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Drilling investigation of Bewick and Stapleton islands

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[Plate 1]

The stratigraphy and sediments of Bewick and Stapleton cays were investigated by rotary drilling. Emphasis has been placed on core collected from the hole, 30 m deep, drilled on the leeward side of Bewick Island. Core recovery using a variety of techniques was variable. However, sufficient material existed for chemical, mineral and petrological analyses, as well as for general biological and fabric description. Samples were also selected for radiocarbon dating. Data suggest three and possibly four disconformities in the Bewick core. The youngest hiatus occurs at *ca.* 3–4 m below low water mark separating Holocene reef and reef flat sediments from pre-Holocene carbonates. An attempt has been made to interpret changes in environments of deposition in the subsurface, and diagenetic effects.

INTRODUCTION

Until the 1973 Royal Society–University of Queensland Expedition, drilling on the Great Barrier Reef has been limited to six holes. Four holes have been drilled in the southern Great Barrier Reef Province, only one of which recovered sufficient samples in the top 200 m to permit any detailed work. This was the Heron Island hole drilled by the Great Barrier Reef Committee (Richards & Hill 1942; Maxwell 1962; Davies 1974). In the northern Great Barrier Reef Province the Great Barrier Reef Committee was also responsible for a bore hole at Michaelmas Cay (Richards & Hill 1942). Initial interpretation of the upper sequence at Heron Island was of post-Pleistocene age, because none of the fauna showed the effects of Pleistocene ice ages (Richards & Hill 1942). Maxwell (1973, p. 266) states: 'The major disconformity between Pleistocene foraminiferal limestone and Holocene coralline limestone is marked in the Heron Island bore by the quartzose sands of the interval 289–308ft'.¶ However, Davies (1974) has reinterpreted the stratigraphy on the basis of a mineralogical change at -20 m, and a marked planar resistivity contrast at this depth. He suggests that at 20 m there exists a prominent solution surface, which could be correlated with the first subsurface 'unconformity' at -27 m on Michaelmas Cay. This interpretation is compatible with dated reef sequences reported from various places in the Pacific (see Stoddart 1969; Tracey & Ladd 1974).

As part of the 1973 Expedition to the northern Great Barrier Reef Province an investigation of the stratigraphy of several reef islands with the use of shallow coring techniques was envisaged. Logistical difficulties limited drilling to two sites, Bewick (14° 26′ S, 144° 49′ E) and Stapleton islands (14° 19′ S, 144° 51′ E). The primary objective at these sites was to test the hypothesis that islands in this part of the Great Barrier Reef have been formed by incremental addition of reefal sediment during successive Quaternary marine transgressions. For this

¶ 1 foot (ft) = 0.3048 m.

purpose, drill performance was recorded in detail and all pieces of core were megascopically described. Chemical, mineralogical, petrologic and geochronologic (^{14}C) analyses were conducted on samples from the core to ascertain if time as well as facies discontinuities existed in the sequence. A secondary objective was to determine if environmental and diagenetic changes were recorded by the petrology of the rocks. This paper represents a preliminary report of findings which resulted from the limited drilling programme.

METHODS

(*a*) *Field*

The technique of drilling involved diamond tungsten bit coring by means of a drill unit of low mass (Thom 1976). As employed on Bewick Island, the trailer-mounted Gemco drill was winched from a barge stranded on the low-tide reef flat onto the upper beach-rock surface. Two coring techniques involving pumped seawater circulation were used: the retractable barrel, and wireline equipment. Recovery with the retractable barrel, especially when coupled with tungsten carbide faced bits, was reasonable although variable. When the wireline barrel was used the core runs retrieved little or no material.

On Stapleton Island, the drill was sited on the upper beach face. Drilling commenced on loose sand requiring casing to 5.8 m. Solid auger rods were employed to insert the casing and recover the sample in wet unconsolidated sand. This hole was terminated at the first discontinuity at 14.6 m after obtaining relatively poor recoveries from five core runs. Wireline equipment was used exclusively at Stapleton.

Core logging procedures followed those reported by the U.S. Geological Survey in their drilling of Bikini Atoll (Emery, Tracey & Ladd 1954, p. 77). After extrusion from the core barrell, all core pieces, fragments or sandy detritus were described and packed in sequence in core boxes, being orientated correctly where possible. Each core piece was labelled.

In general, the cores are believed to provide a reliable indication of the stratigraphy, particularly the Bewick hole. As noted by many authors in their descriptions of drilling operations on coral reefs, there are considerable difficulties in achieving high core recovery rates. The patchy nature of the Bewick core can be attributed to four factors:

(1) occurrence of cavities in the section;

(2) interbedded consolidated and weakly consolidated materials with much of the latter being washed away in the circulating water;

(3) brittle coral rubble which was either pushed aside or easily fell to the bottom of the hole during core barrel recovery;

(4) operator inexperience involving experimentation and error.

The third factor became apparent during laboratory analyses when material from the upper part of several core runs were shown to be out of sequence. Fortunately, excessive caving did not occur and contaminated material could be easily isolated.

(*b*) *Laboratory*

A group of 126 samples from the Bewick core and 15 samples from the Stapleton core were analysed in the chemical laboratory of the Department of Biogeography and Geomorphology, A.N.U. (J. Caldwell, analyst). An infrared spectrophotometer was used to determine the proportion of calcite, aragonite and non-carbonate impurities in the Bewick samples.

The content of strontium and iron in each sample was determined by using an atomic absorption spectrophotometer. X-ray analysis was conducted on the Bewick samples to (i) cross-check the infrared method on calcite–aragonite determinations; (ii) determine if the calcite occurred as low or high-magnesium type; and (iii) look for the occurrence of dolomite.

TABLE 1. RADIOCARBON DATES FROM DRILL CORES

island	sample no.	laboratory number	^{14}C age a B.P.	approximate depth below h.w.s.t. m	material	percentage aragonite	percentage calcite	comment
Bewick	BE-D1	ANU-1386	2 030 ± 70	0	*Tridacna* in beach-rock	—	—	sample collected from surface of beach-rock 100 m ENE of drill site
	2–3–5	ANU-1284	6 920 ± 130	5.2	coral fragment	99	—	
	2–4–1	ANU-1395	6 380 ± 120	5.9	coral fragment	65	35	high-magnesium calcite sp.
	2–7–1	ANU-1283	6 610 ± 130	7.9	coral (*Porites*?) fragment	90	10	displaced by drilling below disconformity
	2–9–1	ANU-1282	$>37\,300^{+2200}_{-1700}$	9.1	coral and coralline algae fragment	—	99	
	2–13–2	ANU-1281	$>34\,400^{+2500}_{-1900}$	11.9	coral fragment	2	98	
	2–15–4	ANU-1280	>30 350 ± 1150	13.3	fine-grained calcarenite	—	94	
Stapleton	1–1	ANU-1663	3 130 ± 80	7.9	carbonate sand	48	52	
	1–2–3	ANU-1664	3 160 ± 90	10.1	reef calcarenite	5	95	high-magnesium calcite sp.
	1–3–3	ANU-1721	5 260 ± 130	12.2	coral fragment	70	40	high-magnesium calcite sp.

Petrographical inspection of the core involved several stages. The first was a description of each piece as seen through a binocular microscope. Secondly, selected pieces of the Bewick core were impregnated with plastic in a vacuum chamber. Thirdly, the prepared blocks were etched and stained by using Alizarin Red S, potassium ferricyanide and Feigl's solution, following the technique described by Davies & Till (1968). Finally, from the blocks peels were taken and thin sections cut. The soft and unevenly lithified nature of the core resulted in peels and thin sections of variable quality. The relative abundance of constituents was visually estimated. It was considered that the thin sections and peels were too inadequate for point count analysis.

Radiocarbon assays were undertaken at the A.N.U. laboratory under the supervision of H. Polach. Six dates were obtained from the Bewick core and three from the Stapleton core (table 1). Bewick core samples of uncrystallized and recrystallized material were submitted for ^{14}C determination. It was apparent that dates on calcite-rich samples were meaningless due to post-depositional mineralogical change (see Chappell, Broecker, Polach & Thom 1974; Chappell & Thom 1978). Unfortunately, no aragonite-rich corals of Pleistocene age were recovered below the first discontinuity, thus eliminating the possibility of accurate uranium series dating.

Drill site characteristics

The northern province of the Great Barrier Reef is characterized by a narrow shelf with prominent ribbon reefs on the shelf edge (Maxwell 1968). Between the shelf edge and the mainland are a number of patch reefs on some of which are 'low wooded islands' (Steers 1929). Bewick Island is such a feature, but Stapleton Island is essentially a sand cay on the leeward side of an extensive reef flat. The depth of water between the islands rarely exceeds 20 m.

Stapleton Island was the first site drilled. This hole was used to test the wireline drilling technique. Landing the drill trailer on this island was quite difficult because of loose sand. The only site available was a leeward-projecting sand beach with deep water nearshore. Drilling was conducted at the high spring tide (h.s.t.) level. Core recovery at Stapleton was poor.

On Bewick Island the drill hole was located on the leeward side on a beach-rock surface. The collar elevation of the hole was 3 m above low water spring tide (l.w.s.t.) datum. The site was inundated by 10–15 cm of water on two occasions during high spring tide. A narrow unvegetated reef flat surrounds Bewick Island. High winds and seas prevented drilling on the windward side of the island. The interior of the Bewick reef flat is heavily vegetated by mangroves, preventing access for drilling. Thus the site selected for drilling was the only one accessible at this time of year (July–August). Furthermore, the barge remained on the reef flat near the drill enabling water to be pumped even at low tide. Another advantage was that the surface on which drilling commenced was consolidated.

Plans to drill on Noble Island closer to the mainland and Waterwitch Island on the ribbon reef were abandoned for a variety of reasons, including rough seas, lack of finance, and other commitments for the drill and barge.

Chemical and mineralogical properties

It is not possible in this brief paper to report all data obtained by chemical analyses of the Bewick core (figure 1). However, the salient points can be summarized.

1. All the samples are calcium carbonates relatively low in magnesium carbonates. Only a trace of dolomite was detected in a few samples (e.g. 2–6–9).

2. Taking the core as a whole, calcite is the dominant mineral. Aragonite is only contained in the upper 6–7 m in any significant quantities (figure 1). Below that depth, high aragonite values are associated with the uppermost sample of any core run. These are probably cave-in materials.

3. The aragonite content of the upper 7 m ranges from 30 to 80 %. Below this depth aragonite rarely exceeds 10 % and mostly is less than 3 % (figure 1).

4. Figure 1 also shows the variation in calcite content down the profile at Bewick. Below 7 m

the proportion of calcite dramatically increases to greater than 90 %. Many samples are composed of 100 % calcite. High calcite values appear to be independent of constituent type. Corals with well preserved structure are composed of calcite (e.g. 2–9–1; see table 1).

5. Above 7 m the calcite mineral could be classed as a high magnesium type, but below that depth only low magnesium calcite occurs.

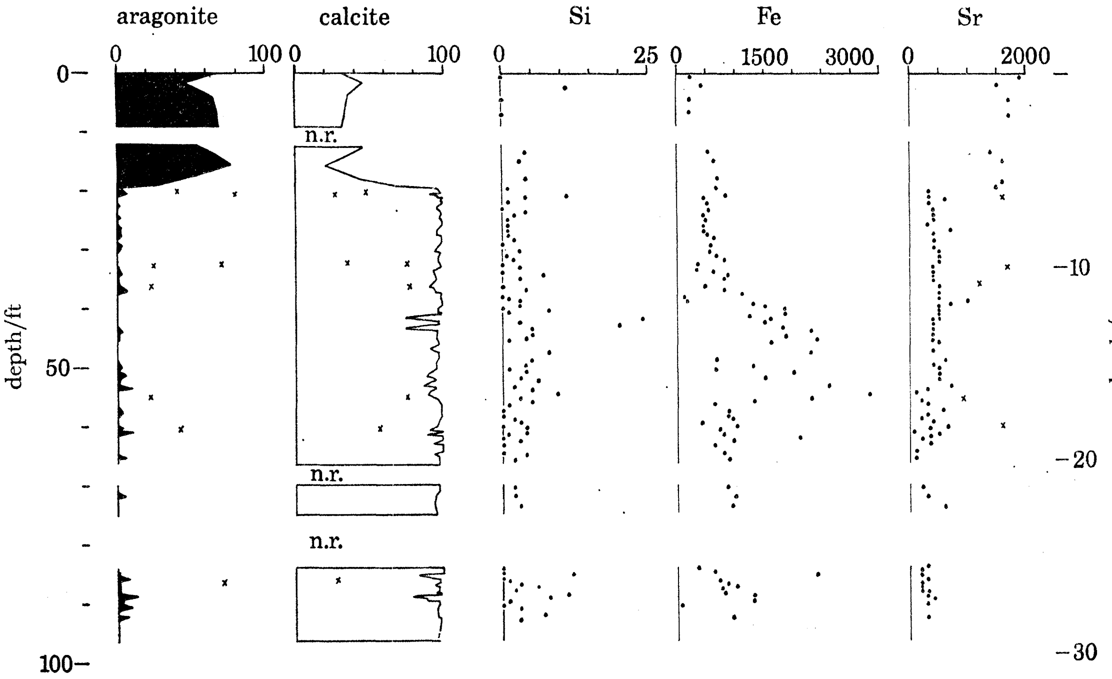

FIGURE 1. Chemical and mineralogical data for the Bewick core; aragonite, calcite and Si are given as percentages, Fe and Sr as parts/10^6.

6. Impurities including silica are mostly below 10 % of total sample. Above 12.2 m the impurity content, with few exceptions, does not exceed 4 % (figure 1). However, below that depth the impure silica values are quite variable ranging from 1 to 24 %.

7. Variation in the strontium content of Bewick samples is closely related to the aragonite pattern (figure 1). The upper 7 m of the core contains 1000–2000 parts strontium/10^6, whereas below that depth strontium does not exceed 1000 parts/10^6, except in samples at the top of some core runs.

8. The amount of iron in the samples shows considerable 'down the profile' variation. Above 12.2 m the iron content only once in 49 samples attains a value of 1000 parts/10^6. Below that depth the amount varies from 340 to 3300 parts/10^6. It is possible to recognize layers in which the carbonates are relatively enriched in iron (e.g. 12.2–14.3 m).

Only limited mineralogical analyses have been conducted on Stapleton material (table 2). Above 14.6 m the sediment is predominantly mixed aragonite–calcite in composition; one sample (1–4–1) is 100 % aragonite, the only 'pure' aragonite value obtained from the Great Barrier Reef drill materials. Two samples at the base of the core contained 1–2 % aragonite and 92–99 % calcite. The amount of magnesium in the samples showed that with the exception of the two lowest samples, which are low magnesium calcites, the calcite species could be described as a high magnesium type.

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Table 2. X-ray diffraction analysis of Stapleton Is core sediments

sample no.	depth below h.w.s.t./m	percentage aragonite	percentage calcite sp.	quartz
1–1 auger	7.9	48	52 Mg_7	—
1–2–2	8.5–11.6	81	19 Mg_{10}	—
2–3		5	95 Mg_{13}	—
2–4		91	9 Mg_7	—
2–5		62	38 Mg_7	—
1–3–1	11.6–12.5	76	24 Mg_{13}	—
3–2		62	38 Mg_7	—
3–3		70	30 Mg_{13}	—
1–4–1	—	100	0	—
1–4–2	12.5–14.6	52	48 Mg_{17}	—
4–3		85	16 Mg_{10}	—
4–4		56	44 Mg_3	—
4–5		2	92 Mg_3	6
1–5–1	14.8	1	99 Mg_0	—

PETROLOGY

In this paper an outline of the petrology of the Bewick core only is presented. Where appropriate the terminology of Folk (1965) is used. A more detailed petrological account is in preparation.

All samples contain recognizable allochemical constituents which are dominantly biogenic and fragmentary. Some intraclasts occur, but oolites and pellets were not recognized. Coralline

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DESCRIPTION OF PLATE 1

Photomicrographs illustrating some aspects of the petrology of the Bewick core. (All photomicrographs are in plane-polarized light.)

Figure 1. Biosparite (lithologic unit 1). Abraded, rounded allochems are cemented by a well developed fringe of aragonite needles. Radially arranged acicular aragonite completely fills some pore spaces (X) and only partly fills others (Y). (Magn. × 56.)

Figure 2. Well developed acicular aragonite crystals, the common cement fabric above the 7 m level. (Magn. × 225.) An enlargement of area (X), figure 1.

Figure 3. Unconsolidated biogenic sand, part of lithologic unit 11. Many of the uncemented allochems are angular to subangular, and the largest allochem in the photomicrograph clearly shows the original aragonite fabrics of the mollusc shell, no inversion having occurred. (Magn. × 56.)

Figure 4. Part of a gastropod shell which has suffered inversion to calcite. The original shell layers have been ‘replaced’ by a coarser calcite mosaic. Micrite veneers the internal surfaces of the whorls. (Magn. × 56.)

Figure 5. Calcite mosaics formed by aggrading neomorphism in a biomicrite. Such fabrics are common in samples from below the 7 m level, especially from the lower half of the core. (Magn. × 90.)

Figure 6. Haematite included in calcite mosaics filling foraminifer chambers. The haematite may have replaced pyrite which commonly occurs at such sites in parts of lagoons where circulation is restricted. (Magn. × 225.)

Figure 7. An inverted coral fragment from the lower part of the core. Original aragonite fabrics have completely disappeared but the general architecture of the coral is preserved in calcite. (Magn. × 90.)

Figure 8. Part of a fossiliferous micrite containing numerous quartz grains of very fine sand-and-silt grade, which are common below the 12.2 m (40 ft) level. The blotchy texture is due to the random concentrations of iron oxides and to some neomorphism of the matrix. (Magn. × 90.)

Figure 9. Coralline algal fragment showing recrystallization in places. Through recrystallization, original calcite fabrics have been replaced in some areas, for example by coarser calcite mosaics. (Magn. × 56.)

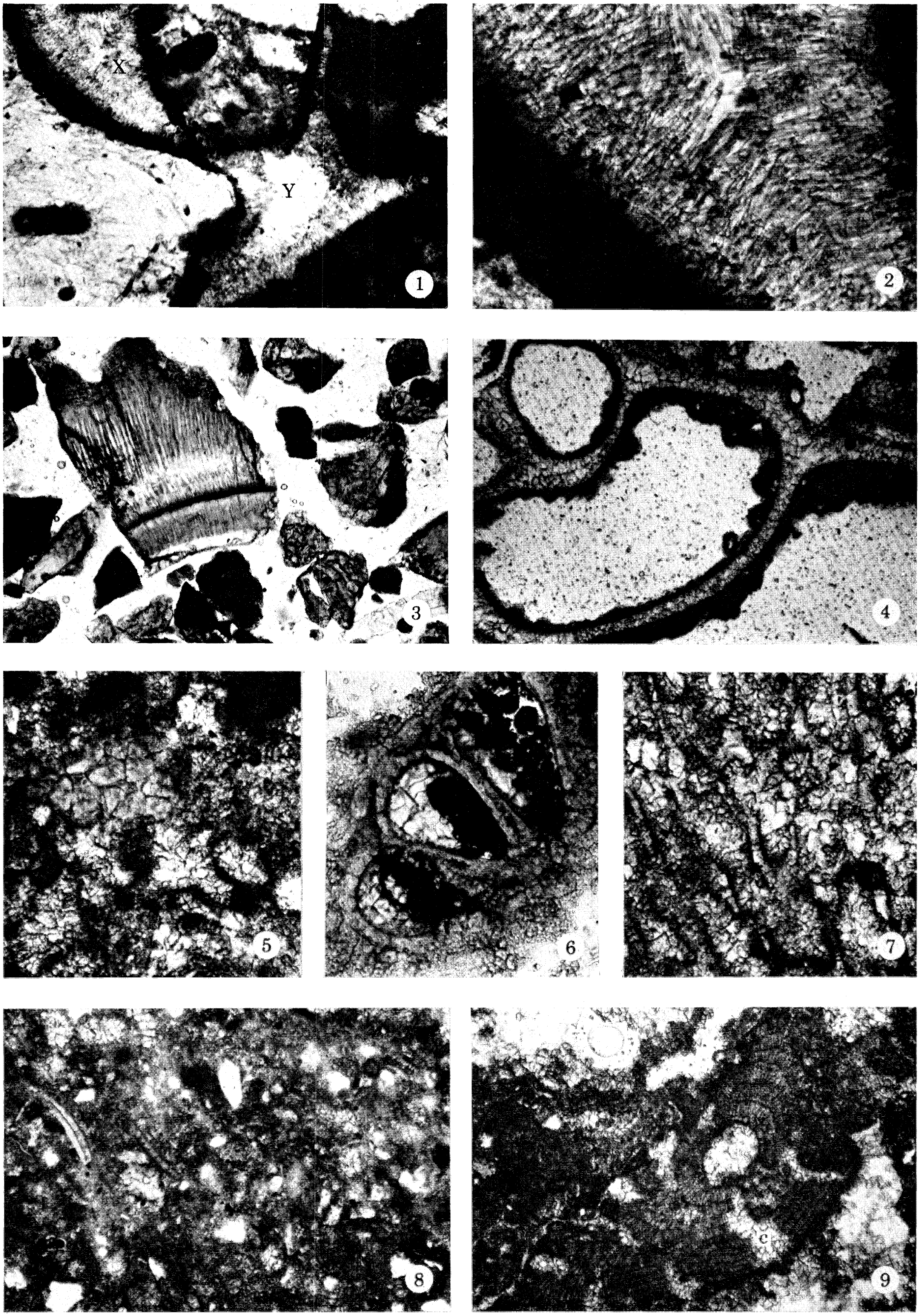

PLATE 1. For description see opposite.

algae are present throughout much of the core, as are molluscs and foraminiferans. Corals, *Halimeda*, and bryozoans were identified in many samples, but were restricted to certain levels. Minor constituents are echinoid plates and spicules. Biosparite (0–3 m) and unconsolidated biogenic sands and gravels are the common types above 7 m, whereas below this level microcrystalline calcite matrix is a major component of many core samples. Owing to variations in size and abundance of allochems, there is a natural gradation in some parts of the core between fossiliferous micrite, fine biomicrite, biomicrite, and biomicrudite. Some samples have reached a more advanced state of recrystallization, *sensu lato*, than others. The appearance of pseudobreccia at certain levels is due to the irregular distribution of neomorphic mosaics and/or the uneven concentration of impurities such as iron oxide particles. Below 12.2 m most samples contain significant amounts of silt grade to very fine sand grade quartz. On the basis of composition and texture it is possible to recognize a number of petrographic types.

(*a*) *Petrographic types*

Biosparite

This rock is light brown to creamy grey in colour, and is composed of well sorted, rounded allochems which have been poorly to well cemented by acicular aragonite (plate 1, figures 1 and 2). The allochems are rounded fragments of corals, molluscs, coralline algae (crustose and articulated types), benthonic foraminiferans, bryozoans, abundant *Halimeda*, and a few intraclasts. Carbonate mud fills chambers in some allochems, e.g. foraminiferans, but is quantitatively unimportant. There is no evidence of inversion. This rock type represents a carbonate beach sand which became cemented to form 'beach-rock'.

Unconsolidated biogenic sand

Fragments of molluscs (pelecypods and gastropods), coralline algae (articulated and crustose types), corals, a few benthonic foraminiferans, and some *Halimeda* plates are the constituent allochems of this coarse to fine carbonate sand (plate 1, figure 3). Many of these biogenic fragments are angular to subangular, but some of the larger pelecypod fragments show a higher degree of rounding; none show any signs of inversion. Acicular aragonite occupies cavities in coral fragments.

Unconsolidated coral/algal gravel (reef rubble)

This sediment consists entirely of bored, subangular pebbles of corals and coralline algae (crustose type). Gastropod shells which are partly filled with acicular aragonite, the needle-like crystals projecting radially into the open spaces of whorls, are incorporated in some coralline algal pebbles. Acicular aragonite also occurs between coral septa, but other cavities are occupied by limonite-stained carbonate mud. Evidence of inversion of the coral debris is local and slight. This sediment, like the unconsolidated biogenic sand, is a reef flat deposit.

Biolithite

Certain sections of the core consist entirely of corals, with here and there an association of cavity-filling biomicrite. Although the gross skeletal forms of the corals have been preserved, they have suffered inversion to calcite and show no evidence of their original aragonitic fabrics. It is possible that this represents part of a reef frame in a growth position.

Coarse algal biomicrite

This type is light grey with poorly sorted allochems dominated by conspicuous, large, white, angular to subangular fragments of crustose coralline algae, and large mollusc fragments. Fragments of corals, some bryozoans and small foraminiferans are also present. Inversion of the mollusc and coral fragments has occurred (plate 1, figures 4 and 7), and the fine calcitic matrix shows evidence also of aggrading neomorphism. The nature and distribution of some calcite mosaics indicate that in parts of this rock type, allochems may have been enclosed originally by cement rather than by carbonate mud. A sheltered, low to moderate energy depositional environment, in which fine sediment was occasionally washed from the deposit, is therefore suggested.

Biomicrite

Here the sediments are creamy grey to light brownish grey in colour. The allochems are numerous, large, angular fragments of coralline algae, foraminiferans, and inverted coral and mollusc fragments, in a very fine calcitic matrix. Molluscs, particularly gastropods, dominate in some areas. In some samples echinoid plates, and in others bryozoans, are minor constituents. Both the microcrystalline matrix and some of the calcitic allochems have been affected by aggrading neomorphism (plate 1, figures 5 and 9), especially in samples from lower parts of the core. This rock is similar to the coarse algal biomicrite, but it has a more homogeneous texture due to better sorted allochems. Very fine sand and silt grade angular quartz grains are common. A sheltered, low energy depositional environment is indicated.

Fine biomicrite

A creamy grey to light brown, fine-grained rock containing a wide variety of allochems, many of which are represented merely as 'ghosts'. The most common allochems are foraminiferans and small mollusc fragments, but fragments of coralline algae and corals are present. Calcite mosaics, which in some cases contain small haematite particles, occupy foraminiferal chambers (plate 1, figure 6). The calcitic matrix is very fine-grained, especially where heavily limonite stained, and includes clay particles, haematite particles and small, angular quartz grains. Mosaics resulting from aggrading neomorphism of the micrite are common. Although in some areas the rock looks like a fossiliferous micrite, 'ghosts' of former allochems indicate that this apparent lack of allochems is due to their almost complete obliteration by recrystallization *sensu lato*. The original sediment probably accumulated in a low energy lagoonal situation with patch reefs.

Recrystallized biomicrite (pseudo-breccia)

Creamy grey to light brown, this type is iron-stained rock with a very heterogeneous texture. The apparent coarse texture, approaching a calcirudite, is superficial, being largely due to neomorphic mosaics and iron staining. The recognizable allochems are angular fragments of pelecypods, foraminiferans and some algae, and the calcitic matrix is a complex of mosaics resulting from aggrading neomorphism. A striking feature is the abundant quartz (silt and fine sand grade) scattered throughout the ground-mass (plate 1, figure 8). It is likely that the original deposit accumulated in a relatively low energy lagoonal situation.

Fossiliferous micrite

Only a few large allochems, namely gastropod fragments and benthonic foraminiferans, with small calcite spicules, some silt and very fine sand grade quartz grains are present in this type. Echinoid plates are a minor component in some samples. The rock is mainly microcrystalline calcite with some clay and randomly distributed haematite particles. Some of the quartz grains show evidence of authigenic growth. This deposit accumulated in a very low energy lagoonal environment.

Biomicrudite

Poorly sorted, large subangular fragments of corals, crustose coralline algae, pelecypods and gastropods associated with smaller allochems including bryozoan fragments are enveloped by a very fine-grained calcitic matrix, throughout which silt grade quartz is distributed. In some samples patchy pigmentation imparts a superficial appearance of a breccia, but the rock is really a biomicrudite. Short transportation, poor sorting, and deposition in a protected area near a reef are suggested.

Calcitic gravels and 'breccias'

In the lower half of the core there are thin layers of creamy grey allochems which are usually coated with reddish brown iron oxide particles, or, in the consolidated form, are enclosed in a reddish brown microcrystalline calcitic matrix. At megascopic level these may be described generally as unconsolidated calcitic gravel or calcitic breccia respectively. However, there are several varieties. In some the allochems are dominantly angular fragments of corals and coralline algae, but unlike those of the unconsolidated coral/algal gravel, they are inverted and usually finer grained. The consolidated variety could therefore qualify for the term biomicrudite. In other types, fragments of micrite and fossiliferous micrite are enclosed in a ferruginous, calcitic matrix and could aptly be named intramicrudite, especially since the assortment of small biogenic grains in the intraclasts and enclosing matrix are similar. In such deposits the angularity of the allochems indicates brief transportation to a shallow protected area of accumulation. One conspicuous layer has some aspects of a 'dismicrite' suggesting mild disturbance of a fossiliferous micrite in a low energy environment. The cavities and cracks created by the disturbance subsequently became filled with iron-stained carbonate sediment. Limonite is the chief iron stain, but irregular concentrations of haematite particles occur in the matrix.

(*b*) *Diagenesis*

Most core samples are light in colour, being creamy grey to light brownish grey. Darker pigmentation is due to iron oxide particles incorporated in matrix and cement fabrics, occurring as a coating of allochems, or as a superficial limonite stain introduced after lithification. Haematite particles have also been noted.

The effects of diagenesis are apparent throughout the core, ranging from the simple acicular aragonite cement of the upper levels to the aggrading neomorphic mosaics which are common below 7 m. The effects of diagenesis also vary with depth and to some extent may reflect disconformities, for instance the change from aragonite to calcite at 7 m, which was shown by the mineralogical analysis, can be observed also in stained peels and in thin sections. This inversion from aragonite to calcite in molluscs and corals is accompanied by the 'replacement' of the characteristic aragonite fabrics by coarser calcite mosaics, but 'ghosts' of original lamellar shell structure survive in some allochems. Micrite envelopes (Bathurst 1966) enclosing drusy calcite mosaics are present in parts of the core.

Some samples have undergone so much aggrading neomorphism that many allochems have been almost completely obliterated and are represented merely as 'ghosts' in coarse neomorphic mosaics.

The authigenic growth of quartz is suggested by its delicately spired boundaries and calcite inclusions, whereas evident mechanical wear and rounding indicates the terrigenous nature of other quartz grains.

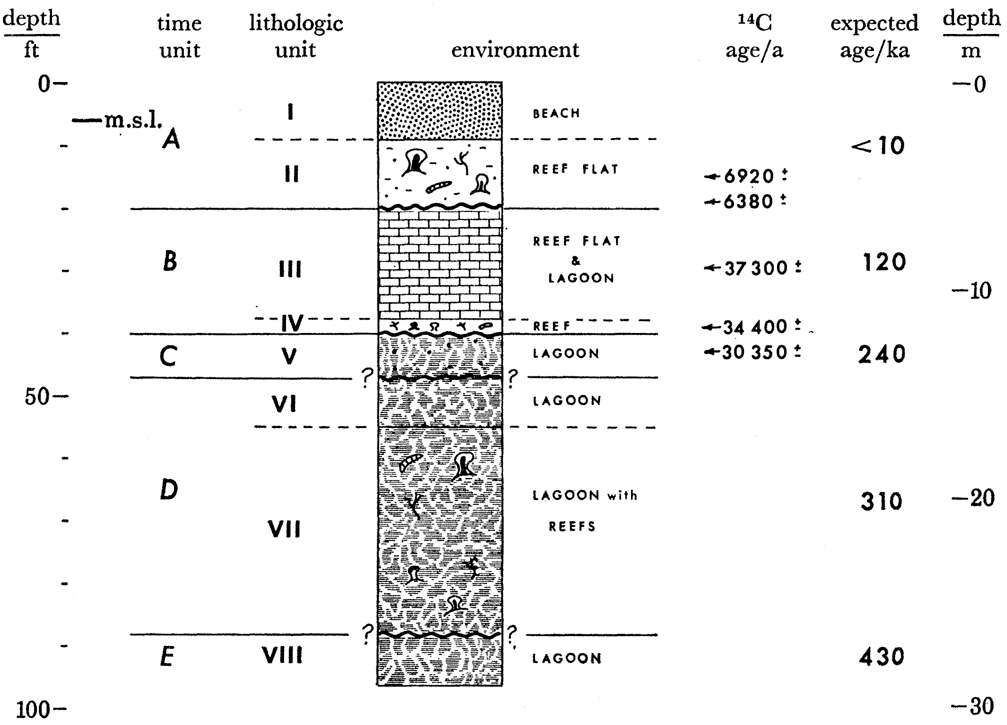

FIGURE 2. Stratigraphic units and possible absolute ages of Bewick core.

STRATIGRAPHY OF THE CORES

(a) *Bewick*

The Bewick core can be divided into eight lithologic units, labelled I–VIII in figure 2, and a maximum of five time units. Lithologic and time units are recognized on the basis of the following criteria: (i) radiocarbon date hiatus; (ii) sharp breaks in mineralogy and/or chemistry; (iii) composition of allochems; (iv) textural and fabric characteristics of core samples; (v) existence of features in core samples, including colour, which could reflect weathering or solution effects; and (vi) change in drilling performance. A lithologic unit can be bounded by either a disconformity or a facies change.

Table 3 summarizes the general characteristics of each lithologic unit. The contact between unit I, the biosparite, and unit II, the reef flat deposits at 3 m below ground surface, is sharp, and is considered to represent a facies change. The reef flat of 6000–7000 years ago has been overwhelmed by cay sands, which at Bewick are at least 4000 years old (R. F. McLean, personal communication). Lithologic units I and II constitute time unit A, of Holocene age (tables 1 and 3; figure 2).

The discontinuity at −7 m below ground surface must have the status of a major disconformity. Although visible signs of weathering on the top of unit III are slight, the recrystallized nature of the limestone and the vastly older ^{14}C ages point to this contact representing the 'Thurber Discontinuity' (Stoddart 1969). Unit III consists of coarse algal biomicrite, biomicrite and some biolithite. Unit IV is a thin bed and is clearly separated from the biomicrite above on the basis of its high coral content, all of which are recrystallized. The change from unit III to unit IV is interpreted as a facies change.

The hiatus at 12.2 m was observed within core run 13. In this run creamy white coral (biolithite) of unit IV overlies an oxidized light brown limestone, which petrologically is a biomicrite interbedded with a fine biomicrite (unit V). The sharp nature of the break between units IV and V suggests a disconformity. The fabric of many samples below the contact shows somewhat more intense recrystallization (e.g. neomorphic mosaics and 'ghosts'). Furthermore, core samples show, under the binocular microscope, oxidized crevices, cavities and grain faces. Unit V also contains noticeable terrigenous material. Time unit C is therefore regarded as beginning at the top of lithologic unit V at 12.2 m below ground surface, and besides biomicrite and fine-biomicrite, consists also of fossiliferous micrite and recrystallized biomicrite.

The break between units V and VI at 14.3 m is also interpreted as a disconformity separating time unit C from time unit D. Samples from the upper part of VI under the binocular microscope have a cavernous appearance. Many of the cavities are filled with a brown micrite containing terrigenous quartz silt. Limonitic staining is apparent and haematite particles occur in the matrix. It could be argued that given the thinness of V (2 m), the weathering features in the upper part of VI are not part of a solution disconformity, but an expression of deeper weathering in V. Until this question is resolved a query should be placed on the disconformity purporting to separate time units C and D.

A facies change separates lithologic units VI and VII at −17 m. The former is mainly fossiliferous micrite containing terrigenous silt and clay, whereas VII consists of several interbedded types (table 3). Within VII, core samples show a wide range of composition and texture. Ferruginous and argillaceous components are common. Fossiliferous micrite, biomicrite, with 'gravels' and 'breccias' of inverted reef rubble, and some recognizable intraclasts suggest reworking of reef and lagoon sediment which accumulated in a protected lagoon situation. The contact between VI and VII is transitional.

At the base of the core, biomicrite and biomicrudite were identified in thin section (unit VIII). The environment of deposition of materials recovered from depths below 26.8 m is not very different from the materials immediately above the contact. However, the core samples in unit VIII are much harder, perhaps more recrystallized (especially the corals), and certainly more iron stained. Iron values jump from 800 to 1300 parts/10^6 at the contact. Again, samples in the fine-grained limestone below the discontinuity possess solution cavities partially filled with brownish argillaceous carbonate mud. It is suggested, but not confirmed, that a time break exists at 26.8 m separating time unit D from time unit E.

(*b*) *Stapleton*

Three lithologic units were recognized at Stapleton, designated upper, middle and lower (figure 3). To 8.5 m below ground surface there exists a carbonate sand, unconsolidated, well

TABLE 3. BEWICK CORE, SUMMARY OF STRATIGRAPHY

time unit	depth below h.w.s.t. m	lithologic unit	dominant petrographic types	dominant components and texture	diagenetic features	postulated depositional environments	representative samples
A	0–3	I	biosparite	rounded, well sorted allochems (corals, molluscs, coralline algae, benthonic forams, bryozoans, *Halimeda*, intraclasts)	acicular aragonite cement	beach	2–1–1 2–1–3 1–2–4
	3–6	II	unconsolidated biogenic sand	coarse to fine sand; angular to subangular allochems (molluscs, coralline algae, corals, some *Halimeda*, (benthonic forams)		reef flat	2–3–1
			unconsolidated coral/algal gravel (reef rubble)	bored, subangular pebbles of coral and coralline algal fragments; some gastropod shells present	acicular aragonite in cavities in corals and gastropod shells		2–3–3 2–3–6
disconformity B	6–11.6	III	coarse algal biomicrite	poorly sorted allochems (coralline algae, molluscs, corals, bryozoan and foram fragments)	inversion of mollusc and coral fragments to calcitic mosaics; evidence for cement in some samples	low–moderate energy reef flat with lagoonal areas	2–4–3 2–4–6 2–5–5 2–5–6
			biomicrite	molluscs, coralline algae, corals, forams, with some detrital quartz in the matrix	mosaics resulting from aggrading neomorphism present in the matrix		2–10–3 2–11–1
	11.6–12.2	IV	biolithite	corals	inversion of coral fabrics to calcitic mosaics	corals in growth position	2–13–2 2–13–5

disconformity C	12.2–14.3	V	varieties of biomicrite (fine biomicrite, recrystallized biomicrite) and fossiliferous micrite	molluscs, forams, some coralline algae and corals; silt and very fine sand grade quartz in a fine matrix, with clay and haematite particles	iron staining and neomorphic mosaics extreme in places, producing pseudobreccia; allochems present in some samples as 'ghosts'	low energy lagoon with patch reefs receiving terrigenous sediment	2–13–7 2–13–11 2–14–4 2–15–2 2–16–1
disconformity D	14.3–16.8	VI	fossiliferous micrite	few large allochems algae and corals, with foram and mollusc fragments. Abundant silt to fine sand grade quartz and also ferruginous particles	cavernous appearance; limonite staining of allochems; authigenic growth on some quartz grains	shallow protected lagoonal area receiving terrigenous sediment	2–18–1
	16.8–26.8	VII	interbedded fossiliferous micrite, biomicrite, and calcite gravels and breccias	coralline algae, coral, forams, and molluscs; silt-sized quartz; ferruginous and argillaceous components	iron stained allochems and matrix; inverted reef rubble	shallow lagoon adjacent to patch reefs (limited transportation)	2–22–3 2–23–8 2–25–3 2–28–3
disconformity or transitional zone E	26.8–29.3	VIII	biomicrite, biomicrudite and breccia	poorly sorted, large subangular fragments of corals, molluscs, etc., in fine-grained matrix	solution cavities filled with brown calcilutite; more severe iron staining; allochems 'recrystallized'	shallow lagoon quite protected but with reef patches	2–35–10 2–36–2 2–37–3

sorted and containing a variety of constituents. The middle unit appears to contain interbedded unconsolidated sand mixed with cemented layers (containing molluscs, coralline algae and foraminifers) and coral fragments. On the basis of aragonite/calcite ratios and ^{14}C dates, this unit is Holocene in age. At the base of the hole at 14.6 m occurs a biomicrite with a calcite mineralogy. This was also a hard layer difficult to penetrate. It is considered to represent the Holocene–Pleistocene ('Thurber') discontinuity.

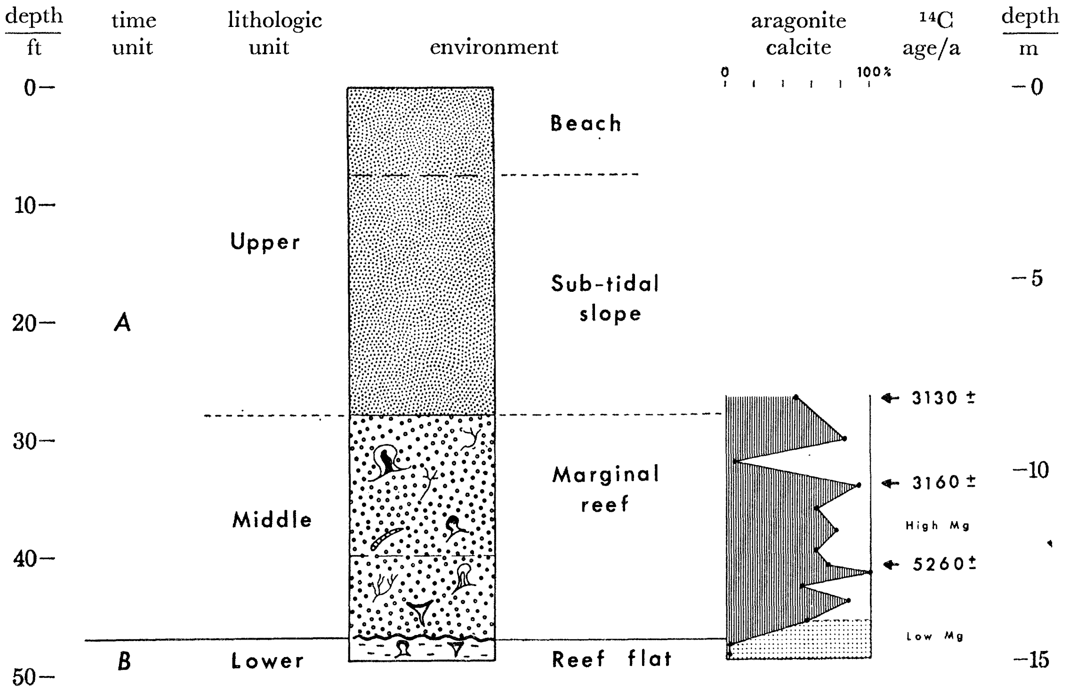

FIGURE 3. Stratigraphic units of Stapleton core.

STRATIGRAPHIC MODEL

From Bewick and Stapleton shallow drill results, it is possible to construct a conceptual model of island genesis in the Late Quaternary. This model is diagrammatically depicted in figure 4, which shows a number of stages in the development of islands such as Bewick.

The model is based on three assumptions. (i) Sea level since the Brunhes-Matuyama magnetic reversal of *ca.* 700000 years ago has oscillated primarily in response to glaciations in the Northern Hemisphere. The amplitude of major oscillations is 100–120 m with a period of 100000–120000 years (Shackleton & Opdyke 1973). Essentially, sea level has spent 90% of the upper Quaternary below its present position. (ii) The northern Queensland continental shelf has slowly subsided throughout the Quaternary, probably since the mid-Tertiary. The thick pile of Cainozoic limestones documented in deeper Great Barrier Reef drill holes supports this assumption. Furthermore, no Pleistocene sediments are exposed above sea level on the continental shelf, and only last interglacial (?) materials are recorded on the mainland (D. Hopley, personal communication). (iii) Biogenic activity continued at or slightly below sea level during each major transgression.

The model requires the return of sea level on a slowly subsiding shelf for periods of 5000 to 20000 years at least six or seven times in the last 700000 years. During each transgression, reef and associated lagoon sediments developed on remnants of older reef–lagoon complexes. During marine regressions the newly deposited limestone was exposed to subaerial processes. It is possible that a karst morphology was developed on much of the exposed terrain during the relatively long intervals when sea level would have oscillated below the level of the former islands. The extent to which these islands would have protruded in the form of tower karst hills is unknown. However, it is expected that the exposed surface would have been subjected to cavernous weathering under a combination of freshwater vadose and phreatic conditions.

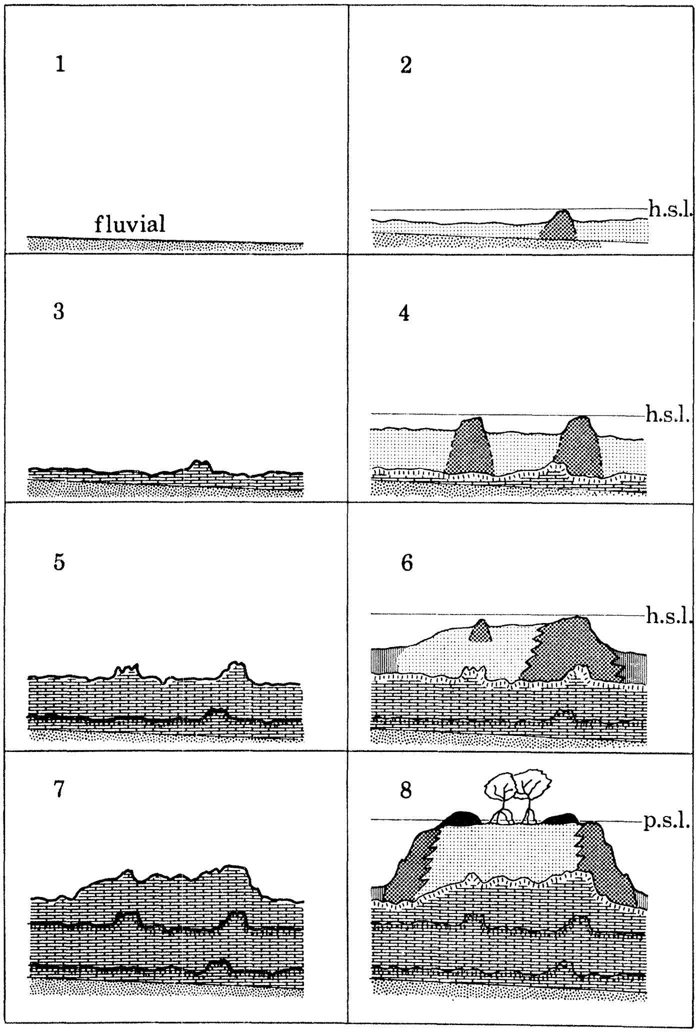

Figure 4. Idealized model of the development of a platform reef with windward and leeward cays during the late Quaternary (based on Bewick core data).

The model also suggests a change in the environment of deposition from Pleistocene time units B–E compared with the Holocene unit A. High energy reefal conditions appear to have dominated the Holocene, but below the upper disconformity more sheltered environments have been interpreted. The biomicrite and fossiliferous biomicrite of the Bewick core reflect shallow lagoonal conditions, and the thin interbedded coarse deposits (gravels, breccias, etc.) indicate occasional disturbances and delivery of coarse reef debris. The shelf itself could have had lower relief or there could have been more protected areas, including lagoons, within a larger reef complex. Without further drilling either view is tenable. However, the increase in terrigenous material below 12.2 m suggests greater opportunity of transport from the mainland, probably across a shallower shelf than now exists.

One implication of the Bewick–Stapleton drilling is illustrated in figure 5. Variation in the depth of the Pleistocene–Holocene disconformity may strongly influence the degree of development of patch reefs and associated cay and mangrove cover. Well developed 'low wooded islands' (e.g. Bewick) could possess a shallow Holocene reef cap compared with reefs which contain little or no cay development. The mechanism responsible for such a pattern involves a more or less constant rate of vertical reef growth which lagged behind the rate of sea level rise before the 'still-stand' of *ca.* 6000 a B.P. Variation in the depth of the Holocene–Pleistocene surface, drowned at different times during the transgression, probably interacts with other factors, such as configuration of the surface (tilted, flat, centrally depressed, etc.), its areal extent, and hydrodynamic and biologic factors, to produce the variety of reef morphologies characteristic of the Great Barrier Reef.

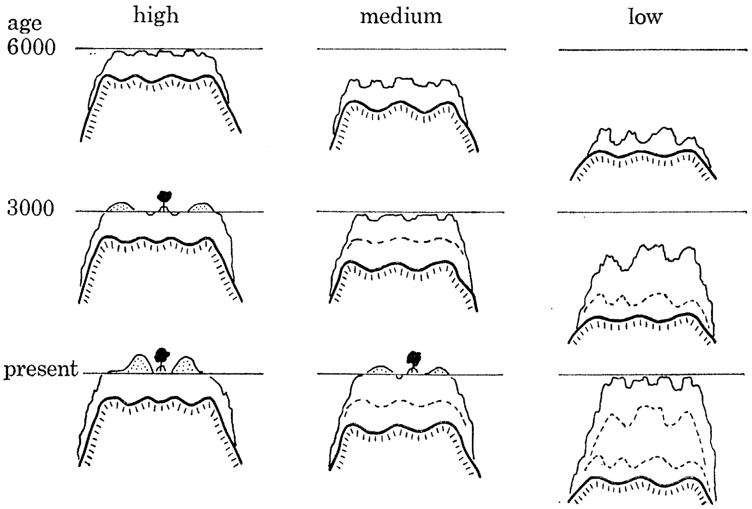

FIGURE 5. Expected influence of variations in the depth of Pleistocene–Holocene disconformity below present sea level on the age and degree of development of reef flats and cays in the northern region of the Great Barrier Reef.

CONCLUSION

Two drill holes undertaken as part of the 1973 Expedition yielded information on the development of reef island complexes in the northern Great Barrier Reef Province in the late Quaternary. The hole on Bewick Island, in particular, suggests the presence of several discontinuities in the subsurface. Here eight lithological units were identified, separated in three instances by facies transitions, and in four other cases by disconformities. The uppermost disconformity is confirmed by several lines of evidence, including radiocarbon dating, and clearly separates Holocene from late Pleistocene sediments. Other time breaks are not as strongly supported, especially the lowest two. At Stapleton, drilling stopped at the upper discontinuity.

The data are interpreted as showing episodic growth of a limestone 'pile' during Quaternary marine transgressions associated with periodic continental deglaciations, i.e. interglacial intervals. The thin nature of each limestone unit is consistent with expected rates of reef growth and associated limestone deposition during the limited time period when sea level reached its high levels relative to the land (P. J. Davies, personal communication). However, this view remains untested and requires detailed geochronologic study of uninverted material of Pleistocene age. It does appear likely that reefal limestones were exposed to subaerial weathering and were karstified during Quaternary marine regressions. The cavernous, recrystallized (*sensu lato*) low-magnesium calcite rocks below 7 m are consistent with this inference.

The Bewick core also shows marked changes in environmental conditions with time. The upper part of the core contains sediments deposited under relatively high energy conditions. Below the upper disconformity the dominant rock types are biomicrite and fossiliferous micrite which suggest somewhat sheltered, relatively shallow lagoonal conditions within which patch reefs grow. The occurrence of terrigenous clastic grains below 12.2 m perhaps requires a shallower shelf, and/or a nearer source of terrigenous material, than is near the Bewick drilling site at present.

The discontinuous stratigraphic sequence at Bewick and Stapleton is similar in some respects to that interpreted from Heron Island and Michaelmas Cay (Davies 1974). The shallow nature of the Holocene as observed at Bewick, where it extends to only 4 m below low water springs, is seen in other reef complexes in the Pacific (e.g. Mururoa; Labeyrie, Lalou & Delibrias 1969). The data from Bewick and Stapleton cores are not inconsistent with the general model of barrier reef development proposed by Purdy (1974).

Finally, it should be apparent that interpretations of reef structure from a limited number of shallow drill holes must be treated with considerable caution. The need to drill at a number of places across the continental shelf in order to test various models of shelf behaviour in relation to sea level change, as well as to examine subsurface characteristics in different environmental conditions, was an objective not attainable in the time available to the 1973 Expedition. Even more frustrating, but equally urgent, was the desire to drill at more than one site on the same island. Furthermore, it was not possible to tie in our drilling with continuous seismic profiling. Given these limitations, it is possible that the information made available by the two holes has only partially answered some questions, but also it has raised a number of new questions, the answers to which will require further drilling efforts.

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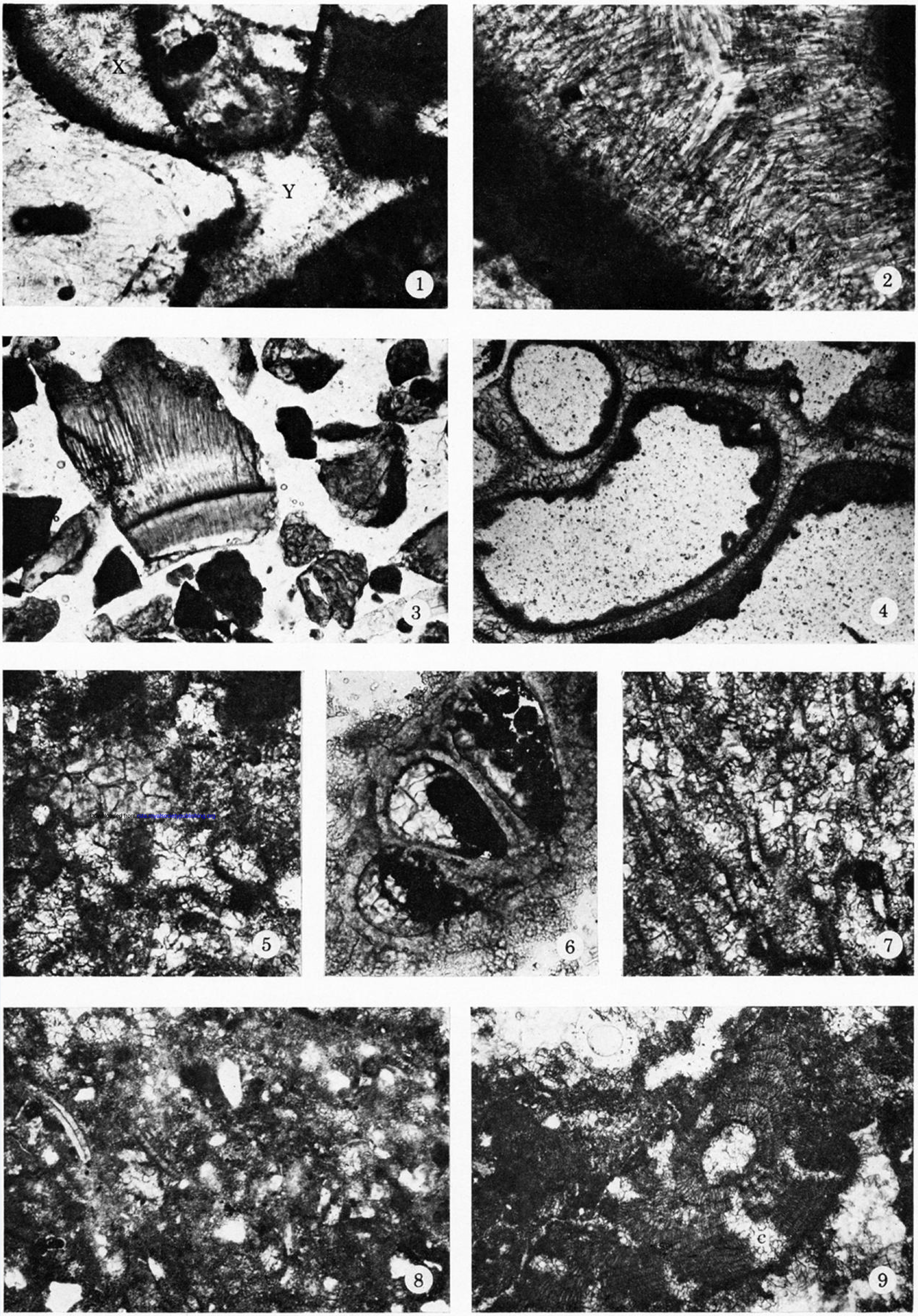

PLATE 1. For description see opposite.