly shaped tops, lacking terraces, and in contiguous structure with reef framework. Without storm ridges, moats are less common and reef flat microatolls are then more prone to develop oriented asymmetric growth forms, depending upon water drainage and the direction of maximum radiation at low tide.

## Movement and stabilization of ridges

Over the months and years following a hurricane any reef-flat storm ridges will be reworked into stable landforms, mainly through the agency of more frequent lower magnitude storms (Bayliss-Smith 1988). After a hurricane there will be an immediate tendency for waves to rework the deposit, since the reef crest corals are too damaged to hold back even average-sized waves. The storm ridges on the seaward side migrate lagoonwards and in some cases join islands. In other cases the debris on the ridge is spread out to form a sheet of rubble. This leeward migration of ridges is reported for several islands (Blumenstock 1961; Baines and McLean 1976; McLean 1993; Stoddart et al. 1978b). Estimates of the rate of migration vary from about 1–10 m per year. Movement in the first year is most rapid, as initially disequilibrium is extreme and reef crest corals are not yet recovered. Also, with time the debris migrates into a more protected location. Baines and McLean (1976) used painted boulders as tracers to detect the movement of particles under normal swell with waves 1.5 m in height on the Bebe ridge of Funafuti. Particles 20–30 cm in diameter were moved tens of metres along and over the ridge during only a few days. Particles in excess of 1 m in diameter were not moved. The really large blocks thrown up on to the windward reef flats are left as lag deposits. Many of the isolated blocks (e.g. Fig. 10) on reef margins were perhaps accompanied earlier by extensive storm ridge deposits of shingle which was subsequently transported away whole or after being broken down by biological agencies. During a ridge's shoreward movement the crest height may initially increase then decrease in later years, and further, the profile of the seaward slope changes from convex to concave (Baines and McLean 1976). On the inner shelf of the Great Barrier Reef of Australia composite islands of shingle and sand composition suggest that the leeward migration of shingle has encompassed partly or wholly the leeward sand cay (McLean and Stoddart 1978).

The intertidal reef flat is a zone of active bioerosion by grazers such as parrot fish, echinoids, chitons, gastropods and by borers such as bivalves, worms, sponges, crustaceans, microscopic algae and fungi. The fresh supply of coral boulders during a hurricane offers a whole new suite of hard substrates for endolithic organisms. Many of the large perched blocks show typical intertidal zonation: e.g. on blocks at Low Isles, GBR (Fig. 12), an upper zone of oysters (*Crassostrea amasa*), with beneath, a zone dominated by chitons (*Acanthozostera gemmata*), a basal zone with borings by the clam *Tridacna crocea*.

The top supratidal surfaces of beach ridges of shingle are commonly blackened by the thin coat of endolithic filamentous algae (Fig. 13). When examined closely (Fig. 14 some of the fragments are a fraction of their former mass. By this means the cycle of reef top sedimentation proceeds: corals grow in shallow water on the reef front, storms break the coral, transport the fragments and drop them as a ridge on the reef flat, the coarse particles are broken down to cobbles, gravel, sand and mud sizes and transported into the lagoon or off the reef. The storm ridges are a half-way house for much of the reef calcium carbonate.

**Fig. 12.** Blocks resting on intertidal reef flat at Low Isles, GBR, Australia, showing distinctive zonation of encrusters and bioeroders

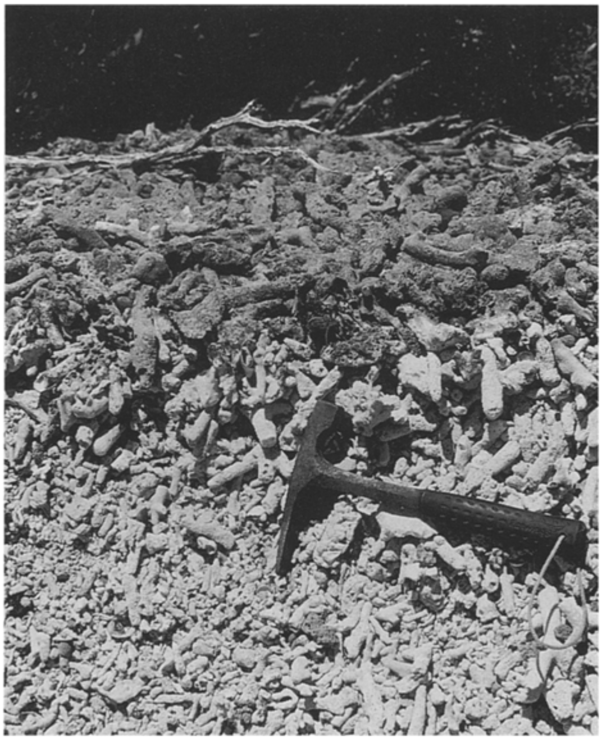

**Fig. 13.** Supratidal (reworked) ridge of storm debris showing dark surface layer of blue-green algae infestation. Low Isles, GBR, Australia

Cross-rim water movement (and hence shingle transport) is reduced on wide reef rims and reef rims with long islands. The leeward migration of storm ridges is arrested by either the route being impeded by earlier ridges and dense woodland or by being stabilized by the growth of rooted vegetation or by lithification. Mangroves commonly find storm ridges suitable substrates for growth on the reef flat (Fig. 15). Thirty-eight platform reefs on the inner shelf of the Great Barrier Reef were surveyed in 1973 and there was a noticeable correlation between mangrove distribution and storm ridges (ramparts) (Scoffin and McLean 1978). Stoddart (1971) described succession which the various mangroves in the Caribbean follow after initial jcolonisation: first, *Rhizophora* (red mangrove), then *Avicennia* (black mangrove), *Laguncularia* (white mangrove) and finally a mature woodland of largely non-mangrove species. Individual storm deposit increments may have their own distinctive suite of plants, with the more mature members of the sequence normally found on the older, more leeward, shingle ridges.

Those trees on the periphery of a mangrove woodland may suffer defoliation by storm wave and spray-laden wind and die. Those in interior parts may survive. However, even dead trees stand for many years (Stoddart 1971), and the impenetrable tangle of tough trunks, branches and roots may continue to anchor down the substrate and trap further sediment for considerable time. Other supratidal vegetation such as vines, creepers, low herbs, grasses and sedges, along with intertidal grasses and algae play a part holding down storm ridge shingle (Fig. 16). This immobilization by vegetation may physically and chemically promote the lithification of the shingle into rock. Most shingle ramparts require some fine interstitial sediment to aid water retention for cementation to proceed, also the particles must be stationary and within the intertidal zone. Typical cements are micritic and peloidal Mg calcite of 14–18 mol% $MgCO_3$ (Scoffin and McLean 1978). They commonly show (marine) vadose fabrics with draped and pendant crusts, up to a centimetre thick, enveloping coral fragments. The surfaces of cement crusts may be smooth or mammilated (Fig. 17). Morita (1976) suggested that the microflora that is associated with coral debris that becomes anaerobic a few centimetres below the surface is responsible for the precipitation of the calcite cement. The cements occurring at different heights above low water may reveal different fabrics and compositions and allow a reconstruction of former sea levels from their distribution (Montaggioni and Pirazzoli 1984). Those parts of shingle ridges (e.g. tongues) that are well removed from heavy surf action are likely to stay immobile the longest and therefore be lithified, making their existence still more permanent. See for example the storm ridges of

**Fig. 14.** Closeup of surface of ridge in Fig. 13 showing the dark pitted surface (phytokarst) of coral branches and gastropod skeleton. Low Isles, GBR, Australia

**Fig. 15.** *Avicennia* mangrove colonizing ridges of storm debris. Pipon Reef, GBR, Australia

various ages on Three Isles GBR (Fig. 18, 19) (Stoddart et al. 1978b).

Lithified storm ridges weather to leave prominent beds of cemented foresets (bassett edges). (Fig. 20). The layers more resistant to erosion have more cement and generally finer constituents than the less resistant layers. The bedding occurs as steeply dipping foresets (40–70°) on the tongue shapes, like anticlines plunging to leeward (Fig. 21), but as shallowly dipping (20–40°) arcuate bands between.

Intertidal areas of sand cays may lithify also, producing beachrock. These rocks have typical beach sand grain composition and texture, bedded character and attitude; but in these rocks the cement is normally fringes of acicular aragonite. The general consensus is that this cement is precipitated from sea water intertidally just below the sediment surface. The process may be rapid but it requires the sand grains to be immobile. Those beaches that are immobile are either out of the way of normal daily surf action, i.e. are formed by some unusual event such as a hurricane, or are held stationary by some form of vegetation. Both cemented storm ridges and beach rock are most likely to be found in areas where extreme events occur infrequently.

## Discussion

*Geological past.* For an event in the geological past to be recorded, there has to be a deposit. For a deposit to be preserved, there has to be 'accommodation space' in the environment. Such space is not normally available above sea level. What is more, though hurricanes may leave a deposit in shallow water, the next event commonly removes it rather than simply adding to it. In Palaeozoic and Mezozoic reef rocks it is the forereef talus that is our best evidence of storm events, as these deposits accumulated

**Fig. 16.** Flat surface of storm shingle stabilised by tufts of grass and mats of filamentous algae. Nymph Reef, GBR, Australia

out of reach of later physical disturbance. The detailed stratigraphy of such deposits is difficult to decipher. Even the raised terraces of Pleistocene reefs exposed on uplifted islands like Barbados are unlikely to be preserved over geological periods of time.

*Recent past.* We should be able to interpret the Quaternary history of hurricanes more easily. We can map reef-top geomorphological features, determine their geometries, elevations and ages by $C^{14}$ dating. But still the hurricane record itself is hard to understand. There are certain paradoxes. In a region where hurricanes occur very frequently, it may be impossible for branching corals to grow successfully in shallow water. That is, the recovery time of the coral colonies is longer than the interval between hurricanes. Consequently no storm deposit of coral debris would be expected, even with strong storms. Woodley (1992) has suggested that the 'classic' description of Jamaican reefs may relate to atypical assemblages for the area. In Jamaica *Acropora palmata* stands of 1 m height take about 12 y to grow, but the total number of years this century in which reefs have been free of major disturbance for longer than 12 y is only 33, and 24 of them (1956–1980) were in a long interval of 36 y from 1944 to 1980, the period when the 'atypical' descriptions were made (Woodley 1992). Pleistocene terraces of Barbados contain, in places, 2 m high in situ massive colonies of *Montastrea annularis* separated by piles of *Acropora* debris. Though tempting to picture that these reefs normally had a cover of both massive and branching corals when alive, rates of growth considerations alone suggest that the *Acropora* (8 cm/y) would be alive for only a fraction of the time the *Montastrea* (1 cm/y) was growing; otherwise the branching corals would swamp and kill the massive forms before they grew to such sizes.

We note that the really major accumulations of storm debris occur when a hurricane hits a reef that has been free of such events for a long time previously. For example, Ophelia struck Jaluit atoll after a hurricane-free period of 50 y (McKee 1959), Allen struck Jamaica after a gap of 36 y (Woodley 1992). Also when a hurricane of similar intensity strikes a reef again before significant coral recovery has occurred, little damage is recorded and few deposits are formed; for example, Gilbert 8 y after Allen on Jamaica's north coast (Woodley 1989) and Betsy 5 y after Donna on Florida Keys (Perkins and Enos 1968). If a storm deposit indicates the incidence of a hurricane following a long period when there were no physical disturbances, do we interpret abundant fossil storm deposits as representing frequent or infrequent storms in the past?

Numerous authors have reported the presence of cemented storm deposits (ramparts or platforms), particularly on Pacific reefs, whose ages cluster around the period 3000–4000 y BP (Curray et al. 1970; Umbgrove 1947; Cloud 1952; Stoddart et al. 1978c; Hopley 1982). Does this abundance of storm deposits represent a time when: (1) there were more storms than usual; (2) more storm deposits than usual were created; (3) the storm deposits created were unusually well stabilized and preserved?

If greater than average storminess occurred in the past, then shingle storm ridge age results should show statistical clumps separated by intervals with few or no age results, assuming a constant source of material was available. After grouping ridge ages in successive 500-year intervals from 0 to 6000 y BP on Lady Elliot Island, Australia, Chivas et al. (1986) concluded that no particular interval had anomalously more records; the radiocarbon ages of 41 *Tridacna* samples from shingle ridges were uniformly distributed throughout the last 3200 years.

During the Holocene transgression, the rate of sea level rise was generally faster than the rate of coral reef growth. This led to the reefs adopting a 'catch-up' style of growth (Neumann and Macintyre 1985). During the period 3000–5000 y BP many reefs (particularly those of the Caribbean and Indian Ocean) would not yet have reached sea level. Consequently they would not yet be able to afford the protection to the coast that they were to provide later. Thus, there would be a time (the "high-energy window", Neumann 1971) when higher waves than normal would impinge on the coast. These high energy times could perhaps be responsible for the mid-Holocene storm deposits. There are arguments against this being the case. First, if the reefs had not yet reached sea level, from where did the coral detritus come that made the storm deposits, and secondly, apart from bordering continental or high coral islands, were there suitable intertidal flats on which the debris could accumulate? Further, the sea level curves for

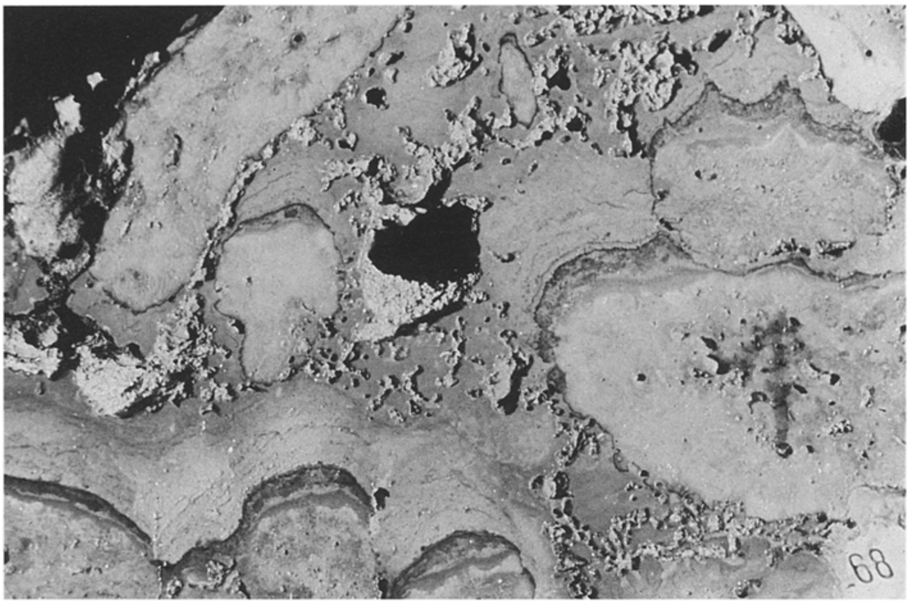

**Fig. 17.** Cross section through coral shingle showing crusts of micritic cements. The crusts are locally banded and show mammilated surfaces. Coral branches approximately 2 cm diameter. Windward platform, Nymph Islands, GBR, Australia

**Fig. 18.** Vertical aerial photograph of Three Isles taken in 1945 (by the Australian Royal Airforce) showing storm ridge locations. Maximum diameter of reef is 1 km

**Fig. 19.** Aerial photograph of the western flank of Three Isles taken in 1973 showing that additional storm ridge material is concentrated at former ridges

the regions of abundant mid-Holocene storm ridges normally point to present sea level being reached 5000–6000 y ago, so there should be no high-energy window at the time of the storm debris deposition.

It has been argued that the mid-Holocene was a time of climatic optimum and consequently the warmer climate would have generated more storms of hurricane intensity. This may be the case, but would this alone account for the number of deposits and their preservation? As pointed out earlier more frequent storms may result in fewer coral shingle deposits.

As evidence from the resurveys of recent hurricane deposits show a rapid leeward migration of storm ridges and windward islands of about 2 m/y (Blumenstock et al. 1961; Baines and McLean 1974; McLean 1993; Stoddart 1974) the question is raised what was special about this period to secure the preservation of the reef flat storm deposits?

There are several studies that suggest (especially from the evidence of raised in situ reef framework), sea level was about 1 m higher than present about 3500 y ago (e.g. Buddemeier et al. 1975; McLean et al. 1978; Woodroffe et al. 1990). During the ensuing fall in sea level a wide bench (the reef flat) of former reef would occur on which later storm deposits would be perched and relatively hard to remove (Cloud 1952). Some authors have discounted this as a cause for the abundance of the 3000 y old ridges because of the absence of exposed former in situ subtidal reef framework, and the fact that the Holocene platforms of coral debris are all within the elevation range of modern storm ridges (Curray et al. 1970), though Hopley (1982) believes the lack of Holocene shingle ridges in the Caribbean compared to their abundance on the Great Barrier Reef may well relate to the different Holocene sea level curves of the two regions.

On the low wooded islands of the northern Great Barrier Reef, though the elevation of the platforms may be commensurate with the heights of modern ridges, the 3500-y-old microatolls contained within them indicate a former level of high-water neap tides about 0.7 m above those of the present day (Scoffin and Stoddart 1978). This change may represent a former high relative sea level or simply a change in the range of the tides.

At the local level, such as across the North Queensland shelf, platforms preserved on inner shelf reefs have been noted (Stoddart et al. 1978). There is no question that the outer barrier reefs suffer violent surf action during storms, as these have been witnessed and the perched blocks attest to earlier occurrences. So why are storm deposits preserved only on the inner shelf reefs? There are several factors that contribute to this situation. Firstly, both continental attenuation and hydro-isostatic effects result in a relative increase in the rate of subsidence of the outer shelf compared with the inner shelf (Hopley 1982). Even though parts of the outer reefs reached sea level at a similar time to the inner reefs, they had not, on account of depth and configuration of foundations, built broad reef-flats that compared in width and elevation with those inshore. So the morphological classification of the reefs on the Queensland Shelf presented by Hopley (1982) of juvenile (essentially vertical Holocene development) to senile (essentially horizontal development) is reflected in their configuration from outer barrier (juvenile) to inner shelf (senile). It is not unreasonable to suppose that the supply of detritus was greater on the inner shelf reefs. Firstly, the outer reefs suffer higher energy conditions and corals on the reef-front will in general be more adapted to this and therefore have more robust skeletons. And secondly, there is a general consensus (e.g. Sammarco and Risk 1990) that the inner shelf reefs suffer greater from the effects of bioerosion, especially boring organisms, possibly on account of the increase in nutrients inshore favouring the abundance of suspension feeders such as *Lithophaga*. Consequently the inner-shelf coral skeletons are more easily broken. A further consideration is that the steep fore-reef slopes of the outer barrier reefs promote the seaward migration of reef crest debris, whereas the inner shelf reefs may be terraced and have more gentle seaward profiles favouring the reef top accumulation of debris.

The most likely cause for this cross-shelf trend is the increase from outer to inner shelf of the difference between the energy of storm and fair-weather waves. The storm waves are so strong on the outer reefs that most storm deposits will be dispersed fairly rapidly and perhaps spread over the back-reef lagoon area, leaving only the giant blocks as relics. The inner reefs are relatively sheltered from the normal ocean wave action, when a storm strikes them the effect is more difficult to erase later (Scoffin et al. 1978).

The abundance of storm ridge deposits of 3000–4000 y age is most probably due to their stability after a slight fall of relative sea level. There are still problems with the rates of the processes: a relative sea level fall of 1 m in 2000 y is unlikely to influence a horizontal migration of storm-ridge shingle of 1–2 m per year. Likewise, though lithification may be swift in the intertidal zone, the few dates available (Scoffin and McLean 1978) indicate that the cement is about 1000 y younger than the coral shingle. However, on recently emerged reef rims, the eroding and transporting wave action will not normally impinge on the innermost portions of the intertidal reef flat. Consequently any storm debris that was deposited there would be better sited for stabilization by vegetation and/or interstitial cement. Any subsequent storm deposits migrating across the reef would then be arrested and accreted on the windward side of the older ridge. This barrier may require only one major deposit to get it started and thereafter it builds to proportions that are impossible to erode by all but the most extreme events, becoming lithified and more stable as time goes by. The initiating trigger may be considered a random event, in that it is contingent both on existing reef morphology and on individual cyclone behaviour, and this, together with the rapidity of subsequent morphological changes may explain some of the spectacular differences between the surface features of closely adjacent reefs on the Inner Shelf of the Great Barrier Reef (Stoddart et al. 1978c).

Though a few researchers have reported differences in reef-top geomorphology on reefs in hurricane belts versus non-hurricane areas, I am unaware of publications that indicate the major differences in the three-dimensional structure and geometry of reefs from the two contrasting areas. Beside differences in the framework structure, result-

**Fig. 20.** Steep leeward margin of unconsolidated storm ridge overlying the projecting bands (bassett edges) of a cemented former storm deposit. Turtle III Reef, GBR, Australia

**Fig. 21.** Cemented and partially eroded storm ridge shingle preserving former tongue shape. Beds approximately 20 cm thick. Low Isles, GBR, Australia

ing from the greater predominance of fragile platy and branching corals in the protected seas and more massive and encrusting skeletons in the rougher seas, other differences may be expected. The periodic truncation of reef front coral growth and the development of cemented crusts on the bare surface may create a type of layering within the framework that is absent in similar positions in reefs growing in undisturbed locations. Whether or not the $CaCO_3$ production rate (as well as style) differs significantly in hurricane belts versus non-hurricane areas is open to debate. Some authors (e.g. Stoddart et al. 1978c) have suggested a slowing down of $CaCO_3$ production as a result of hurricanes, but other authors (e.g. Hubbard et al. 1991) suggestes that the sweeping away of sand from the reef crest will facilitate greater colonization of newly exposed hard substrates by corals. It is presumed that reefs in calm seas will have internal structures in which windward framework growth predominates over the leeward accumulation of prograding wedges of coral shingle.

## Summary

Hurricane waves and storm surges may erode reef crest corals and sediments down to about 20 m depth. The deposits of debris accumulate as talus at the foot of the fore-reef slope, on submarine terraces and in grooves on the reef front, on the intertidal reef flat as storm ridges of shingle or boulders and as isolated blocks of reef framework, as accreting beach ridges of leeward migrating shingle, as lobes and wedges of debris in back-reef lagoons, as drapes of carbonate sand and mud in deep off-reef locations in the fore-reef and lagoonal areas.

The recognition of past storm conditions may rely as much on factors such as the assemblage of corals and other reef biota, the occurrence and shapes of microatolls, the petrography of reef framework structure, as on the existence of reef flat storm deposits.

The violence of a given storm relative to normal fair-weather conditions influences the extent of damage. The length of time since the previous major storm influences the amount of coral debris created and the length of time after the hurricane before a subsequent storm influences the degree of stabilization of reef top storm deposits and hence their chance of preservation.

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