PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1978 **291**, 167-186
doi: 10.1098/rsta.1978.0097

Phil. Trans. R. Soc. Lond. A. **291**, 167–186 (1978) [167]
Printed in Great Britain

Sea level change in the Holocene on the northern Great Barrier Reef

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[Plates 1 and 2]

Detailed studies, utilizing a range of both well controlled sea level criteria and dates, are required if Holocene time–sea level curves are to be established with any degree of confidence. This paper is restricted to an interpretation of Expedition results from the northern Great Barrier Reef, excluding those from the drill core. Extensive colonies of emergent fossil corals in growth position indicate that present sea level was first reached about 6000 a B.P. Elevations of cay surfaces, cemented rubble platforms, microatolls, coral shingle ridges, reef flats and mangrove swamps, referenced to present sea level show an array of heights. However, levels of particular features are accordant on many reefs: it is believed that these can be related to particular sea levels. Radiometric dating provides the time framework. Ages of samples from similar deposits on different reefs are surprisingly consistent. Oscillations in sea level since 6000 a B.P., relative to present sea level, are identified with varying degrees of confidence. This history of relative sea level does not separate eustatic from non-eustatic components.

1. Introduction

While a massive rise in the level of the sea (> 100 m) since the maximum of the last glaciation is universally accepted, there is little agreement as to when this transgressing sea first reached its present position in the Holocene. Nor is there agreement as to the directions and magnitudes of sea level change since that time. Thus there is even conflict as to whether the most recent significant change has been a fall or rise in sea level. Detailed local studies, with the use of a range of both well controlled sea level criteria and dates, are required if Holocene time–sea level curves are to be accepted with any degree of confidence. Because reef areas possess an array of present and palaeo sea level markers together with abundant datable materials they are particularly appropriate sites for the investigation of recent sea level changes. Nevertheless, serious problems in identifying changes based on reef data exist, although they are not always readily acknowledged. During the Royal Society – Universities of Queensland Expedition to the northern Great Barrier Reef in 1973 we became particularly conscious of both the utility of reef data and problems associated with its interpretation. In this paper results from that Expedition are discussed. Our intention is to present the evidence for a recent sea level history by utilizing data solely obtained from the Expedition without recourse to earlier commentaries on this or adjacent areas of the Great Barrier Reef (for a review of these see Hopley 1978, this volume) nor to sea level histories from other regions. In addition we document the problems found and assumptions used in interpreting the evidence.

2. Problems associated with reef data

2.1. *Establishment of common tidal datum*

The most optimistic changes in sea level since the main Holocene transgression are of the order of ±4 m relative to present sea level. Thus, except in areas of high tectonic activity, any evidence for recent sea level history is within a few metres of present mean sea level. Most deposits, surfaces and features which may be related to former sea levels fall within the present intertidal range or within the reach of contemporary storm wave levels. On the northern Great Barrier Reef the maximum altitude of any low island is less than 10 m above extreme low water level. Given the concentration of features within such a limited vertical range levelling accuracy and reference to a survey datum become very important. The problem of obtaining absolute levels between particular features on the same reef, and of comparing altitudes of equivalent deposits on surfaces between reefs is acute. Ideally, a precise datum is required on each reef visited. These do not exist in the northern Great Barrier Reef. Therefore, the establishment of a realistic common baseline as a substitute is necessary. For our work all levelled profiles were reduced to low water datum, which is the mean height of lower low waters at spring tides. Individual levels have been related to low water datum by reference to predicted tides at Cairns: for most of the area investigated the predicted tides do not differ significantly in amplitude or timing from those at Cairns, and corrections to the Cairns curves only need to be made north of Cape Melville.

It is important to realize that there are several sources of error in these reductions and we cannot accurately evaluate their magnitude. First, there may be differences in tidal curves between Cairns, the secondary stations for which predictions are available (these include several of the islands studied, notably Green Island, Hope Islands, Howick Island, Low Isles, Low Wooded Island), and the islands on which profiles were measured. Secondly, local tidal levels may have been distorted by meteorological effects: the Trades blew strongly through most of the Expedition, and it would be surprising if on some days at least local tidal levels were not distorted by up to 0.3 m. Third, and perhaps most important, all reductions to datum were made by observing a still water level at a known time on a particular profile and relating this to a predicted tide curve. Determination of a still water level is often difficult, either because of rough conditions, especially at middle and high waters, or because of ponding of water on reef flats at low tides. Relation of the still water level to the tidal curve is also more difficult on irregular low-amplitude neap tides than on springs.

In the absence of tidal records at each of the sites surveyed the height data represent the best estimate of elevations related to the mean level of lower low water springs as datum, and enable different sections to be directly compared. All heights are given in metres. For comparison, at Cairns, mean high water springs are at 2.3 m, mean high water neaps at 1.6 m, mean low water neaps at 1.2 m, and mean low water springs at 0.5 m; these figures probably apply to all the islands north to Cape Melville, from which the bulk of the evidence reported here comes.

2.2. *Relation of features to sea level datum*

If inferences are to be drawn regarding late Holocene sea level change it is essential that the deposits and levels of interest can be referred to a specific level of the sea such as mean low water neaps, mean sea level, extreme high water springs, etc., at the time of their formation.

This is by no means simple and often can only be done with coral microatolls in growth position. Sedimentary deposits for instance may show a variety of levels even on the one reef as a result of variations in exposure and cannot easily be related to a specific tidal level.

The problem of equating features with a specific level of the sea is brought sharply into focus if we consider the range of levels of features related to present sea level. For instance the heights of living corals vary considerably depending on whether they are in free draining situations such as on the reef flat or reef edge, or in areas of impeded drainage such as moats. Levels for the tops of open reef flat corals range through 0 to 1 m; and for moated corals range through 0.4 to 1.7 m. Likewise the heights to which island beaches and sedimentary deposits are built under present conditions are highly variable and depend on such factors as relative exposure, distance from reef edge, surface roughness between reef edge and deposit, size and shape of sediment, and storm frequency and intensity. For instance measured elevations for sand cay beaches range through 2.5 to 4.0 m and for outer shingle ramparts from 1.1 to 3.2 m. Furthermore, if we are to utilize the surfaces of cemented deposits such as beach-rock and rampart-rock as palaeo sea level markers, what do these surfaces represent? Are they erosional levels, depositional levels or levels of cementation? Can we identify an upper limit of marine cementation related to present tidal datum? Marine cements are known to precipitate up to the level of extreme high water spring tide and more commonly to mean high water spring tide. In the northern Great Barrier Reef these levels are 2.9 and 2.3 m respectively but we cannot be certain that such levels are either reached or not exceeded.

If we cannot identify with certainty levels of particular features with specific present sea levels – and it is clear there is a range of values within and between reefs – then we cannot expect the situation to have been greatly different in the past. Indeed, it is possible that variation is *less* now, as a result of a few thousand years of 'stable' sea level, than it was immediately following the Holocene transgression when great changes occurred on the reefs, and between-reef differences may have been more marked. Nevertheless, it is important and necessary to make an intelligent assessment of the relation between present sea level and contemporary features to serve as a baseline for comparison with older features. Such an assessment is made when the specific evidence is discussed below.

2.3. *Identification and interpretation of features*

Problems also arise in field identification and interpretation of features; some may be given a sea level connotation when it is not justified. For instance, raised beach-rock may be identified when the material is in fact either aeolianite or cay sandstone in which the cement is partly phosphatic, and which cannot be regarded as sea level markers. The question of corals in growth position versus transported corals is another example. Some transported corals can be deposited the right side up and could be interpreted as *in situ* when indeed they are not. Further difficulties arise when corals are covered by later deposits and observed only in section. Thus, the distinction between deposited corals and those in growth position as exposed in the basal unit of some rampart-rocks in the area was not always clear. Fortunately most of our dated *in situ* fossil corals were from areally extensive fields of microatolls where there was no doubt that they were in growth position. However, in such cases the problem relates to the height of microatolls. Rarely with the fossil microatolls could we determine for certain whether or not their growth environment was a free-draining or moated situation. A third problem focuses on distinguishing storm-wave from normal-wave shingle deposits and wind-deposited from wave-deposited sands. In the first case reef blocks and boulder tracts result from catastrophic storms, while shingle ramparts and ridges likely result from both rough and quiet weather conditions. In the second case lenses of drift pumice in sandy deposits proved useful indicators of the reach of wave-wash, but the presence of such material does not negate the possibility that wind may have had a rôle in cay building. Granulometric parameters of the sands provide useful clues, however, to environments of sedimentation.

2.4. *Time scale and radiometric dating*

There are also problems associated with establishing a time scale. When focusing on the last few thousand years it is necessary to establish a chronology which is accurate within tens, and certainly within one or two hundred years. The time scale used here is the radiometric one, and all dates are conventional ^{14}C ages B.P. All ages reported in this paper were determined by the Radiocarbon Laboratory, Australian National University, and are considered valid ages. Details of the multidisciplinary approach to the problems of obtaining valid radiocarbon dates as well as detailed sample descriptions and locations are given by Polach, McLean Caldwell & Thom (1978, this volume).

In the present context problems arise in the interpretation of ages, not in their determination. The most obvious question is: does the dated material yield a realistic age for the deposit, feature or surface from which it was obtained? Excluding bulk samples of calcarenite which consist of both constituent grains and cement and coral clasts known to contain secondary void infills, ages refer to the time of life of the organisms. With transported material such as shingle ramparts there may be a considerable discrepancy between that time and the time when the deposit accumulated. In addition, in bulk samples of cay sand the dated sediment comprises a suite of bioclasts and not just a single organism. Thus for the sands it is assumed that dates refer to the average age of all constituents which individually may have a wide age range. For both single and bulk samples from sedimentary deposits the reported dates must be regarded as maximum ages for the time of their formation. Multiple samples from equivalent units were dated and the consistency of these results together with geographic, geomorphic and stratigraphic evidence enable an assessment of the lag between the time-of-life of the organism and the time-of-formation and subsequent history of the deposit. This problem does not arise with dated *in situ* fossil organisms.

2.5. *Other problems*

The foregoing discussion is not exhaustive. There are additional problems relevant to the construction of a late Holocene sea level history for the area. These include the possibility that tidal range and/or climate have varied during the last few millennia and that tectonic movements and/or hydro-isostatic warping of the land and shelf may have taken place. Such possibilities on the northern Great Barrier Reef are discussed elsewhere by Hopley (1978, this volume) and Thom & Chappell (1978, this volume) and need not be developed further here.

3. Summary of problems, error terms and assumptions

The establishment of a common tidal datum, difficulties in relating contemporary features to specific levels of the sea to serve as present baselines, problems in identifying and distinguishing between those fossil features which possess a sea level connotation from those that do not, problems in relating radiometrically dated samples to features relevant for a sea level history, as well as the possibilities of temporal variations in oceanographic factors and land movements, are common to all workers interested in documenting late Holocene sea level history but are rarely mentioned or acknowledged.

At most we are dealing with potential sea level variations of ± 4 m and a time period of a few thousand years. Our evidence for sea level change, if any, is thus to be found within or close to the present tidal range or within the range of contemporary storm surge levels. We therefore must acknowledge our error terms. Relative levels between features on the same traverse and between traverses on the same reef can be regarded as accurate to within a few centimetres. But between reefs there may be discrepancies of up to 0.5 m. Absolute levels in relation to Cairns datum may be in error by an equivalent amount. The statistical error term

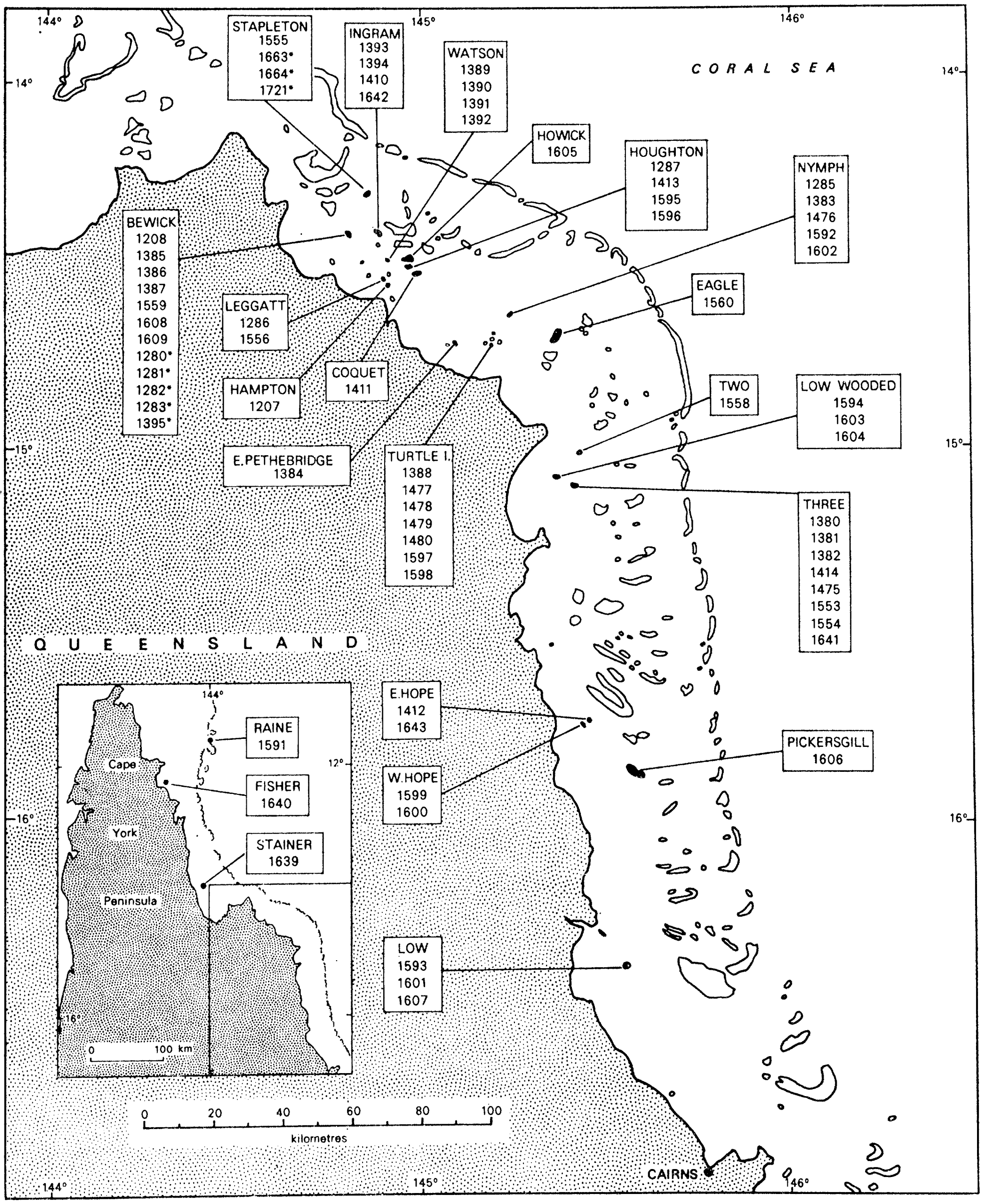


Figure 1. Location of radiometrically dated samples on the northern Great Barrier Reef identified with A.N.U. Radiocarbon Laboratory code numbers.

associated with the radiocarbon results ranges from ± 70 to 170 years. Because of this and because our time scale extends over some thousands of years it may well be easier to identify the dates of palaeo sea levels more accurately than their specific levels. Moreover, because the lower limit of most of our observations was low water level there is a bias toward recognizing features that would relate to higher rather than lower sea levels relative to present.

We must also acknowledge our assumptions, the major ones being: (1) features equivalent in form and composition, but at higher or lower levels than their contemporary counterparts, developed with a sea level that was higher or lower than present, the magnitude of sea level change being the difference between the two levels; (2) features inferred to be related to present sea level are indeed so related; (3) ranges in elevation between equivalent contemporary features for all reefs surveyed are similar to the ranges of relict features. We also assume in the first analysis that there have been no significant changes in tidal range or wave climate within the region, nor any land or shelf movement in the last few thousand years. That is, we assume the only land/sea changes have been eustatic and levels are relative to present sea level.

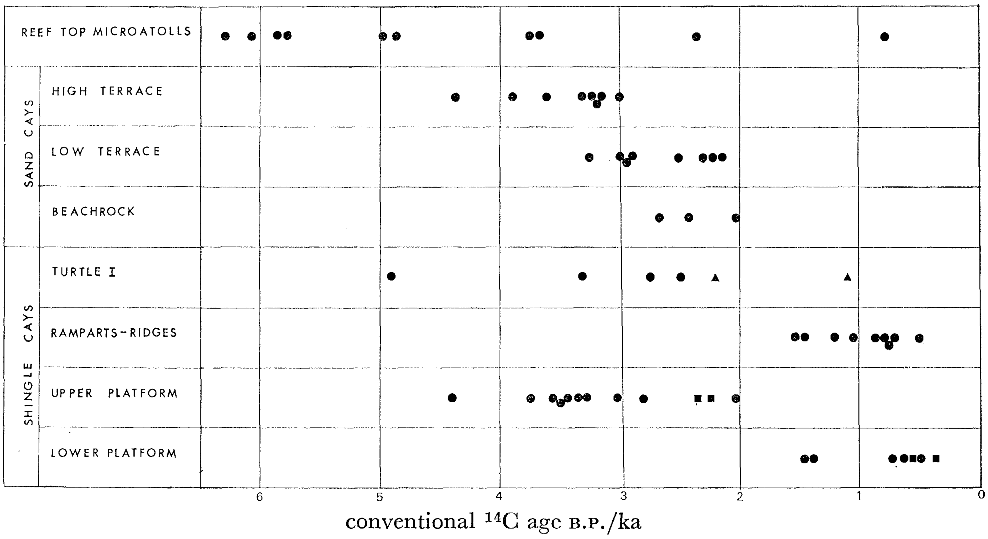


FIGURE 2. Summary of radiocarbon dates: ●, skeletal carbonate; ▲, fibrous mud; ■ cement.

4. SUMMARY OF RADIOCARBON DATES

The locations of samples on the northern Great Barrier Reef radiometrically dated for the Expedition are given in figure 1. Figure 2 summarizes all dates from above low water level grouped in terms of features identified in the field. It is clear from these results that there is considerable clustering of data; the consistency in age of comparable features on different reefs gives confidence in interpreting the late Holocene history of reefs and reef islands in the area.

5. SUMMARY OF LEVELS

Figure 3 summarizes the surveyed levels in relation to datum of a variety of features from the reefs between Low Isles in the south and Stapleton in the north (figure 1). The range of any one feature is not less than 1 m. Nevertheless, it is clear that levels of equivalent features are generally accordant among the reefs such that particular forms extend over a definable vertical range. While overlaps between fossil and contemporary forms do occur, some are considerably higher than their modern counterparts and probably reflect changes in the level of the sea relative to present.

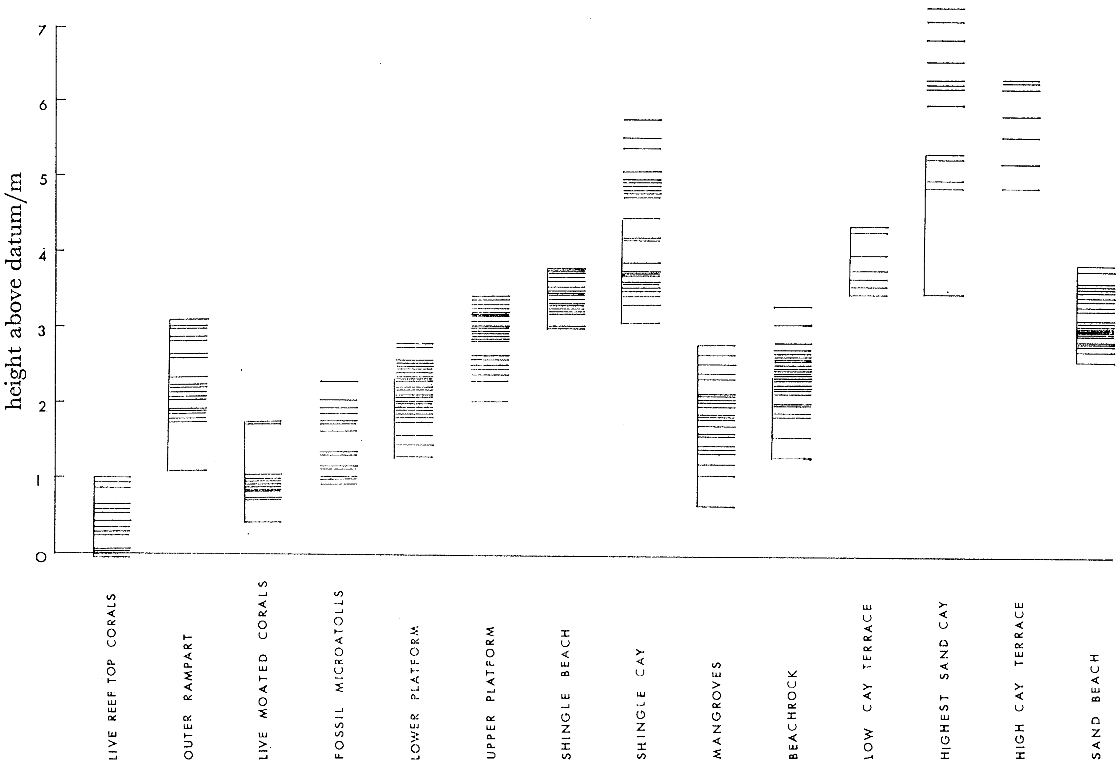


FIGURE 3. Levels of a variety of reef features on the northern Great Barrier Reef referred to tidal datum arranged from left to right in order of their occurrence across a reef top from the windward to leeward side. Vertical lines represent range of levels of features known or believed to be related to present sea level.

6. EVIDENCE FROM FOSSIL MICROATOLLS

Reef-top corals in growth position, particularly those of microatoll form, provide the most certain evidence of the position of local water levels. Scoffin & Stoddart (1978, this volume) give details of the utility of microatolls as water level recorders in the area. They conclude that mean low water springs (0.5 m) represents an effective upper limit to coral growth in free-draining reef flat locations, while for living moated microatolls the approximate upper limit is mean low water neaps (1.2 m) though *potential* altitudes of modern moated corals are higher.

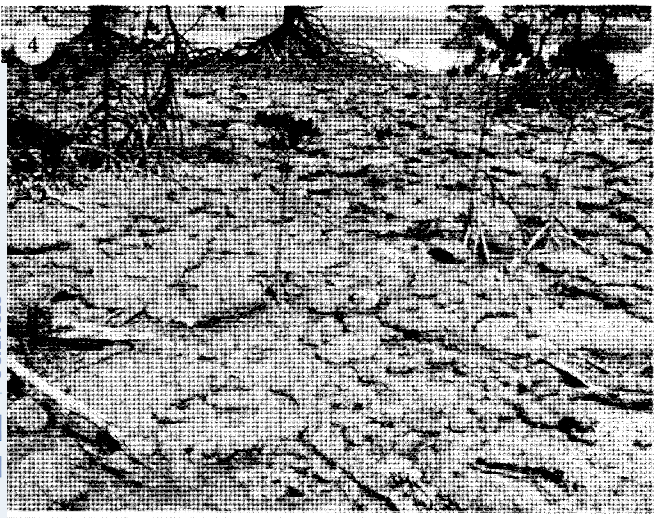
Fossil corals and tridacnids from microatoll fields were dated from a number of reefs, and elevations from some of these sites in relation to living open reef flat corals and/or living moated microatolls are available (table 1). In most instances the dated corals and clams are from extensive fields of microatolls and are not just isolated occurrences. Fossil microatoll fields typically occur in central portions of reef tops within mangrove swamps where flat-topped colonies are emergent above the level of mangrove mud (figures 4 and 5, plate 1). Alternatively, they are exposed in the basal facies of rampart-rocks with individual corals sometimes emerging seaward of the rock scarps (figures 6 and 7, plate 1). In both cases, corals and clams are exceedingly well preserved with little evidence of post-death contamination, borings, encrustations, etc. Field observations and X-radiographs of corals from the Low Wooded Island site showed that the tops of some of the formerly rounded coral heads (e.g. *Platygyra*, ANU-1604) had been planed down as a result of later erosion, though this was not evident at the other dated microatoll sites. We envisage that modern counterparts of fossil microatoll environments are found in the central portion of Turtle IV and Low Isles reefs and in moats such as at Houghton and Watson reefs.

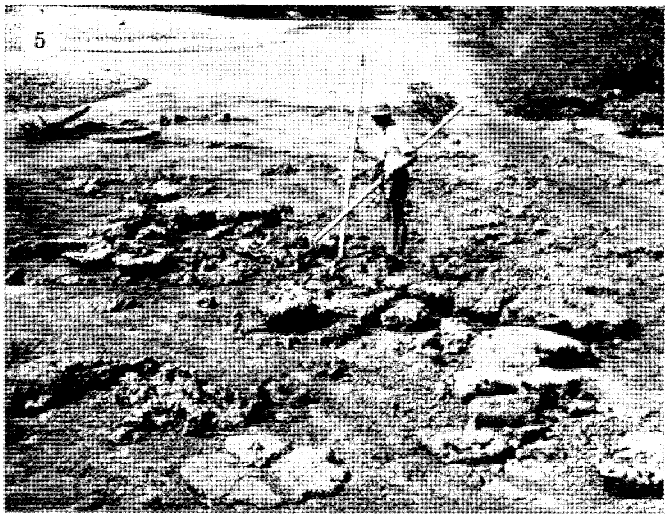
TABLE 1. AGES AND RELATIVE LEVELS OF MICROATOLLS

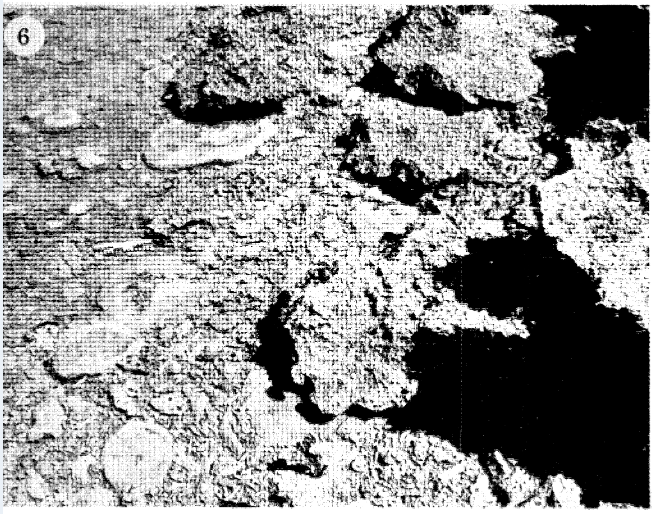
A.N.U. code	reef	age/a	comment
1640	Fisher	6310 ± 90	*Tridacna* resting on microatoll beneath shingle ridge. Level of fossil microatolls equivalent to living moated corals
1604	Low Wooded	6080 ± 90	*Platygyra* in growth position in microatoll field passing beneath rampart rock. Fossil corals are 0.6 m above present living reef edge corals
1287	Houghton	5850 ± 170	Faviid in growth position from microatoll field. Fossil microatolls are 1.1 m above highest living reef flat corals
1286	Leggatt	5800 ± 130	*Tridacna* in growth position from microatoll field. Fossil microatolls are 1.0 m above highest living reef flat corals and 0.35 m above highest living moated corals
1639	Stainer	4980 ± 80	*Favites* in growth position from microatoll field. Fossil microatolls are at a similar level to living moated corals
1639R		4960 ± 80	
1207	Hampton	4870 ± 70	Faviid in growth position from microatoll field. No height data, but microatolls definitely emergent above present living corals
1380	Three Isles	3750 ± 110	*Pavona* in growth position exposed at base of upper platform. *In situ* fossil corals are 0.8 m above moated corals
1285	Nymph	3700 ± 90	Faviid in growth position from microatoll field. Fossil microatolls are 1.3 m above living reef flat corals and 0.9 m above moated corals
1384	E. Pethebridge	2370 ± 70	Faviid in growth position from microatoll field. Fossil microatolls are 0.6 m above highest living reef flat corals
1594	Low Wooded	800 ± 60	*Porites* microatoll in moat. No height data but coral emergent by 20 cm above moat low water level

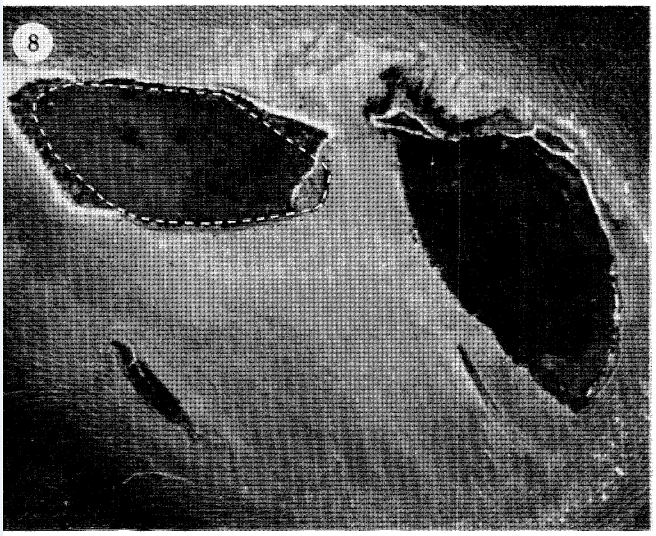
Radiometric ages and measured or estimated elevations of concordant coral colonies provide indisputable evidence that sea level in the northern region of the Great Barrier Reef first reached its approximate present position about 6000 a B.P. Dated materials of this age from four different reefs which cover some 3° of latitude indicate the spatial extent of the evidence and the likelihood that similar aged materials could be preserved on other reefs in the region. The levels of the extensive Houghton and Leggatt microatoll fields relative to living reef flat and moated corals suggest that by 5800 a B.P. the sea had passed above its present level. The possibility of moating at these two central reef sites at such an early stage in the development of reef-top features is considerably less than would be likely later on. The Stainer and Hampton corals also indicate that sea level was above present level a thousand years later (4900 a B.P.) while those from Three Isles and Nymph suggest that the highest level for which we have evidence, in excess of 1 m, was attained around 3700 a B.P. However, dates of transported clasts from cemented shingle ramparts of equivalent ages at these two sites illustrate that the fossil *in situ* corals could have been in moated situations. The level of the surface of the fossil microatoll field at East Pethebridge is 0.6 m above measured living reef flat corals, but this could also have been a moated situation. Nevertheless, the age of 2370 ± 70 a B.P. (ANU-1384) indicates that sea level was then close to or marginally above its present level at the time.

One obvious feature of the results in table 1 is the grouping of ages with gaps of about









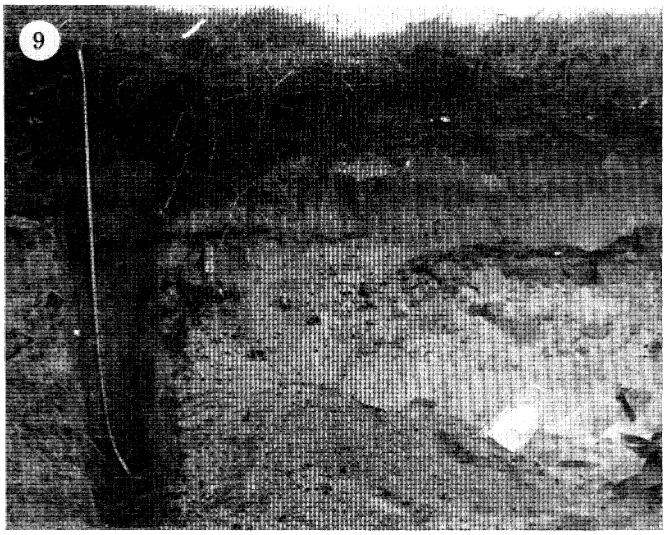


FIGURE 4. Field of emergent fossil microatolls at Leggatt Reef. A clam from this site dated 5800 a B.P.

FIGURE 5. Emergent fossil microatolls exposed in pond outlet at Nymph Reef. A coral from this site dated 3700 a B.P.

FIGURE 6. Fossil microatolls exposed beneath rampart-rock at Low Wooded Island. A coral from this site dated 6080 a B.P.

FIGURE 7. *Porites* microatoll exposed in scarp of upper platform rampart-rock at Three Isles. A coral from this site dated 3750 a B.P.

FIGURE 8. Aerial view of Three Isles showing sand cay upper left and shingle islands on right and lower left. Outline on sand cay represents 3000 a B.P. shoreline.

FIGURE 9. Sand cliff cut in high terrace at eastern end of Three Isles cay showing extent of surface soil development, buried soils and pumice layers. Two bulk sediment samples from this section were dated 3220 and 3350 a B.P.

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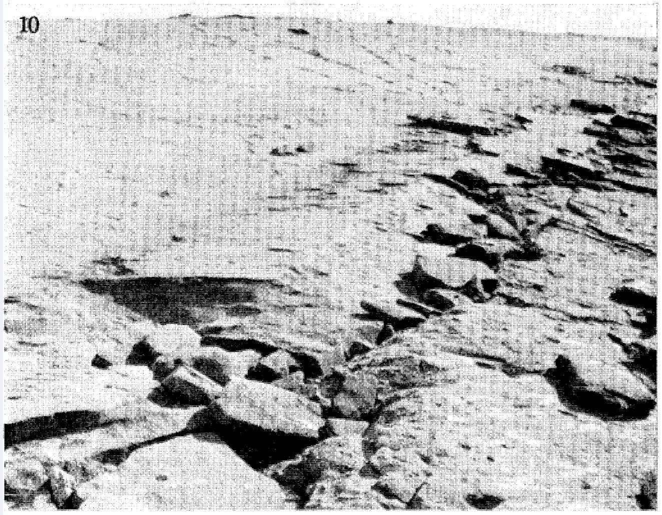

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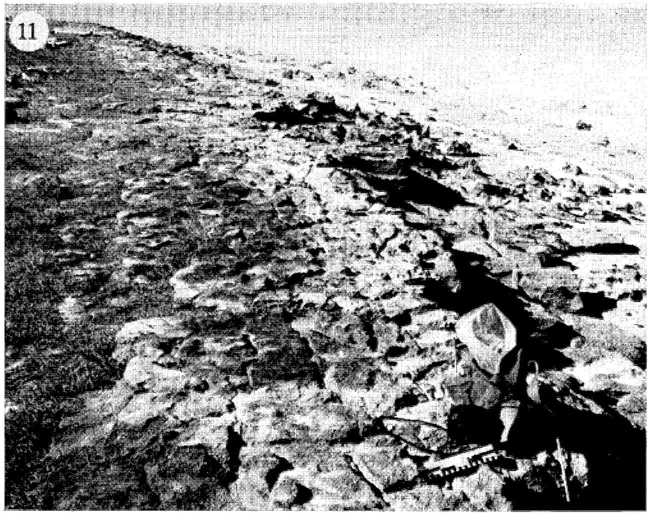

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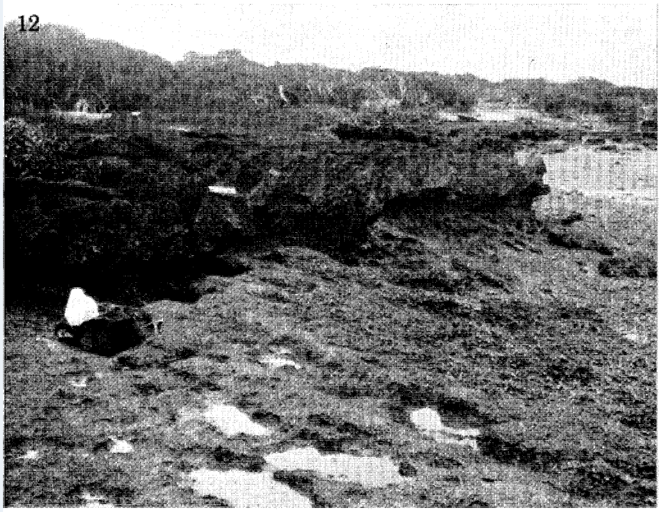

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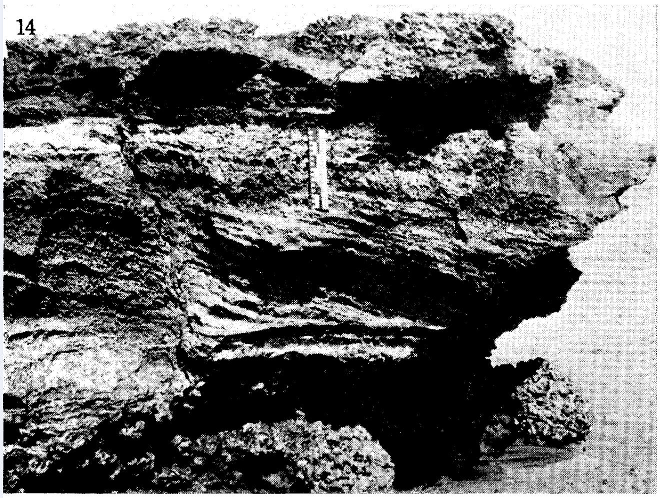

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FIGURE 10. Contemporary beach-rock at Waterwitch cay.

FIGURE 11. Relic beach-rock at Ingram cay.

FIGURE 12. Upper and lower platforms of rampart-rock at Watson Island.

FIGURE 13. Upper platform rampart-rock forming shore of shingle island at Three Isles. At this site a basal coral dated 3750 a B.P., a surface clam 3050 a B.P. and cement 2260 a B.P.

FIGURE 14. Bedded calcarenite overlying basal corals and topped by cemented coral shingle at western end of Houghton cay. At this site a basal coral dated 3330 a B.P., bulk calcarenite 2670 a B.P. and surface clam 3550 a B.P.

FIGURE 15. Residual block of upper platform rampart-rock on reef flat at Sinclair–Morris Reef.

1000 years between groups. These gaps may be an artefact of sampling or alternatively may reflect falls in water level. However, this evidence alone is insufficient to infer an oscillating sea level or the precise magnitude of sea level change. What is important is that we have definite evidence that sea level reached about its present position some 6000 years ago, that it subsequently rose above that level, and probably reached a maximum height around 3700 a B.P. The subsequent course of sea level and the time of its return to present level is not well documented although by 2300 a B.P. it was close to or still marginally above present level. Also of importance is the realization that reefs and superficial reef-top deposits at least on some reefs in the area have had up to six millennia in which to evolve and adjust to a sea level around its present position. Even if some of the corals were moated and hence reflect locally perched water levels these fundamental conclusions are not affected.

TABLE 2

cay	beach limit/m	low terrace/m	high terrace/m	difference/m
Combe	3.1	3.5	6.8	3.3
East Hope	3.5	3.6	6.3	2.7
Two Isles	3.2	3.5	6.0	2.5
Ingram	3.0	3.2	5.4	2.2
Three Isles	3.4	3.5	5.4	1.9
Howick	2.5	3.4	4.7	1.3
Leggatt	3.1	3.5	4.6	1.1
Houghton	3.3	3.4	4.5	1.1
Three Isles	3.6	4.5	5.6	1.1

7. EVIDENCE FROM SAND CAYS

Sand cays are present on many of the high reefs of the inner shelf of the northern Great Barrier Reef. Sediments making up these cays typically consist of moderately well sorted coarse sand composed of coral, Foraminifera, *Halimeda* and molluscan skeletal fragments which have been transported by wave action from surrounding reef top source areas to build the cays. Details of the nature and origin of cay sediments and history of cay sedimentation in the area are given by McLean & Stoddart (1978, this volume), while geomorphological features are considered by Stoddart, McLean & Hopley (1978, part B of this Discussion).

On a number of cays two distinct levels exist, here called the high terrace and low terrace. The altitude of these terraces where surveyed on continuous traverses together with the altitude of the beach/vegetation line are given in table 2.

On these traverses the present beach/vegetation limit reaches 3.6 m (mean high water springs 2.3 m) and is commonly within a few centimetres of the level of the lower terrace. Differences in elevation between the low and high terraces range from 1.1 to 3.3 m and are believed to reflect a relative change in the position of sea level within this range.

7.1. *Age of high terrace*

The high terrace is expressed in a variety of morphological types: as a relatively planar horizontal surface (e.g. Ingram), as an encircling continuous ridge (e.g. Three Isles), or as a single linear ridge (e.g. Stapleton). Bulk sand samples taken from the surface, pits or exposures in the high terrace were dated as given in table 3.

The high terrace is at a level well above the limit of contemporary cay sedimentation. The presence of thick or degraded soils, the extent and morphological homogeneity of the surface and the age range of samples suggest that reef flats were highly productive 3000–4000 years ago and that skeletal material produced at that time was swept from reef flats to greatly extend incipient cays and develop new ones. Because dated samples are generally from near-surface and island-edge locations the ages likely reflect the later rather than earlier phase of major cay development. Greater ages could be expected from the basal interior portions of cays, but no sediment was collected from such sites on simple cays. Thus by 3000 a B.P. the basic outlines of the larger cays in the area were well established (figure 8, plate 1). A sea level relatively higher than present is the simplest mechanism to account for the height of the high terrace. The presence of weathered drift pumice in surface soils and lenses of unweathered pumice at shallow depths argues against a wholly dunal origin for the high terrace and clearly indicates that wave-wash played a rôle in its formation (figure 9, plate 1).

TABLE 3

A.N.U. code	cay	age/a	elevation/m
1555	Stapleton	3240 ± 70	7.3
1558	Two Isles	3900 ± 80	6.3
1412	East Hope	3020 ± 70	6.3
1559	Bewick	4380 ± 80	5.9
1554	Three Isles	3640 ± 70	5.6
1410	Ingram	3230 ± 80	5.4
1553	Three Isles	3350 ± 80	5.0
1414	Three Isles	3220 ± 80	5.0

TABLE 4

A.N.U. code	cay	age/a	altitude/m
1557	Low Isles	2550 ± 70	4.5
1387	Bewick	2950 ± 80	4.4
1643	East Hope	2990 ± 80	4.2
1560	Eagle	2960 ± 70	4.2
1642	Ingram	3280 ± 80	3.7
1641	Three Isles	2190 ± 70	3.5
1606	Pickersgill	2230 ± 70	3.5
1556	Leggatt	2330 ± 70	3.4

7.2. *Age of low terrace*

On the larger cays the high terrace is frequently fronted by a lower surface, while on the smaller cays the main surface is at a comparable level to this lower terrace. The lower terrace and smaller cay surfaces are commonly developed within an altitudinal range little different from that reached by contemporary wave action and berm building but if anything above rather than below that level. Radiocarbon ages of bulk sand samples together with surface levels are listed in table 4.

As a group the ages for the lower terrace and smaller cays are younger than the higher surface, but there is overlap between the two groups. Thus for East Hope and Ingram the ages of samples from the two levels are not statistically significantly different. Moreover, the range of values for the low terrace is less than would be expected for deposits accumulating in sympathy with present sea level. In this case we would anticipate a greater range of dates with perhaps some samples reaching modern ages and certainly some being younger than 2000 a B.P.

The lack of such young samples, together with geomorphological evidence, strongly suggests that much of the sediment which has gone into building the lower berm terrace and smaller cays has been derived from reworking of the older cay sands with only a small addition of recent skeletal material. Thus it is impossible on this evidence alone to indicate precisely when the lower terrace of the larger cays and main surface of the smaller cays were formed except that they post-date 3000 a B.P. and have developed in harmony with a sea level comparable to or marginally above present level. In the cases of Two Isles and Three Isles there is comparative survey evidence to show substantial lower terrace construction in this century.

7.3. *Sea level change: interpretation*

Differences in elevation of 1 to 3 m between the high and low terraces of sand cays on the northern Great Barrier Reef suggest that sea level was relatively higher than present level by more than 1 m during the formation of the high terrace some 3500 years ago (average age of high terrace samples) but was similar to the present level or marginally above during formation of the low terrace which post-dates 3000 a B.P. It could be argued that the differences in level are not the result of a change in sea level but rather reflect a reduction in exposure and wave energy on the leeside of reefs as a result of the development of shingle ramparts and ridges on the windward side at a time between the accumulation of the high and low terraces. Obviously, such features have influenced leeside refraction patterns and caused local variations in the spatial distribution of at-cay wave energy convergence and divergence zones through time; erosion and accretion patterns so created are easily recognizable in cay plan geometry and morphology. However, we believe that the magnitude of this effect has not been sufficient to account for the required difference in wave run-up heights in all cases, over 2 m in the case of Ingram, East Hope, Two Isles and Three Isles where both the high and low terraces are most clearly and extensively developed. All these reefs contain broad reef flats and possess negligible or relatively minor windward shingle accumulations in relation to the extent of open reef flat. In the case of Ingram and East Hope, bare open reef flat accounts for 98 % of the reef top and for Two Isles and Three Isles the corresponding figures are 74 and 75 % respectively. Furthermore, the ages of the older shingle islands are similar to the sand cays (see below) indicating synchronous formation of windward and leeward structures. They do not fall between the time of development of the high and low terraces as a hypothesis invoking local variations in wave energy necessitates.

On this evidence, sea level was more than 1 m above present around 3500 a B.P., but we lack data from the sand cays to indicate when this level was first achieved. The oldest cay sand dated, from the surface of the highest ridge on Bewick cay (ANU-1559, 4380 ± 80 a B.P.), is nearly 1000 years older. While suggesting that the sea was at a comparable level to that pertaining about 3500 a B.P., neither the age nor elevation are alone sufficient to establish the palaeo sea level at the time with any certainty. Likewise, sand cay data relating to the subsequent pattern of sea level change is not strong, except for the obvious fact that it has fallen below its earlier level and subsequently reached its present position. The presence of sediments dated 3020 ± 70 a B.P. (ANU-1412) from the high surface at East Hope suggests that sea level was still relatively higher at least 3000 years ago. Moreover, the ages greater than 2000 a B.P. for the lower terrace sediments could indicate that sea level was at or above present in the 2000–3000 a B.P. interval. This may well be the period when the major fall from the level at 3500 a B.P. took place.

The fact that none of the dated cay sands were younger than 2100 a B.P. bears close scrutiny. Although this may be a result of sample selection the age of clean sand taken from the small unvegetated cay, Pickersgill (ANU-1606, 2230 ± 70 a B.P.), does suggest that the production and recruitment of post-2000 a B.P. sediment has been minor. One obvious explanation for the deficit of sand cay building sediment at least on some reefs is that reef-top sand supply areas have been reduced considerably. The development of shingle ramparts and ridges some of which encircle the reef and enclose a pond, and particularly the expansion of mangroves across the reef flat in sheltered environments has resulted in an incremental diminution of sand supplies. At present on Houghton, Coquet and Newton reefs, for example, little sand is being produced, while on Bewick, Nymph and Low Wooded Island reefs virtually none is being produced. In these cases the extant sand cays are essentially fossil forms.

An alternative view which would account for the deficiency in post-2000 a B.P. sand supply and cay nourishment, is that many reef tops were emergent for much of the last 2000 years and have only recently been reoccupied by the sea as a result of a small rise in sea level. Much of the geomorphological evidence is consistent with such a view. First, the larger sand cays, notably those possessing the high terrace, retain much of their fundamental pre-3000 a B.P. outlines. Preservation and retention of such outlines through to the present would be greatly enhanced by a fall in sea level. Secondly, a contemporary rise in sea level would result in the rectification of cay outlines, particularly on those cays on relatively open reef flats. Thus shore cliffing, exposure of relict beach-rock, accumulation and extension of fresh berms and downdrift spits on such cays as Three Isles, Two Isles, Ingram, Sinclair–Morris and Combe may be quite recent in origin. Such a suggestion is also consistent with only a small dilution of pre-3000 a B.P. sediments by contemporary materials, thus bringing the radiocarbon ages for these deposits into the 2000–3000 a B.P. bracket.

8. Evidence from beach-rock

Cemented sand in the form of beach-rock is exposed around many of the sand cays in the northern Great Barrier Reef. The nature and formation of beach-rock in this area is discussed by Scoffin & McLean (1978, this volume).

In the field, two types of beach-rock were recognized on morphological grounds: (1) high or horizontal beach-rock and (2) inclined beach-rock, the latter being similar to that usually described in the literature. The horizontal type is believed to represent cementation within the berm or backshore of a beach immediately landward of the seaward dipping foreshore bands. Contemporary examples of single beach-rock outcrops passing abruptly from inclined to horizontal surfaces were seen on Waterwitch and Combe cays (Figure 10, plate 2), while older examples, where both surfaces were preserved, occurred on Two Isles, Three Isles and Ingram cay (Figure 11, plate 2). At other sites on these three cays and also at Howick and Bewick the horizontal surface was truncated to seaward by an erosional scarp which dropped steeply to the reef flat. In such cases removal of the inclined portion is indicated, one destination for the eroded slabs being the sand ridge immediately islandward of the horizontal exposure.

Extreme high water spring tide is the likely upper limit for beach-rock cementation, though the more frequently obtained level of mean high water springs may be a more realistic limit. At present these levels are 2.9 and 2.3 m respectively on the northern Great Barrier Reef.

TABLE 5

cay	top/m	base/m	type	comment
Leggatt	3.1	1.2	inclined	relict
Bewick	3.1	1.4	horizontal	relict
Three Isles	2.8	n.a.	horizontal	relict
Three Isles	2.6	1.6	horizontal	relict
Three Isles	1.8	0.8	inclined	contemporary
Two Isles	2.7	n.a.	horizontal	relict
Two Isles	1.6	0.5	inclined	contemporary
Ingram	2.7	1.5	horizontal	relict
Ingram	2.5	1.3	horizontal	relict
Ingram	2.3	0.9	inclined	contemporary
Eagle	2.3	0.8	inclined	contemporary
Combe	2.2	0.9	inclined	contemporary
East Hope	1.8	0.4	inclined	contemporary

TABLE 6

A.N.U. code	cay	age/a	comment
1605	Howick	2420 ± 70	coral head
1386	Bewick	2030 ± 70	*Tridacna*

Elevations of tops and bases of beach-rock exposures together with a field classification of outcrops are given in table 5.

Clearly, these data do not provide positive evidence of sea level change. On the one hand the maximum surface levels fall generally within the range of present extreme spring tides, and on the other considerable variation in outcrop morphology has been reduced to two types, inclined and horizontal. Moreover, the relict/contemporary classification allows accusations of circular argument, though it is based on a suite of criteria including the presence or absence of terrestrial or marine vegetation, surface weathering and solution features, occupied or unoccupied boreholes, surface coloration, etc. Despite these problems, both the upper and lower levels of horizontal beach-rock are invariably higher than inclined equivalents. Where both are present in close proximity on the one cay as at Two Isles and Three Isles, a difference of approximately 1 m is found. We believe that outcrops designated as contemporary reflect formation during a sea level similar to present, while those designated as relict could have formed when sea level was higher than present. In the absence of a suite of dates on bulk samples of beach-rock, evidence from the location of outcrops with respect to loose cay sands immediately behind them suggests that beach-rock formed soon after the older cays developed, thus stabilizing their early outlines. In other words, at least some of the relict beach-rock represents part of the shores of cays when they were at their high terrace stage some 3500 years ago, whereas the inclined beach-rock equates with the lower terrace. This is well illustrated at Three Isles and Ingram (Figure 11), while at Bewick relict beach-rock which forms the western shore of the cay is surmounted on its inner edge by a high sand ridge whose constituents were dated at 4380 ± 80 B.P. (ANU-1559). At the western end of Houghton cay (figure 14, plate 2), beach-rock is exposed overlying reef flat corals and is in turn topped by a thin cemented coral stick veneer yielding ages of 3300 ± 80 and 3550 ± 80 a B.P. (ANU-1595, ANU-1413). A bulk sample of calcarenite from this beach-rock was aged 2670 ± 70 a B.P., which because of the presence of cement gives a minimum age for its constituents. Individual bioclasts from the surface of two other beach-rock outcrops were dated as shown in table 6.

These smaller ages may illustrate a later phase of relict beach-rock formation, although the large size of the dated materials, which contrast markedly with the calcarenite below, indicate deposition during stormy conditions and need not represent the period of sand accumulation and cementation.

9. Evidence from shingle cays, ridges and ramparts

9.1. *Shingle cays*

On the reefs of the Turtle Group cays built of a mixture of both sand- and shingle-sized bioclastics have developed (McLean & Stoddart 1978, this volume). On the larger cays of this Group two surfaces are apparent. Levels of the present beach/vegetation limit, low and high terraces and differences between the terrace elevations on continuous traverses are given in table 7. Samples from the high and low terraces on Turtle I were dated as given in table 8.

Table 7

cay	beach limit/m	low terrace/m	high terrace/m	difference
Turtle I	3.4	4.4	5.6	1.2
Turtle I	3.5	4.1	5.6	1.5
Turtle II	3.5	3.5	4.7	1.2
Turtle V	3.3	4.0	5.4	1.4
Turtle VI	3.6	3.8	5.1	1.3

Table 8

A.N.U. code	age/a	altitude/m	comment
1388	3320 ± 80	5.5	high terrace
1598	2760 ± 80	4.2	low terrace
1597	2480 ± 70	4.2	low terrace

Table 9

A.N.U. code	age/a	altitude/m	comment
1480A	1100 ± 80	2.1	fibres, rootlets
1480B	2210 ± 170	2.1	organic mud
1479	4910 ± 90	1.5	coral shingle

Both ages and levels accord with those from the sand cays and it is believed that they reflect a comparable sea level and geomorphic history with that described above for the sand cays. Samples from a shallow borehole in a small enclosed depression between two coral shingle ridges near the centre of the island indicate the antiquity of cay development and the presence of mangroves. The depression is occupied by living mangroves and is floored by a deposit of mixed sand and coral shingle overlain by a black fibrous mud. Levels and ages of these materials are shown in table 9. These ages and levels indicate that superficial sands and shingle were accumulating on this reef top nearly 5000 years ago and incipient cay development likely dates from around this time, while mangroves were present on the reef top before at least 2000 a B.P.

9.2. *Shingle ridges and ramparts*

In contrast to the cays of the Turtle Group which possess broad, near-planar core surfaces, some of the shingle islands are built up of a series of closely spaced shingle ridges separated by narrow swales. Ridges are generally at accordant levels and suites of 5–15 ridges are common. Watson and West Hope provide the best examples of islands made up of such ridge sequences, though comparable sequences are found on some of the more complex islands such as Nymph and Low Wooded Island. On other shingle cays, particularly those on the windward side of low wooded island reefs, more discrete asymmetrical ramparts occur, not greatly different in height and dimensions from ramparts presently accumulating. Sediments making up these features are principally fragments of branching corals, broken from reef flat and reef edge colonies during storms and built into ridges and ramparts during rough and quiet weather conditions. Ages and surface elevations of dated samples are given in table 10.

Table 10

A.N.U. code	island	age/a	altitude/m	comment
1391	Watson	1550 ± 70	3.6	inner ridge
1392	Watson	1480 ± 70	4.4	inner ridge
1390	Watson	810 ± 70	2.1	loose platform shingle
1389	Watson	510 ± 70	3.1	outer rampart
1600	West Hope	850 ± 70†	3.2	inner ridge
1559	West Hope	1210 ± 70	3.3	outer ridge
1411	Coquet	1070 ± 60	n.a.	main ridge
1593	Low	800 ± 70	2.0	inner rampart
1608	Bewick	760 ± 65	3.5	inner rampart

† Sample contaminated (see Polach *et al.* 1978, this volume).

Table 11

reef	lower platform/m	upper platform/m	difference/m
Houghton	2.0	3.2	1.2
Watson	2.1	3.3	1.2
Three Isles	2.0	3.1	1.1
Nymph	2.1	3.2	1.1
Watson	2.1	3.2	1.1
Low Wooded	2.5	3.5	1.0
Turtle I	2.5	3.5	1.0
Bewick	1.6	2.6	1.0

Radiometric ages of components and levels of these ridges and ramparts do not provide clear evidence of a sea level significantly different from present. What the ages do indicate is that coral shingle accumulated and islands were formed or extended on the windward side of reefs during the last 1500 years or so, the period when leeside primary sand production and accumulation was at a minimum. Whether or not reef flats were emergent during part of this period, which was one possibility earlier discussed with reference to sand cays, cannot either be substantiated or negated on this evidence because of the rôle of storms in the origin of shingle ramparts and ridges.

10. Evidence from rampart-rocks

One rather unique feature of the low wooded islands of the northern Great Barrier Reef is the presence of cemented shingle ramparts, here termed rampart-rocks. These exposed limestones occur typically but not exclusively on the windward side of reefs. In the field, two surface levels were recognized and called the upper platform and lower platform (figure 12, plate 2). On some reefs the distinction between the two surfaces was not always clear and on other reefs only one, the lower platform, was present. Considerable variation in the absolute elevation of platforms between reefs was noted. However, where continuous traverses were run across both platforms, results were as given in table 11.

In the above instances a distinctive scarp separated the upper from lower platform. A difference in level of about 1 m between the two features is indicated. The possibility that these platforms are raised reef flats is discounted on grounds of stratigraphy and fabric. Questions relevant for a time/sea level interpretation of the platforms include (1) the age of the constituent rubble components, (2) the nature, age and origin of the cementing matrix, and (3) the significance of the levels of the cemented surfaces. These aspects are considered in detail by Scoffin & McLean (1978, this volume).

TABLE 12

A.N.U. code	reef	age/a	altitude/m
1383	Nymph	3540 ± 80	3.8
1592	Nymph	3415 ± 75	3.8
1604	Low Wooded	3320 ± 70	3.5
1478	Turtle I	4420 ± 90	3.5
1413	Houghton	3550 ± 80	3.1
1595	Houghton	3330 ± 70	3.1
1380	Three Isles	3750 ± 110	3.0
1382	Three Isles	3050 ± 70	3.0
1208	Bewick	2840 ± 70	2.6
1609	Bewick	2050 ± 70	2.6

10.1. *Age of upper platform*

The surface of the upper platform is either nearly horizontal or promenade-like such as at Three Isles and Houghton or consists of a highly irregular karstic topography such as at Watson Islands. Within the upper platform three and locally four vertical facies are recognized, the last being a veneer of stick coral deposited after the main mass. Ages of constituent components indicate that accumulation of the initial rampart was both a rapid and a discrete event. Where present and dated, the ages of the basal corals in growth position (ANU-1285, 3700 ± 90 a B.P.; ANU-1380, 3750 ± 110 a B.P.) have been dealt with earlier. Ages of bioclastic components other than these together with the altitude of the surface at the sample location are given in table 12.

Excluding the Bewick results, where the altitude of the field-identified upper platform and age of constituent components are less than the others, the results suggest a large accumulation of rampart rubble before 3000 a B.P. This would be a minimum age for the major influx of coral shingle, because in most instances samples were taken from the outer scarp or outer surface of the platform and not from inland exposures, except at Turtle I where the material is 800–1000 years older than the other sites. Thus in the period 4500–3000 a B.P. the windward flats and crests of many of the reefs in the area between Three Isles and Bewick possessed large thickets of living branching corals which were broken up and accumulated as loose shingle ramparts. At least for Nymph, Houghton, Low Wooded Island and Three Isles, this last event took place around 3300–3600 a B.P.

Once the ramparts were formed and stabilized, cementation began. Details of this process are given elsewhere (Scoffin & McLean 1978, this volume). The cementing matrix suggests that lithification took place in an intertidal environment adjacent to mangrove swamps. Ages of two cements indicate that cementation was completed within about 1000 years of rampart formation (table 13). These ages are from the cementing matrix towards the base of the platforms at their outer exposed seaward edges and probably reflect the last phase of upper platform cementation. Older cements are likely to occur in outcrops further inland.

Table 13

A.N.U. code	reef	age/a	level/m
1602	Nymph	2350 ± 70	3.8
1381	Three Isles	2260 ± 80	3.0

Table 14

A.N.U. code	reef	age/a	altitude/m
1475	Three Isles	1460 ± 70	2.0
1477	Turtle I	1430 ± 70	2.4
1385	Bewick	640 ± 70	1.6
1476	Nymph	520 ± 70	2.1
1607A	Low Isles	740 ± 70	1.7
1607B	Low Isles (cement)	560 ± 110	1.7
1601	Low Isles (cement)	380 ± 80	1.7

10.2. *Age of lower platform*

The lower platform whose surface elevation is generally between 1.5 and 2.1 m, but which may reach 2.8 m, has an extremely variable morphology. In places it abuts the outer scarp of the upper platform while in others it is separated from the latter by a moat. Elsewhere it occurs as a promenade fringing an island or an isolated unit on the reef flat which in some cases has a 'bassett edge' morphology. Ages of components from four sites classed as lower platform and of components and cementing matrices from one site classed as bassett edges are given in table 14. Ages of bioclasts accord with those from the loose uncemented shingle ridges and ramparts discussed earlier, while the ages of cementing matrices indicate the rapidity of rampart lithification.

10.3. *Sea level change: interpretation*

It is not known what precisely controls the height of platform surfaces and therefore whether they can be used as definitive sea level markers. Scoffin & McLean (1978, this volume) reject an explanation invoking marine erosion and suggest an origin by deposition and/or lithification up to a level to account for the fairly uniform platform surfaces. Marine cements are known to precipitate today at heights up to extreme high water springs (2.9 m), although mean high water springs is a more common upper limit. In this region of the Great Barrier Reef the latter is 2.3 m above datum. However, platform surfaces need not necessarily represent the upper limits of lithification. Instead they may relate more closely to the height of the original ramparts which could be below the potential cementation ceiling. The assumption that platform surfaces do reflect the upper level of cementation therefore tends to be conservative, but is adopted here.

Thus we believe that the surface of the lower platform that occurs within present mean spring tide range illustrates the level of rampart-rock formation associated with present sea level. On this evidence no change in sea level relative to present is thought to have taken place in the last 1500 years. On the other hand the upper platform is developed at levels in excess of 1 m above adjacent lower platforms and its surface at 3 m above datum is above the range of contemporary cementation. Our evidence suggests that the shingle ramparts which accumulated in the period 4500–3000 a B.P. and were initially bonded at that time to form the upper platform did so with a sea level about 1 m higher than present. The cluster of ages between 3300 and 3700 a B.P. (mean age of eight samples whose surfaces are all above 3 m is 3546 a B.P.) may represent the time when sea level was at its highest.

At present, upper platform limestones are not in equilibrium with the conditions and environments in which they formed. Instead, the processes are essentially of a destructive nature. Where exposed as the inner edge of windward reef flats, notches occur at the base of scarps and outer upper surfaces display a karstic topography (figure 13, plate 2). On some reefs (e.g. Sinclair–Morris, Leggatt), small high isolated blocks of upper platform rock occur as residuals of what were formerly far more extensive features (figure 15, plate 2). These observations suggest that destructive processes have been operating for a considerable time and are consistent with a fall in sea level since the formation of the upper platform some 3000 years ago. The younger ages and lower levels of the dated Bewick site classed as upper platform in the field may indicate the period when sea level was falling from its earlier higher level and certainly indicate that rampart-rock formation continued after the main phase of development. It is also likely that some of the features classified as lower platform in the field, particularly the higher, more extensive, promenades, also date from this time. Thus in the period 3000–2000 a B.P. the distinction between lower and upper platform is blurred. As we envisage platform formation as a relatively continuous process, the assignment of platforms to either the upper or the lower category is somewhat arbitrary in cases where there is an overlap in levels between the two. Nevertheless the end-members are quite discrete and the distinction in level between the older upper platforms and younger lower platforms is clear.

11. DISCUSSION AND CONCLUSIONS

In the first part of this paper we outlined the problems, limitations and assumptions on which our analyses have been based. These included problems in establishing a contemporary tidal datum, recognition of the range in levels to which features are developed with modern sea level, and discussion of problems associated with the interpretation of field evidence and the use of radiocarbon dates. Before any results purporting to show sea level changes can be accepted as valid, a necessary first step is the recognition of the limitations of the data. In addition we have stated a number of assumptions, one being that there has been no movement of the land and shelf in the last few thousand years and that departures from present sea level are of a eustatic nature. Nor have we attempted to test any hypothesis relating to sea level change, being aware that any such stance would prejudice our interpretation. Indeed, if we did have a framework it was to see how far back in time it was possible to go before it became necessary to invoke any sea level departure from present. Thus, we have tended to be conservative and minimize rather than magnify the resulting palaeo sea levels. While we fully accept that our results do have limitations, fewer ambiguities have arisen than initially expected, considering the large number of surveys and radiocarbon dates which could obscure rather than clarify any pattern. Results in level and age of any one feature on different reefs are surprisingly consistent, and perhaps even more surprising is that different types of features produce complementary rather than contradictory sea level histories:

1. Levels and ages of microatolls at four sites in the northern Great Barrier Reef provide firm evidence that the present level of the sea was attained in the Holocene some 6000 years ago and that shortly after (by 5800 a B.P.) it was marginally higher than at present.

2. We have no evidence to indicate the pattern immediately following, but certainly less than 1000 years later emergent microatolls at two other sites aged 4900 a B.P. show sea level was still higher at that time. It is likely that incipient sedimentary features began accumulating on at least some reef tops in the area about this time.

3. In the following two millennia incipient sand and shingle cays were greatly extended so that by about 3000 a B.P. the basic outlines of many of the larger leeside sand cays and windward shingle ramparts were established. Reef-top productivity reached its zenith during this interval. Many of the fossil reef-top features on a large number of reefs have ages clustering between 3200 and 3800 a B.P. There is considerable evidence to indicate that in this period the highest sea level in the Holocene was reached. Levels of two extensive emergent fossil microatoll fields dated 3700 a B.P., the high terrace of the larger cays (average age of 8 samples 3500 a B.P.) as well as the cemented shingle ramparts of the upper platform (average age of 8 samples 3546 a B.P.), indicate that sea level was at least 1 m above present.

4. It remained at that elevation at least until 3000 a B.P. and continued higher than at present for the following 1000 years, though falling gradually from its maximum during this period. Slightly emergent fossil microatolls at East Pethebridge, lower levels and younger ages of clasts in the surface of the upper platform at Bewick and of beach-rock at Howick and Bewick, bulk sands from the lower terrace on a number of sand cays and upper platform cements at Nymph and Three Isles, all of which have ages in the 2000–3000 a B.P. bracket, are believed to represent the falling sea level.

5. Coming closer to the present, in the last 2000 years the pattern of sea level change becomes less clear. Perhaps the most startling feature is the deficiency of material dated younger than 2000 a B.P., excluding clasts from loose and cemented windward shingle ramparts and ridges which owe at least part of their origin to storm wave activity. Moreover, in our records there is a complete absence of material dated in the 2000–1500 a B.P. range. Notwithstanding the build-up of shingle ramparts and ridges on some reefs and the extension of mangrove swamps on others, sometime around 2000 a B.P. reef tops shifted from depositional to erosional environments. Such a shift could result from a slight fall in sea level to present from a marginally higher level at 2000 a B.P., or alternatively could result from a fall to below present level with a late contemporary rise. While we tend to favour the last hypothesis the evidence is not at all conclusive.

6. It is thus the most recent phase of sea level change, the direction and magnitude of change that has given our present level, where the major ambiguities have arisen. Moreover, it is obvious that while we have been able to document certain past times and levels higher than present, we have not been equally able to document levels lower than present. Nevertheless, it would appear that for a substantial proportion of the last 6000 years sea level has been above its present level for longer than it has been below.

7. The foregoing study provides the most extensive regional investigation of late Holocene sea level change based essentially on reef-top features.

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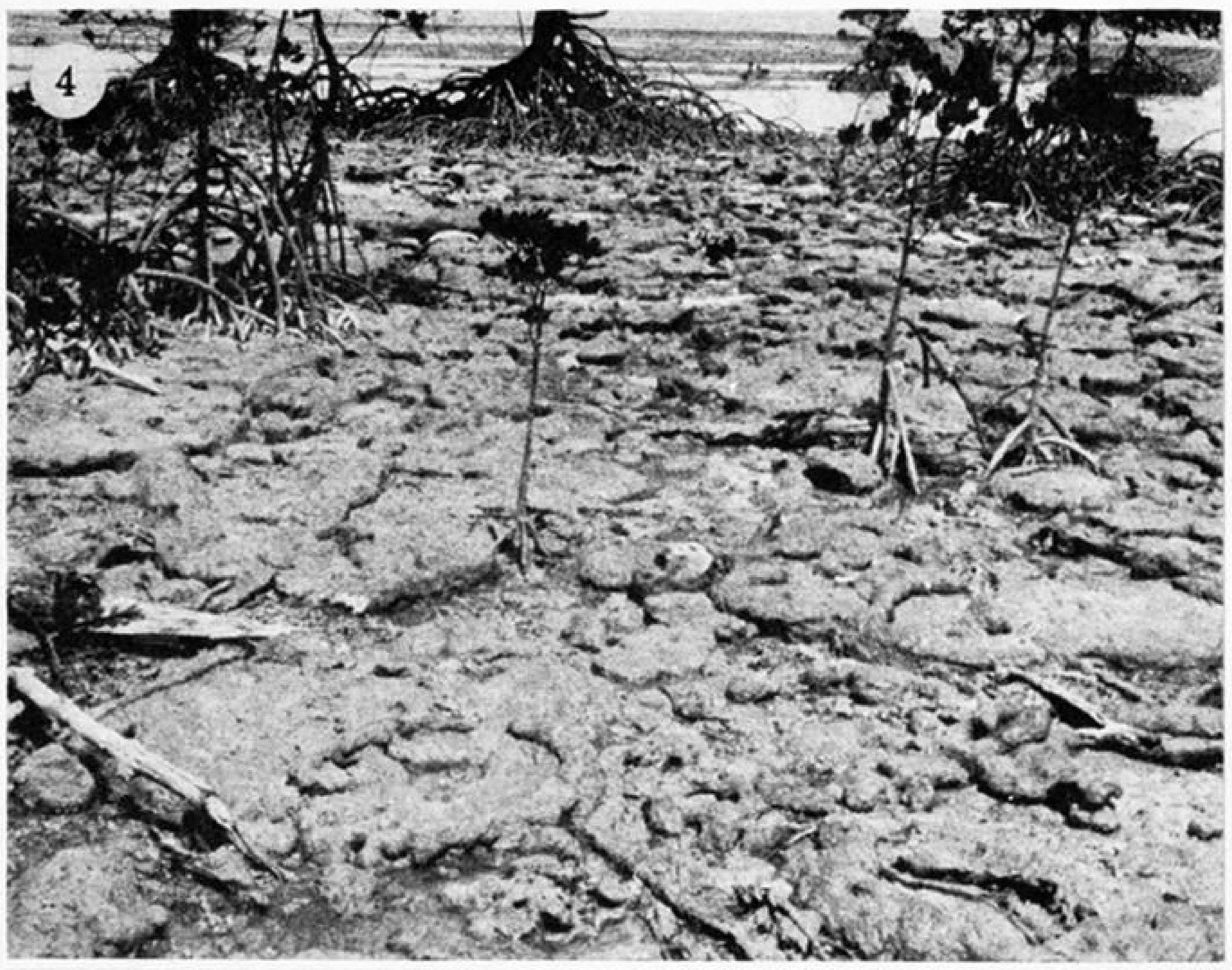

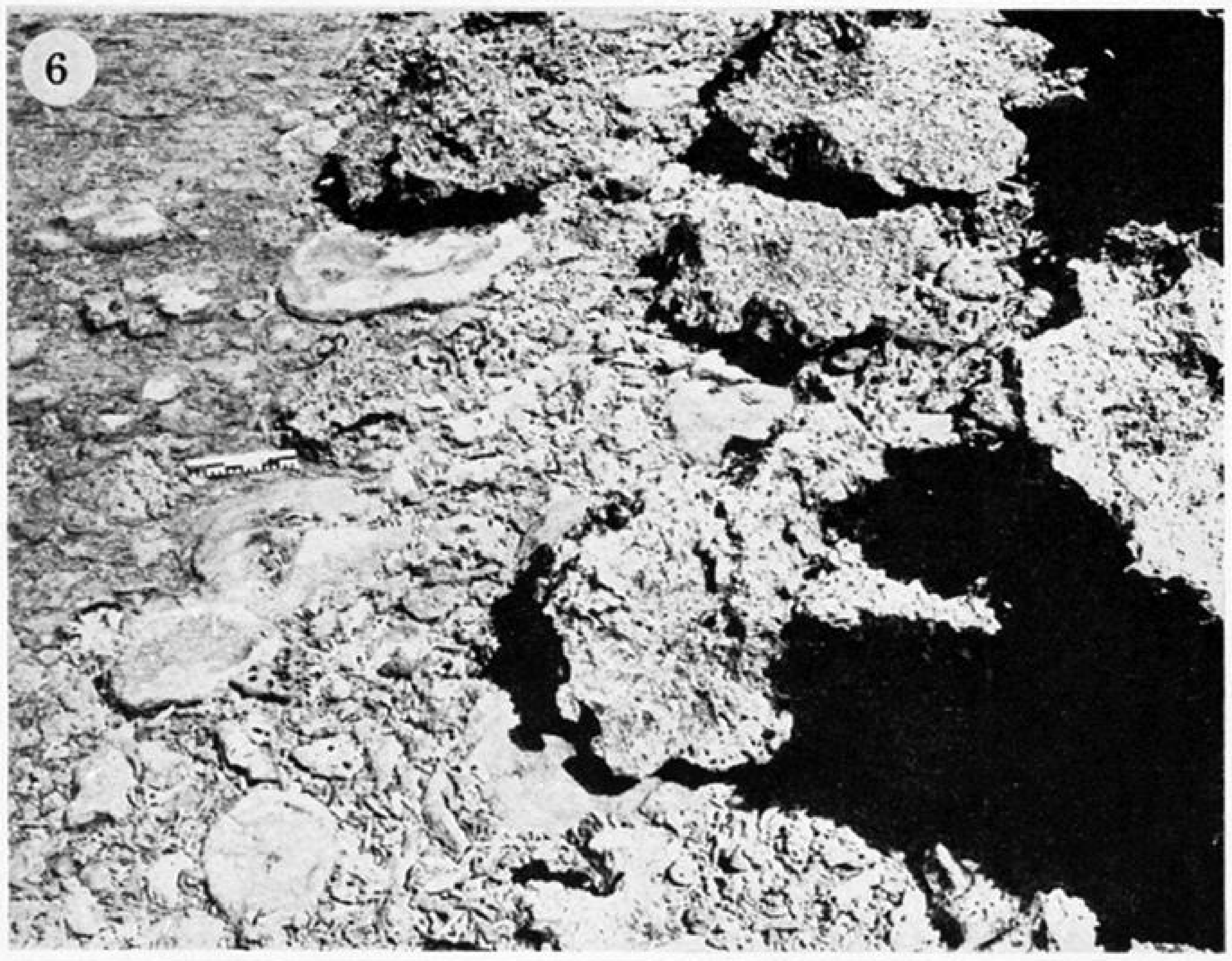

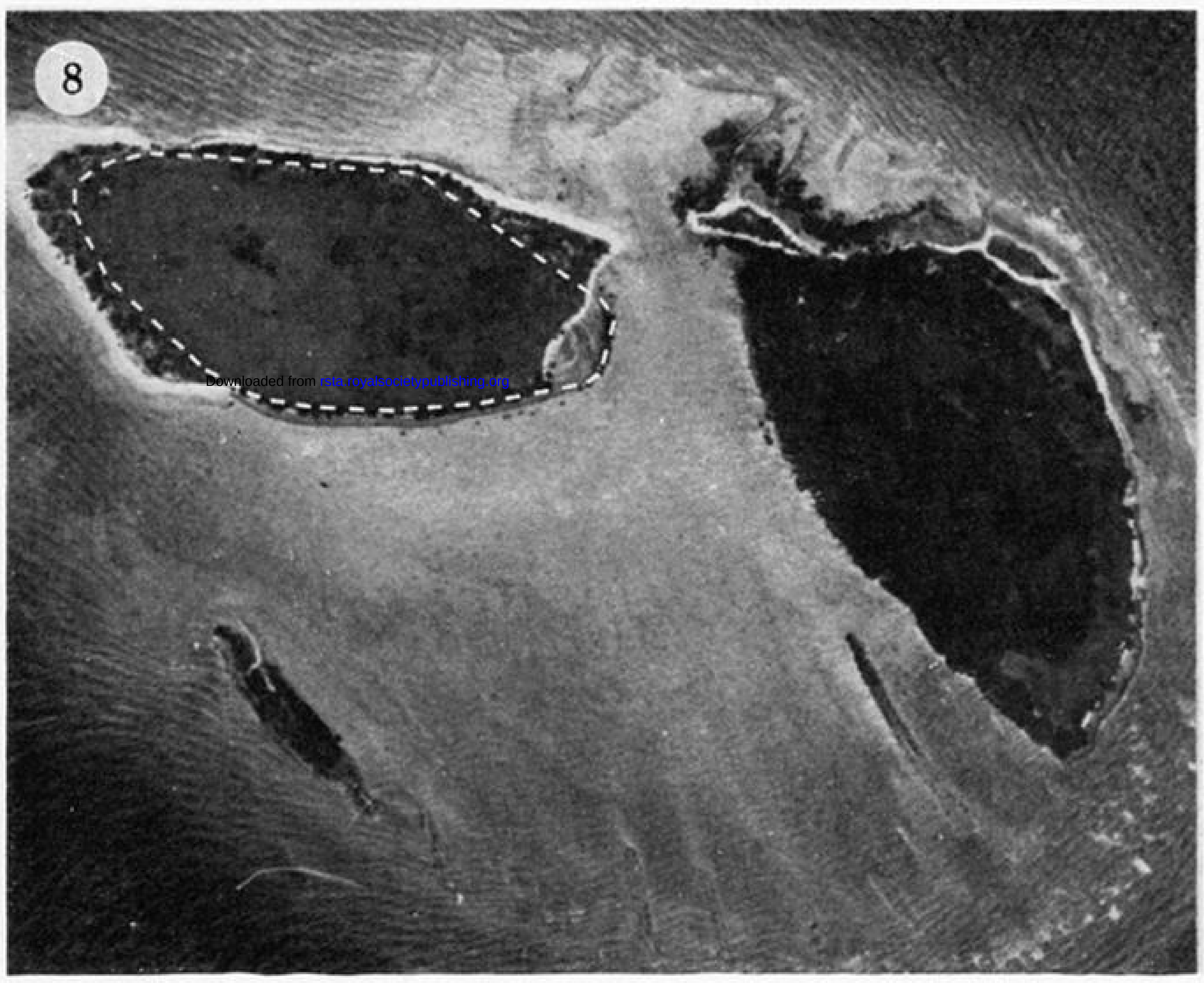

FIGURE 4. Field of emergent fossil microatolls at Leggatt Reef. A clam from this site dated 5800 a B.P.

FIGURE 5. Emergent fossil microatolls exposed in pond outlet at Nymph Reef. A coral from this site dated 3700 a B.P.

FIGURE 6. Fossil microatolls exposed beneath rampart-rock at Low Wooded Island. A coral from this site dated 6080 a B.P.

FIGURE 7. *Porites* microatoll exposed in scarp of upper platform rampart-rock at Three Isles. A coral from this site dated 3750 a B.P.

FIGURE 8. Aerial view of Three Isles showing sand cay upper left and shingle islands on right and lower left. Outline on sand cay represents 3000 a B.P. shoreline.

FIGURE 9. Sand cliff cut in high terrace at eastern end of Three Isles cay showing extent of surface soil development, buried soils and pumice layers. Two bulk sediment samples from this section were dated 3220 and 3350 a B.P.

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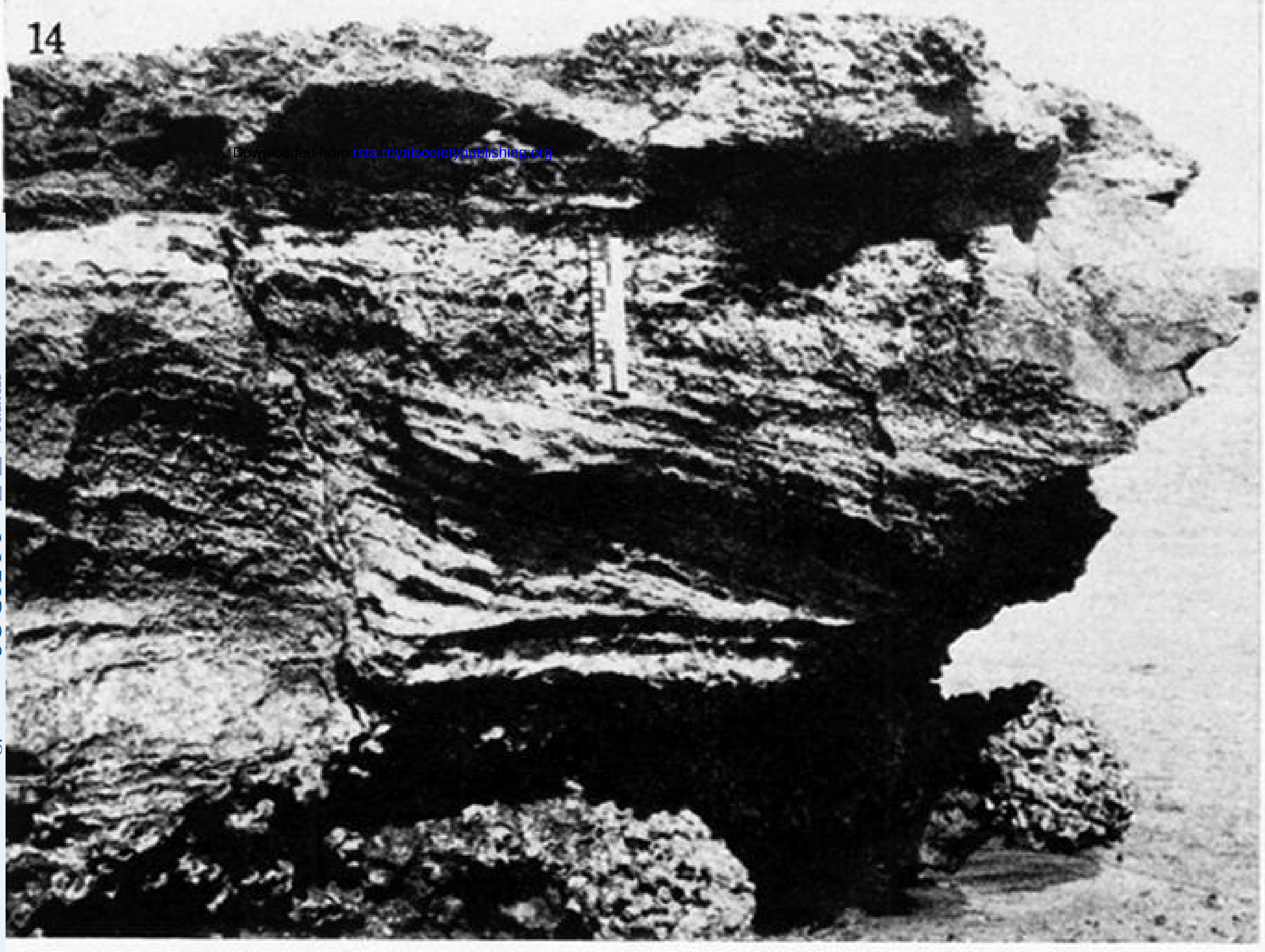

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FIGURE 10. Contemporary beach-rock at Waterwitch cay.

FIGURE 11. Relic beach-rock at Ingram cay.

FIGURE 12. Upper and lower platforms of rampart-rock at Watson Island.

FIGURE 13. Upper platform rampart-rock forming shore of shingle island at Three Isles. At this site a basal coral dated 3750 a B.P., a surface clam 3050 a B.P. and cement 2260 a B.P.

FIGURE 14. Bedded calcarenite overlying basal corals and topped by cemented coral shingle at western end of Houghton cay. At this site a basal coral dated 3330 a B.P., bulk calcarenite 2670 a B.P. and surface clam 3550 a B.P.

FIGURE 15. Residual block of upper platform rampart-rock on reef flat at Sinclair–Morris Reef.