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REEFS OF THE SEYCHELLES : PROBLEMS AND INTERPRETATION*

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ABSTRACT

The results of work on reefs on Mahé, Seychelles and Pleistocene limestones on Aldabra are briefly presented. These are used in discussion to highlight problems of reef description and illustrate the author's views on reef structure.

Reefs are presented as growing by a series of discrete increments controlled by sea level changes. This interpretation suggests that they are bedded structures with recent growth and deposition forming a thin veneer on a reef morphology which was already broadly defined.

INTRODUCTION

THIS paper is intended to fulfil two main functions. The first of these is to throw some light upon descriptive problems common to all reef workers. The second is to provide, for the purposes of this Symposium, a summary statement of some observations and conclusions on the structure of certain Indian Ocean coral reefs. From these, inferences concerning the structure of reefs in general have been drawn which, it is believed, have wider application in this and other areas.

The need to study structures is largely a geological one, the geologist being concerned with the recognition of similar environments in ancient rock sequences. There are, however, areas of biological study in which it is also important, and this is the justification for its inclusion here.

The first section is concerned with an examination of concepts underlying the use of the term "reef". With these in mind, environments and modes of deposition in the Seychelles are discussed, followed by notes on the evidence available from subsurface and raised limestone outcrops. A brief examination of causes underlying sea level changes in the Indian Ocean is followed by a statement of conclusions.

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PROBLEMS OF NOMENCLATURE

Speculation about fossil reefs began almost as soon as modern reefs became objects of scientific interest, made popular by the writing of workers such as Lyell (1832) and Darwin (1890). It is to Darwin that we owe our present nomenclature and many of our ideas concerning coral reef behaviour, first propounded in about

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1837. Reef studies, however, seem from the start to have been destined for controversy. Judd (1890) in his preface to an early edition of Darwin's "Coral Reefs" noted the "varied and often mutually destructive views put forward by different authors". Few would deny the truth of this statement eighty years later.

The publication by Darwin and certain of his contemporaries of their theories and observations led directly to the recognition by many authors of what they thought were fossil reefs. As an example of these Worth (1888) compared a sequence of middle Devonian Limestones in southwest Britain with reefs in the Solomon Islands. It has since been shown (Braithwaite, 1967) that the comparison was not a close one, and it is clear that this and similar studies were not based on any detailed knowledge of the internal structures and depositional history of the modern structures, analogies they were presumed to reflect.

Because of their greater interest in such matters most of the argument over precise definitions of reefs has been and is now generated by geologists. The biologist is concerned with defining only one of the physical parameters of the situation in which the organisms under study are found. Within limits it makes very little difference what the long term causes underlying the substrate are, provided that its morphology and superficial textures are described and understood. The geologist on the other hand must also consider time and, thus, the accurate description of the feature in three dimensions in order that its form and sedimentary relationships can subsequently be recognized in ancient rock sequences.

The term "reef" is a useful one, equally applicable to all latitudes and stating in clear non-technical language the physical situation of the organisms or ecosystem described. But what does it state? Most English language dictionaries give definitions which can be paraphrased as "a ridge of rock, shingle or sand, at or near sea level, such as to constitute a hazard to navigation". As European navigators moved into warmer seas in the 15th and 16th centuries they found that there were a large number of "reefs" and they were later to discover that these bore large numbers of corals.

There are similarities between a tropical littoral or sublittoral "reef" which may bear hard corals, soft or stony alcyonarians and calcareous algae and, for example, a sub-littoral rocky platform in British waters which might bear large numbers of soft alcyonarians and both crustose and coralline calcareous algae. In rejecting such a parallel, the reasons given are less likely to be those which say that the two groups of organisms are dissimilar, than those which question the similarities of the two "reefs". There are, of course, differences notably in the rates of accretion, but these could be more easily overlooked if it were not for the mass textural and structural differences which underlie the basic morphology.

It is important to recognize that the term is only satisfactory as a morphological description. It was in use and well understood long before it came to have any additional biological or geological meaning.

Much of the enormous geological and some biological literature published is based upon speculation. Some is conceptually reasonable; for example, Cloud's (1952) models of the relationship between facies distribution and rising or falling sea levels. There are, however, others in which little or no attention is paid to modern structures. It is in this area that most confusion has arisen. Many of the structures described are certainly not "reefs" in the normal dictionary sense. Periodically various authors have tried to clarify the situation, either by defining new and hopefully unambiguous terms (e.g. Cummings, 1932) or by a review and re-definition of existing terminology, as in the American Association of Petroleum Geologists Symposium of 1950 (see particularly the opening address by Wilson 1950) and MacNeil (1954 a , b). This is not the place to go into a detailed discussion of what these and similar papers have involved. It is, however, significant that they all suffer from the same limitation: there are few existing reefs anywhere in the world described in terms of their three dimensional sediment relationships. This is partly because of lack of finance for such work but there are also difficulties in developing suitable techniques for investigation.

Comparisons of ancient structures with modern reefs are thus a mixture of drawing parallels between ecosystems (which are not always similar), of comparing supposed morphological features (which are not always proved), or simply recognizing that some organism is, or is potentially, frame-building. These would all be interesting points but they would not in themselves allow direct equation with a modern coral reef since it has yet to be shown, either in biological or geological terms, exactly what this is.

The most distinctive features of the environment are the presence of frame-building organisms and their construction of pinnacles or banks. There are, however, reasons for supposing, particularly in the Seychelles, that such growth is not *necessarily* related to the reefs. It therefore ceases to carry quite the same weight as a criterion for their recognition. The argument may seem abstruse, but the point being made is that corals, or indeed any other organisms, seem often to have formed reefs where a "reef" in the morphological sense was already available for them to grow on.

The great bulk of work on coral reefs is, and is likely to remain, biological. This is a plea for those who do not already do so to make the distinction in their writing between the organisms and their immediate ancestors and the bases on which they grow. There are clearly situations in which this is difficult, but the attempt should be made.

DESCRIPTION OF SEYCHELLES ENVIRONMENTS

The approach advocated in the above discussion is seen in the work of Taylor (1968) on invertebrate communities on Mahé, Seychelles, and of others, notably Stephenson and Stephenson (1949) and Doty (1957). They regarded reefs with a generally platform-like profile as behaving as a complex laterally expanded rocky shore, diversified by the presence of surface sand bodies providing a range of infaunal environments. There are thus two principal substrate groups, those providing a hard "rocky" surface and those providing soft sediment. These correspond broadly to the two main kinds of accumulation taking place on reefs today. These are accumulation by 1. Bioconstruction and 2. Normal sedimentation.

It is my intention to show how these are presently influencing reef growth.

The work on which these thoughts are based is concerned with two principal areas and situations. Recent reefs and associated sediments in the Seychelles and an Upper Pleistocene (?) succession on Aldabra. Some observations on the structure of the Seychelles reefs have already been published (Braithwaite, 1970).

The reefs of the Seychelles have been divided into windward and leeward groups. This system was used by Lewis (1968, 1969) and others and is based partly on a comparison with Pacific reefs. It gives greatest prominence to the south-east monsoon, blowing from May till October with 80% of winds in July and August coming from this direction (Taylor, 1968). Reef platforms are best developed on the east coast, but they do not reach their maximum widths in sectors exposed to these winds. Observations show, moreover, that the reef platforms do not consistently form the basis for the most prolific areas of coral growth and that growth can be severely limited by excessive exposure.

Bioconstruction, by corals, calcareous algae and other organisms, and the accumulation of fragments of these and other non-constructing (vagrant) organisms (molluscs, echinoderms and others) form the main components of bulk accretion. Organisms such as calcareous algae are also important in the production of rigid frame works from material which would otherwise remain as loose sediment.

Sediment Accumulation

Sediment in the majority of reef environments is derived within the system from the breakdown of carbonate secreting organisms. Where high islands or mainland situations are concerned there may also be additions, of varying importance, of non-skeletal debris, quartz grains, clay minerals, etc. derived from the hinterland. On Mahé these are associated almost exclusively with deltaic salients, some of the larger of these discharging into the northern sector of the east coast (the Port Victoria area) and formerly supporting mangrove swamps.

Accumulations providing a hard substrate are related particularly to two groups of organisms, calcareous algae and corals. In the Pacific, in exposed situations, calcareous algae form a high rim on reef edges (e. g. Emery, Tracey and Ladd, 1954). This is not the case on Mahé where their principal function appears to be the crusting-over of dead coral, limestone or granite surfaces which are not subject to abrasion or are otherwise unsuitable. In addition, they are the largest, single element responsible for the binding together of calc-rudite or coarser debris to form a rigid, if somewhat cavernous surface. As noted in a previous paper (Braithwaite, 1970) one of the main areas for this kind of accumulation on Mahé is immediately behind edges. Many of the back-reef areas lie a metre or more below low-water spring sea level. Tongues of algally coated "cobbles" extend shorewards, sometimes by as much as 100 metres and are believed to have been transported in that direction. The amount of algal encrustation increases to seaward and the mounds become bound together to form first an open cavernous framework and, finally, an almost continuous rocky platform.

Accumulations of coarse calc-rudite also occur locally in off-reef areas. Isolated banks which, at least superficially, appear to consist of little else occur north of Port Victoria. These are generally loose and unconsolidated but examples approaching sea level become algally crusted in their upper margins and the upper surface, exposed at low water, is indistinguishable from the algally bound cobbles described above. The main problem which these involve is the recognition of source areas. Much of the debris appears to be broken fragments of "stagshorn" *Acropora*, and to occur in areas which do not now support significant growths of these species. It seems possible, therefore, that within comparatively recent history there have been marked changes in the character of the corals growing in this area.

Recent accumulations of sediment may rest upon a lithified or partly lithified bench. Individual coral colonies can be found beneath the sediment surface with their tops planated by erosion. These are not common but have been found associated with lithified sediment extending two or three metres below low water in particular areas. Lithification is not necessarily significant of emersion, as shown by Land and Goreau (1970), but in this case the almost total absence of lithified sediment in dredged material from lower levels suggests that a narrow near surface horizon may have been associated with some particularly reactive zone such as sea level. The fact that cemented limestones form rocky platforms extending to greater depths at the southern end of Mahé, may indicate that these are older or that they lay in an area offering a more active diagenetic environment.

Coral Accumulations

The major varieties of coral growth are structurally distinct, their internal and external characters depending upon the nature of the corals involved. Two main associations have been recognized: 1. An *Acropora* assemblage and 2. A *Porites* assemblage

Details of these have already been outlined (Braithwaite, 1970). The *Acropora* assemblage is dominated by species of that genus. Variations in environment encourage the local dominance of corals of either the *A. formosa/A. phaoronis* type or more tolerant and robust *A. humulis, A. digitifera* and related forms. The more delicate members of this association are limited in their distribution, first by their obvious fragility and second by a low tolerance for conditions of variable salinity or water turbidity. The upper limit of the more robust members is set by their sensitivity to wave impact. It seems that on normal edges they are set back a few metres from a zone occupied by *Pocillopora* of the *P. danae-meandrinae* group and stony alcyonarians, species of *Millepora* and *Heliopora* (though this is not the only place where the latter grow). *Millepora* in particular seems to require the active turbulent waters of a surf zone for satisfactory growth, though they are stunted and ultimately eliminated by increasing wave strengths. With decreasing exposure to wave attack, as in the comparatively sheltered edges north and south of Port Victoria *Acropora* moves forward to form the dominant coral of the edge zone. Parallel changes take place on the reef front. These may be related to depth-induced light reduction, to increased water turbidity, varying temperatures, salinities, or any or all of these.

It is common around Mahé, at depths of 10-15 metres, that *Porites* and the corals normally associated with it (*Echinopora, Platygyra*, etc.) form a mixed assemblage with various species of *Acropora*. In the Port Victoria area where the reef platform is particularly broad and divided by deep channels this association occurs in progressively shallower water. Ultimately, in those channels where water conditions are least favourable for the growth of other corals *Porites* forms the reef edge, awash, though not normally emersed, at low water. Because Mahé rests upon the shallow Seychelles Bank there is no clear evidence of what the lower limits of coral growth are in this area. Coral associations (see also Rosen, 1970) can be regarded as a series of parallel zones.

1. Calcareous algae, no corals
2. *Millepora, Heliopora, Tubipora, Pocillopora*
3. *Acropora* of the *A. humulis, A. digitifera* type

4. *Acropora* of the *A. phaoronis* type with *A. irregularis*
5. *Porites, Echinopora, Platygyra, Galaxaea*

This series is less discontinuous than a list suggests, and a complete scheme would involve a spectrum-like gradation with considerable overlap of individual species. The main structural effect of these arises from the broad differences in colonial morphology, from robust to delicate-branching and massive forms. These are related to two main factors, the mechanical strength of the colony influencing the degree of possible exposure, and a probable need to adopt lower polyp density colonial patterns in adverse water conditions (in response to reduced light or food supply?). These zones can be seen as a gradational series with extremes of coral growth at either limit. At one end waters are clear and circulation good and at the other minimum coral growth requirements. Where conditions are uniform the zones are essentially parallel to the surface but, with an increasing lateral gradient of diversity as, for example, in the entry to a channel mouth, they come to lie at progressively steeper angles, bringing the 'lower' zones to the surface and causing the whole system to lie diagonally across the reef front.

From the point of view of structures the framework produced by the *in situ* growth of generations of corals one upon another is distinctive in itself and for each of the zones. Geologically it is the easiest to recognise and has been used by a number of authors as the sole criterion for the presence of a reef.

Around Mahé, structural and environmental differences are linked to morphology. The *Acropora* assemblages in general lie on gentler slopes and the *Porites* assemblage is commonly on cliff-like channel margins. Since, however, both are able to and do grow on essentially flat off-reef floors, recognition of such morphology preserved within the structure of the reef must rest upon sedimentological evidence.

Having considered the major kinds of sediment accumulation and coral growth structures it now seems necessary, at least briefly, to indicate how these are related to actual reefs on Mahé.

Around Mahé there are four main types of coral/reef associations.

1. The "reef", a more or less broad platform extending from the shore with a steep seaward face (edge) clothed with and apparently constructed by corals.

2. The "reef knoll" standing a little offshore and clothed with corals, again presumably constructed by them.

3. Areas of prolific coral growth which are not associated with morphological "reefs".

4. Reef platforms which bear little or no coral growth. Some of these are rock and are believed to have formed during an earlier depositional cycle.

These have been considered in greater detail in a previous publication (1970).

There are two main conclusions to be drawn from their association. First, prolific coral growth may occur with or without a reef being present if the conditions are favourable. The second is a conclusion already suggested by the preceding discussion, reefs are "reefs" with or without corals and the fact that corals are seen on the surface of a reef of any kind does not automatically mean that the structure has been formed solely by the efforts of these organisms.

FOSSIL EVIDENCE ON STRUCTURES

This includes limited observations from dredging excavations and boreholes on Mahé and from surface outcrops on Aldabra and the East African Coast (see also Thompson, 1956).

Viewing these as a whole there is no convincing evidence of either of the standard models of reef development; of an upward growth keeping pace with subsidence, or of seaward accretion at a constant sea level. Growth frame occupies only small areas and the general impression is one of consolidation of an "edge" on a particular site. Upwards growth seems often to have been very narrowly limited by depth. This can be seen in individual planated and bored *Porites* colonies visible in some areas in the Aldabra limestones and by the fact that in all areas examined the deposits are bedded. That is to say, that the sediment changes its character more or less abruptly over wide areas at the same time. On Aldabra these changes are particularly dramatic, sediments in some cases overlying marine erosion surfaces and being strongly contrasted faunally and sedimentologically with those below. It is interesting to note that, within the limits of these bedding units, the planated corals point to a more or less stationary sea level, at least for the life of the individual coral colony. This was not at some indefinite interval above so that the colony grew in deep water, but at a level represented by the planated top of the colony itself. The rate of sea level rise is not known, but it can clearly have been little more (and possibly less) than the rate of sediment accumulation. It is hard in the case of Aldabra to imagine any period within more recent history when it did not include a reef in the popular (nautical) sense, since it rises from oceanic depths and evidence points to deposition close to sea level. On the other hand, no sediment increment seems to have been large enough to have included a reef-like formation, i. e. a reef was present irrespective of any contemporary deposition.

Examination of borehole records from Mahé show what appear to be a series of discrete increments, often of contrasted sediment types. These do not form any rational pattern over wide areas, but this may be because attempts at correlation were based upon comparisons of facies, and quite different results could follow from more careful measurement of intervals of change. This assumes that it is the event bringing about the facies change which is important rather than the kind of sediment being deposited in a particular area.

Borehole records from Funafuti (Cullis, 1904) Bikini (Emery, Tracey and Ladd, 1954) Eniwetok (Schlanger, 1960) and Midway (Ladd, Tracey and Gross, 1970) all show similar facies changes over rather greater thicknesses.

Caswell (1953) showed that on the East African Coast a thickness of limestone approaching 100 metres formed during the last interglacial (interpluvial). Of this more than 28 metres are above present sea level. There is little evidence available on structures below surface but present natural outcrops and quarries show accumulation to have taken place in discrete beds, clearly differentiated from each other on lithological grounds. Areas of coral growth frame are strictly limited (best seen on some of the present seaward cliff faces) and it is clear that only in these areas is there any approach to an edge environment.

These limestones are cut by a number of well defined benches, clearly visible in the Mombasa area and corresponding to still-stands in a gradually falling sea level. The present datum is one of these benches and there is no doubt that the reef at Mombasa is simply an erosional bench, probably cut by solution. The outer margins have been modified by growth of corals, but these are clearly an addition to the structure. No platform at this level is seen either on Aldabra or on Mahé, though it is not clear precisely why. It seems likely that there is some kind of bench present, but that in both cases it lies at a greater depth, was probably formed by more active mechanical erosion rather than by solution and has now been covered by recent deposition.

There has to date been no detailed drilling investigation designed to unravel the relationships of sediment bodies underlying a reef complex. In the absence of this it is only possible to speculate. The facies changes shown by reef borehole records suggests that sediment accumulation, and presumably reef growth, was interrupted by events which brought about changes in the character of deposition.

It is the author's contention that these "events" were in fact periods of rapidly changing sea level, and it therefore seems appropriate to examine briefly the major causes of sea level movements in the area under consideration (the Indian Ocean) and speculate on their effects.

SEA LEVEL CHANGES

Evidence of changing sea levels in generel, and in relation to reef growth in particular, is often contradictory. Much of the best documented work is from the Pacific area, but even here adjacent island groups may have had significantly differing histories. The recent paper by Curray, Shepard and Veeh (1970) describing the results of the CARMASEL expedition illustrates this point in relation to the Caroline and Marshall Islands.

Within the boundaries of the Indian Ocean there are clearly a variety of factors likely to have influenced sea-level. Volcanic activity around Mauritius, Reunion, probably the Comoros and Amirantes (Fisher, Engel and Hilde, 1968), Christmas Island and other eastern areas are likely to produce situations analogous to those outlined in Darwin's classic subsidence hypothesis. The excess weight of a volcanic pile being compensated by isostatic adjustment. The more stable areas such as the Seychelles Banks, or continental margin areas on the other hand, can be expected to be dominated by the effects of eustatic changes associated with recent glaciations, though perhaps not to the extent envisaged by Daly in his Glacial Control hypothesis (Ladd and Hoffmeister, 1936). Isostatic changes comparable to those which influenced sea level in north European and northern American areas may also have taken place, not as a result of ice loading but by the accumulative weight of sediment. These are probably most significant in areas adjacent to the Ganges, Indus or similar rivers, but are probably also of measurable amplitude even in smaller areas such as Aldabra and the Seychelles islands where the accumulation of carbonates is sufficient to have upset any balance which may have exited before their deposition.

There is also the possibility that sea-floor spreading and the intricacies of plate tectonics may have brought about movements on individual plate margins, particularly in the Red Sea. The northward drift of India (Le Pichon and Heirtzler, 1968) and the relative movement of Madagascar to the south (Fisher, Engel and Hilde,

1968) and the gradual widening of the Gulf of Aden can also be expected to have had their effect, though they seem to have been overlooked in this context. Such changes will have been most important in their cumulative influence since the Cretaceous but they are, nevertheless, still in progress. In addition to these, local uplift associated in some cases with volcanic activity occurred on the Kenya Coast as late as upper Miocene or lower Pliocene times (Thompson, 1956).

The common features of recent history are undoubtedly the sea level stands related to Pleistocene glaciations but these are overprinted in different areas by the effects described above. It thus seems, even at this early stage in our research, highly unlikely that it will be possible to erect a chronology based on levels alone which will have any application other than to the area in which it is first described. We can go further and say that, since only actual deposition can be dated by either palaeontological or radiometric methods, many events recorded by well defined benches will remain undefined except in the broadest terms. It may be possible at a future date to erect a detailed chronology for increments of reef growth. This is not likely to be for some years unless new and less expensive methods for probing reef structure and dating the materials obtained are evolved.

CONCLUSIONS

The conclusions drawn from this analysis can be stated briefly since they are already embodied in the text.

1. Present coral reefs are structures which have grown up over an extended period.

2. Coral growth and sedimentation appears in many cases to be a superficial addition to a pre-existing structure.

3. Corals are associated with reefs because these provide a suitable basis for growth and not necessarily because they have themselves grown to form the reef.

If these statements are correct, recognition of the coral/reef association can no longer carry the same connotations concerning the history of an area. The reef fauna and flora can be regarded as analogous to a "climax vegetation" growing on a platform or bank-like substrate in response to a fixed set of conditions, and while upward or seaward advancement is theoretically possible it has probably not taken place to any significant extent within the history of Recent reefs.

It is suggested that modern reef development has been by a series of discrete increments. Sea level changes, where positive, were at a rate slower than the rate of deposition. They were probably intermittent, with more rapid "events" producing the large scale bedding characteristic of Recent sediments. This clearly carries important implications for the recognition of fossil structures, and illustrates the need for both biologists and geologists to provide *accurate* descriptions of the environments rather than the present vague term "reef".

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