Reports

Fossilization of Bermuda Patch Reefs

Abstract. *Living corals on Bermuda patch reefs build a primary framework which, in places, is so destroyed by boring organisms that the reef surface subsides. Organisms that encrust the reef cavities are preferentially preserved as the framework is bored. Burial by loose sediment stops framework growth, encrustation, and boring. Finally, cementation completes fossilization.*

The Bermuda Platform is situated in the North Atlantic Ocean at 65°W longitude and 32°N latitude. The Bermuda islands, built chiefly of calcareous eolianite, occur on the southeast side of the platform. Living reefs abound on the shallow margins of the platform and in the open lagoon to the northwest of the islands. The living surfaces and fossil interiors of several patch reefs of the North Lagoon were studied to elucidate reef fossilization processes.

The patch reefs are roughly circular in plan, 100 to 800 m in diameter, and rise from a lagoon floor 18 m deep, reaching to within 1 to 4 m of the sea surface (*1*). The reefs have irregular top surfaces consisting of knobs and ledges separated by valleys (Fig. 1a). The knobs are 1 to 5 m in diameter and project 1 to 3 m above the valley floors, whereas the ledges are 1 to 10 m in diameter and project up to 1 m above the valleys. Corals are abundant on the surface of knobs, common on ledges, and rare in valleys. Valley floors normally have a thin cover of loose sand.

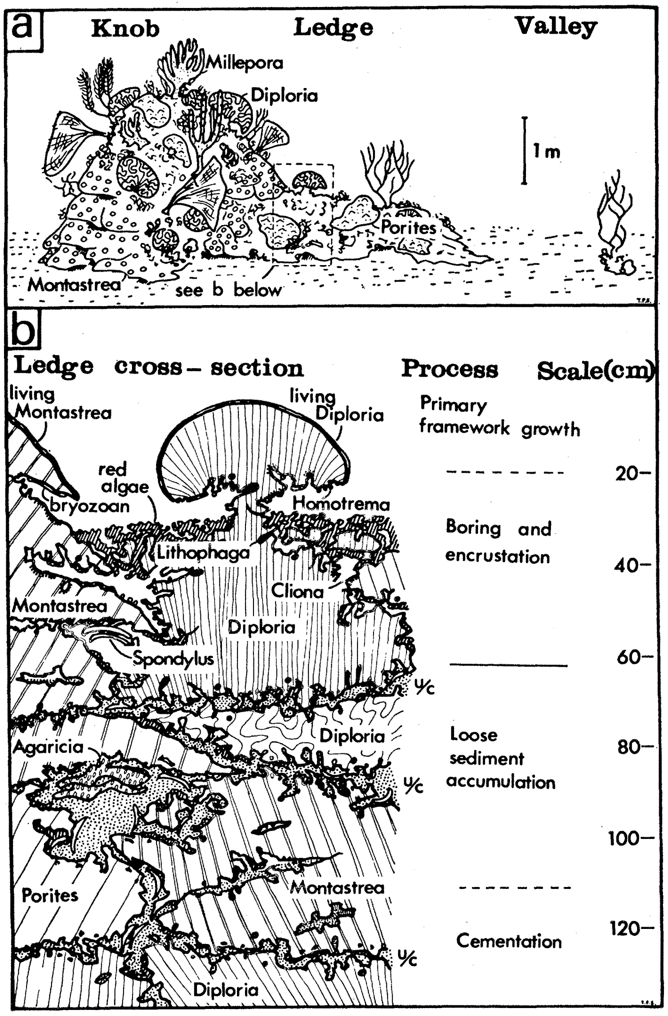

Fig. 1. (a) Typical knob, ledge, and valley of a patch reef of the North Lagoon, showing principal corals of the primary framework and their common growth forms. (b) Cross section of a ledge showing the depth zonation of active processes. The *u/c*'s represent surfaces of small unconformities.

Observations of the living surfaces of reefs were made during scuba dives undertaken in summer 1971. Information on the internal structure of the upper 2 m of the reefs was obtained from serial sections through large reef blocks. Fifty blocks of reef rock (the largest piece was 2 m^3 in volume) were excavated underwater with the aid of a 25-kg pneumatic drill. The specimens were floated to the sea surface with inflated tire inner tubes, towed to land, and then sawed by hand with a 110-cm masonry saw with a blade tipped with tungsten carbide. Comparative studies of the growth and fossil structures reveal that the chief processes that interact to produce the internal structure of these patch reefs are (i) growth of a primary framework, (ii) boring action of organisms, (iii) organic encrustation, (iv) burial by sufficient particulate sediment to kill organisms, and (v) cementation.

The primary framework consists mainly of corals. The six species *Diploria labyrinthiformis, D. strigosa, Montastrea annularis, M. cavernosa, Porites astreoides,* and *Millepora alcicornis* represent about 90 percent of the living corals. *Diploria* colonies occur as massive, mushroom-shaped domes common on all surfaces, *Montastrea* as massive domes or as shingle-like growths of branching plates most abundant on knob sides, *Porites* as platy domes common on all surfaces, and *Millepora* as branching radiating spires occurring predominantly at knob crests (Fig. 1a). In the deeper water on the flanks of patch reefs the tree-like branching corals of *Madracis decactis, Porites porites, Oculina diffusa,* and *O. valenciennesi* are common.

Many forms of reef borers occur on the reefs (*2*); these include bivalves (*Lithophaga nigra, L. bisulcata, Gastrochaena hians*), polychaetes (*Eunice schemacephala*), sponges (*Cliona vastifica, Cliona* sp.), and endolithic algae. *Lithophaga* and *Cliona* are the most conspicuous. Boring is most active on dead, porous reef surfaces in sheltered areas beneath the exposed corals. Most borers only penetrate a few centimeters into a massive skeleton. However, successive generations and composite borings (such as a vacated *Lithophaga* hole later infested by *Cliona*) cause the skeleton to crumble away along an advancing "front" of boring. When boring is arrested, a zone of bored skeleton (up to several centimeters thick) results, with the inner part retaining best the coral structure (and perhaps the only identifiable fossil boring tubes), the outer part being so riddled with holes that it readily disintegrates. The timing of the termination of boring by burial will determine how much original coral remains. Thoroughly bored coral surfaces are common inside the reef and represent small-scale unconformity surfaces.

Encrusting organisms abound between corals on the reef surface and on the walls of cavities within the primary framework. The dominant calcareous encrusters are red algae, bryozoans, serpulid worms, corals (*Agaricia fragilis* and encrusting forms of *Millepora alcicornis*), bivalves (*Spondylus americanus* and *Chama macerophylla*), and attached foraminifera (*Homotrema rubrum*). As a rule the plant encrusters (and also *Millepora alcicornis*) inhabit the well-lit areas, whereas animal encrusters predominate in the dark cavities (*1*). Borers and encrusters can tolerate water of slower circulation than the corals of the primary framework, but permanent burial by particulate sediment kills frame builders, borers, and encrusters.

The loose sand on the patch reefs is produced by the calcareous green alga *Halimela*, *Homotrema*, mollusks, corals, and coralline algae. Doubtless, much of the fine sediment is derived from the coral framework by the activity of boring organisms. Loose sediment produced on the reef surface falls until it reaches a resting place from which it cannot be dislodged. Seawater circulates the cavity network within prominent knobs, flushing out loose sediment and bringing nutrients to the resident reef borers and encrusters. Particulate sediment accumulates within the lower interstices of the reef, generally to a level about 30 cm below the living framework on the low ledges (Fig. 1b). Loose sand also overlies the reef rock on the valley floor to a depth of about 10 cm and some escapes off the reef through gaps in the rim, or collects in the bowl-shaped central areas of large patch reefs.

Cementation commences at a depth of at least 30 cm beneath the level of loose particulate sediment inside the lagoon patch reefs. Generally, however, the reef rock has by this stage reached its final organic composition and internal structure (for this position of sea level), so cementation merely consolidates the sediments and fills minor cavities with fine spar.

These processes operate roughly sequentially down through the reef (Fig. 1b). Sawed sections reveal that the greatest influence on the internal structure of the reef are the corals of the primary framework. The fabric of the primary framework built at the reef surface is best preserved when one coral grows, reaches maturity, dies, and is overgrown by another. Unimpeded coral growth of this sort is seen most at the reef margins. However, in the central, more sheltered areas of Bermuda patch reefs, boring and encrustation play a vital role in modifying the original structure. When the primary framework is attacked by borers the dead undersurfaces and interiors of corals are excavated. The holes so produced are suitable dwelling places for encrusters, or more borers, but are rarely suitable sites for renewed growth of the primary framework, the corals of which prefer well-lit, well-circulating waters. This, coupled with the observation that borers preferentially attack dead, porous coral skeletons rather than living encrusters, means that as more reef rock is bored, more primary framework is removed, allowing thicker encrustations to build up on the fresh cavity walls. Thus, encrusters may progressively replace the primary framework, so that if a long time elapses before burial by particulate sediment (which terminates these organic processes) very little original coral may remain. The buried reef may consist predominantly of the skeletons of those organisms that could grow best in dark, protected cavities of limited water circulation; for it is such organisms that became attached to the reef so late (that is, just before burial) that they escaped extensive boring. Consequently, where boring is prevalent, corals that prefer to live high on knobs—such as the branching varieties of *Millepora*—are rarely found in growth position in the fossil reef. Encrusting animals, rarely conspicuous on the open reef surface—such as *Spondylus*, *Homotrema*, bryozoans, and *Agaricia*, which grow in dark, sheltered cavities—are common in the fossil reef rock.

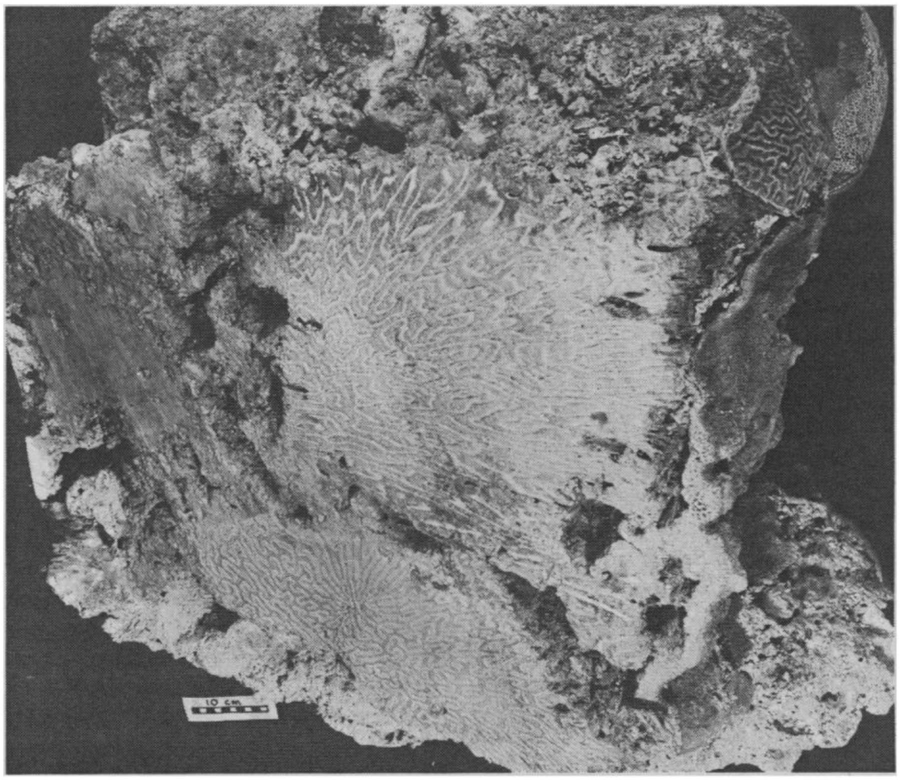

Fig. 2. Cross section of a small knob. Two (living) *Diploria* colonies, with very small areas of attachment, have been removed to reveal the bored substrate at the top of the knob. Note the bored surfaces around all parts of the massive corals in the interior of the knob.

It also follows that intensive boring and encrustation can reverse the primary structural relationship between framework and cavity, so that original framework cavities are filled by encrusters while borers remove the frame. The cavity dwellers have a variety of growth attitudes, and the reef stratigraphy can be modified so that, in places, old skeletons overlie young ones. One reef section revealed 30 cm of successive generations of *Agaricia fragilis*, one on another all pointing downward with the oldest at the top. The reversal of the primary framework-cavity structure is best preserved in reef rock made originally of corals having closely knit upright branches, such as *Madracis decactis* and *Porites porites*. For in these examples an interlocking network of encrusters fills in the space between branches, and this is commonly capable of supporting the overlying living coral once the lower branches are merely bored-out passages. Where borers attack the undersides of massive corals, such as *Diploria*, thick encrustations at the base of the resulting mushroom shape are necessary to support the mass of the coral head. For, with time, intense boring at the base of the skeleton nips off the head. Therefore, early burial causing premature death of borers is necessary to preserve, in situ, the mushroom-shaped form of *Diploria*. If not supported by neighboring skeletons, an undermined coral head either topples over into a valley—where it may continue growth, be destroyed by borers, or be buried—or falls onto the lower part of its own skeleton so that it comes to rest a few centimeters below its former position on an "unconformity" surface, along which (with sufficient water circulation) borers may continue their excavation. Inside prominent knobs, several active excavation surfaces are common under one growing coral surface (Fig. 2).

The rate of growth of massive corals (*3*) and the rate of boring by sponges and bivalves (*4*) are of the same order of magnitude. Under certain conditions where boring is favored, and perhaps coral growth is impeded, coral knobs will diminish. For a knob interior may be disintegrating faster than a (seemingly healthy) growing coral can raise the surface. The relative rates of the processes that operate together to produce reef rock will control the nature of the internal structure. The presence of an elevated reef structure indicates the overall predominance of the building processes, but the depth and water circulation limits for vigorous boring activity and the level of loose sediment on a reef may ultimately control the amount of reef framework preserved.

In summary, the upper 2 m of the interior of these patch reefs is composed chiefly of the massive corals, *Diploria*, *Montastrea*, and *Porites*. Commonly, their skeletons have lost the original structure of both their anchorages and final growth surfaces. Unknown quantities of framework have been removed and converted into loose fine sediment by boring organisms. These phases of erosion are preserved as minor unconformities between corals. The collective time significance of these unconformities may be considerable. Selective boring and the relatively late addition of cavity dwellers to the reef structure can result in a progressive substitution of surface-grown corals by cavity encrustations inside the reef. These changes in composition and structure that happen during the fossilization of Bermuda patch reefs show why students of Recent carbonate sedimentary processes should attempt to follow through to the state of preservation, thus making interpretation from depositional to fossil (and vice versa) more complete.

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References and Notes

1. P. Garrett, D. L. Smith, A. O. Wilson, D. Patriquin, *J. Geol.* **79**, 647 (1971).
2. N. P. James, *Bermuda Biol. Sta. Spec. Publ. No. 6* (1970), p. 19.
3. J. E. Hoffmeister and H. G. Multer, *Bull. Geol. Soc. Amer.* **75**, 353 (1964).
4. A. C. Neumann, *Limnol. Oceanogr.* **11**, 92 (1966); G. W. Otter, *Sci. Rep. Great Barrier Reef Exped.* **1**, 323 (1937).
5. I thank K. Sinclair for assistance with underwater operations, the staff of the Bermuda Biological Station for their cooperation, and the Natural Environment Research Council for financial support.

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Direct Phase Determination from Neutron Diffraction Data of the Structure of Melampodin

Abstract. *The structure of a large complex molecule, $C_{21}H_{24}O_9$, has been solved directly from neutron diffraction data by using sigma-2 and tangent refinement methods. As a consequence, the neutron diffraction technique must be reevaluated as a possible primary tool for crystal structure determination.*

Sikka (*1*) has suggested that "direct methods" of phase determination should be applicable to neutron diffraction data when the amount of scattering from hydrogen atoms, defined by

$$Q_{\mathrm{H}} = 100 \sum_{\mathrm{H}} b_{\mathrm{H}}^2 / \sum_i b_i^2$$

(b_i is the neutron scattering length of atom *i*), is less than about 30 percent. He further suggested that the upper limit for the number of atoms in the unit cell is about 100. Subsequently, Verbist *et al.* (*2*) successfully applied the Σ_2 and tangent refinement methods to the solution of L-proline monohydrate ($Q_{\mathrm{H}} = 27$ percent, 80 atoms in the unit cell). We report here the successful solution by direct methods, involving neutron diffraction data, of a noncentrosymmetric crystal structure containing 216 atoms per unit cell.

Melampodin (*3*) is a sesquiterpenoid lactone derived from a Texas ragweed plant and has the composition $C_{21}H_{24}O_9$ (Fig. 1). Its crystal structure has been determined by x-ray diffraction analysis and reported in a brief communication (*4*). The neutron diffraction analysis was undertaken in order to determine precise internuclear distances and angles in this highly strained, fused-ring natural product (*5*).

The crystal data are as follows. The

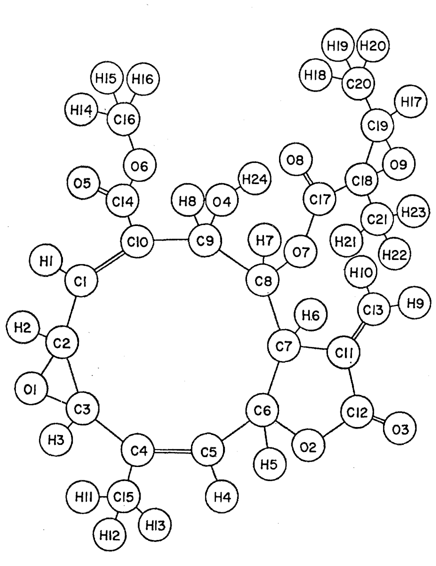

Fig. 1. Schematic diagram of melampodin. The numbering scheme is from (*4*).