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Sea level change on the Great Barrier Reef: an introduction

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Evidence for Holocene shorelines from the Queensland coast, off which the Great Barrier Reef lies, has epitomized the problems of eustatic fluctuations over the last 6000 years. While some areas of southern and central Queensland show evidence of no sea level higher than the present over this period, other areas, particularly within 150 km of Townsville on the mid-North coast, have provided radiometrically dated evidence for an emergence of up to 4.9 m. The area in which the 1973 Expedition worked has been described previously by several authors, and evidence for higher shorelines in the form of cemented platforms, raised reefs and related features suggesting higher sea levels, though without isotopic dating, has been noted. Research was aimed at confirming and accurately measuring and dating such evidence and relating it to the pattern described elsewhere. Any divergences must then be explained in terms of spatially and temporally varying oceanographic or geomorphic conditions and Earth movements of tectonic and/or isostatic origin.

The nature and magnitude of sea level changes over the Holocene period, and in particular the length of time sea level has been close to its present position, have direct implications for coral reef response. Unfortunately, it is over this period that the greatest divergence of views on sea levels exists, both on a world wide scale (e.g. Guilcher 1969; Mörner 1971*a*, *b*; Curray & Shepard 1972) and in Australia (Hails 1965; Thom, Hails & Martin 1969; Hopley 1971*a*; Gill & Hopley 1972; Thom, Hails, Martin & Phipps 1972; Thom & Chappell 1975) (figure 1).

Evidence from eastern Queensland

The evidence from the Queensland coast (figure 2) in many ways epitomizes the global problem (Hopley 1974*a*). To the south of the reef, at Coolum on the mainland, Thom *et al.* (1969) indicate that sea level has not been higher than present in the Holocene. However, 500 km to the north at Broad Sound, detailed mapping and dating of chenier sequences by Cook & Polach (1973) show a continuous progradation of the shoreline for 5500 years during which sea level has been continuously at or close to its present position. In contrast, at Stannage Bay on the peninsula to the east of Broad Sound, Jardine (1928) has described a raised beach rock rising to about 2 m, and offshore on Hunter Island along the same structural alignment, Steers (1937, 1938) has noted two higher cemented levels, the upper one rising to about 2.7 m. Although not dated, the similarity of these two sites to those described further north suggests that they record higher Holocene sea levels. No work pertinent to sea levels has been reported from the 90 km of coastline between Broad Sound and Mackay, but to the north the off shore islands of the Cumberland Group have been surveyed in detail (Hopley 1975). Within this island group, conclusive evidence of higher sea levels is lacking though at Cockermouth Island, a notch in a Pleistocene dune calcarenite at about 1 m, producing an enigmatic date of 6980 ± 130 a B.P., may represent a marginally higher mid Holocene sea level (see

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Hopley (1975) for discussion). Elsewhere, the oldest Holocene deposits appear to be no more than 3000 years in age.

Immediately north of the Whitsunday Passage, from the northern extremity of the Cumberland Group, the offshore islands and mainland display an abundance of evidence related to higher sea levels in the form of raised reef and beach-rock on the islands, and mangrove peats and other depositional evidence from the mainland. Maximum levels exceeding 3 m are

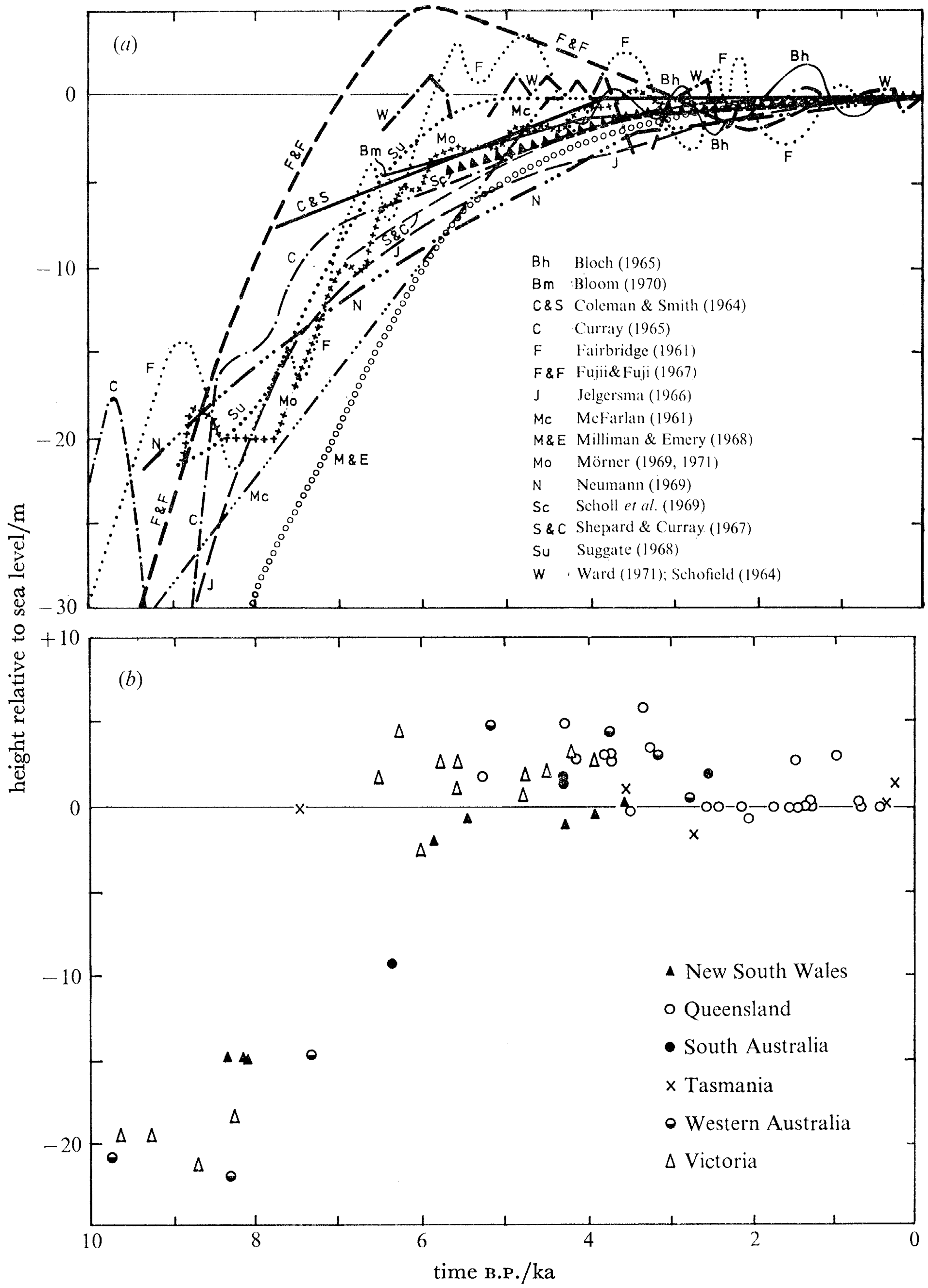

FIGURE 1. (*a*) Different interpretations of sea level history in the last 10 000 years. (*b*) Radiocarbon ages indicating sea level positions on Australian coastlines in the last 10 000 years.

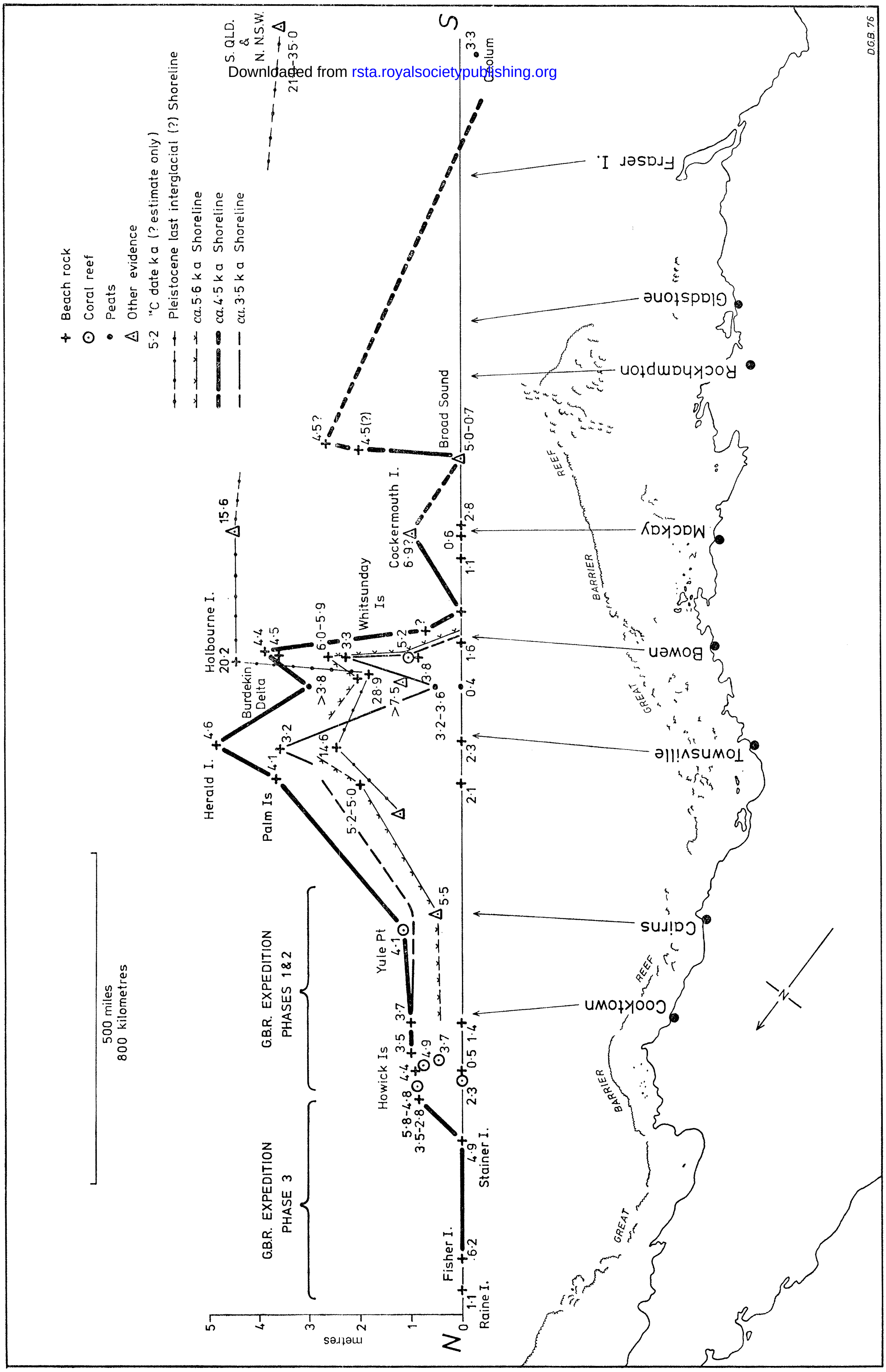

FIGURE 2. Interpretation of sea level history along the east coast of Australia in the last 10000 years.

maintained for 180 km at least as far north as Hinchinbrook Island. Significantly, shorelines of three separate ages may be recognized in this area: a largely terrigenous beach deposit of reworked corestones from the last glacial regolith marking the first time Holocene sea levels reached present level and dating between 6000 and 5000 a B.P.; a maximum level rising at its highest to 4.9 m and dating close to 4500 a B.P.; and a regression shoreline somewhat lower with dates in the order of 3500 a B.P. Islands in the Bowen area suggest higher sea levels 3.7–3.9 m above present (Hopley 1975), the Burdekin delta only 3.0 m (Hopley 1970), Herald Island near Townsville 4.9 m, and the Palm Islands 3.7 m (Hopley 1971 *b*). It is unfortunate that the coastline between the Palm Islands and Cairns has not been studied in detail, for it is clear from the work of Bird (1970, 1971 *a*, *b*) that at Cairns and at Yule Point just to the north, although a higher Holocene sea level is recorded, its maximum height does not exceed 1.2 m.

The area north of Cairns from pre-1973 literature

To the north of Cairns lies the area investigated by the 1973 Royal Society Expedition. In the light of the variation in levels displayed further south and the features described from the islands north of Cairns by earlier expeditions, evidence for higher sea levels might be expected. Research was thus aimed at confirming and accurately measuring and dating such evidence and relating it to the pattern of the whole Queensland coastline.

Most of the evidence described north of Cairns comes from the low wooded islands of the reef patches closest to the mainland. However, the cemented platforms which comprise much of this evidence have been related to reef flat level and not to the modern counterpart level of cementation. Indeed, the exact nature and origin of the platforms has not been determined. Thus Agassiz (1898) describes a 'coarse beach rock' elevated 2.4 m above h.w.m. on Three Isles and a similar feature on nearby Two Isles, while Steers (1929, 1937, 1938) and Spender (1930) describe two levels of cementation on these islands and others of the Turtle and Howick Groups further north, suggesting emergences in the order of 1.5 and 4.0 m. However, at Nymph Island at least, the difference in height between the two platforms is only 1 m (Steers 1938), and only on Nymph Island is there supplementary evidence in the form of *in situ* raised reef. Unfortunately, before the work of the 1973 Expedition, the only radiocarbon dates for this part of the Great Barrier Reef confused rather than clarified the sea level picture. Maxwell's (1969) dates of 250 ± 80 a B.P. for 'high beach rock' on Turtle Reef and 530 ± 80 a B.P. for reef-rock from Nymph appear anomalously young or cannot be related to higher sea levels.

To the north of the Howicks, Steers (1938) describes other low wooded islands, up to latitude 12° 53′ S (Chapman Island). However, although the 'low platform' related to the lower of his two emergences is ubiquitously present the higher level is apparently absent. Possibly parallel evidence from the Flinders Islands is mentioned by Lucas & de Keyser (1965), but they give no exact locations, heights or descriptions of their site.

Still further north the amount of data available becomes even sparser and more ancient in its source. Jukes (1847) and Rattray (1869) describe raised beach rock and reef on Raine Island and adjacent parts of the Great Barrier Reef which Fairbridge (1950) considers to indicate an emergence of 3.1–3.7 m. There are also reports of similar elevated features in the Torres Strait region (e.g. MacGillivray 1852; Haddon, Sollas & Cole 1894; Mayer 1918) though it is difficult to define precisely the height differences between the higher features and their modern counterparts.

Discussion of the evidence

The evidence presented suggests that not only are there discrepancies in the maximum height of sea level during the Holocene along the Queensland coast (variations between 0 and 4.9 m above present sea level) but also great variation exists in the time at which sea level reached its present position (variations between *ca.* 6000 and *ca.* 3000 years) (figure 2). Further, it would appear that sharp dislocations occur in the Holocene shorelines notably to the east of Broad Sound, and at the northern end of the Whitsunday Passage, though with the present spacing of sites studied in detail the dislocations may be spread over as much as 25 km.

Explanation of the variation should incorporate reasons for the sharpness of the dislocations. However, an even greater problem may be found by examining the height of Pleistocene last interglacial shorelines along the same coast (figure 2). With dislocations of almost 5 m in the Holocene shorelines, vertical variation of at least this amplitude might be expected in the older levels. This does not take place. As in the remainder of eastern Australia, a double barrier system representing beach ridge accumulation of Holocene and presumably last interglacial age is found intermittently along the entire Queensland coast. Surveyed heights of the Pleistocene shoreline do not exceed 5 m (figure 2). The vertical range is apparently less than that for the mid-Holocene shorelines. Moreover, the trend does not follow the pattern of the younger shorelines.

Three sets of reasons may be identified to explain these apparent anomalies in the Holocene shorelines.

1. *Error in measurement or interpretation*

The relatively narrow height range (5 m) within which the variations lie may be exceeded by short term oscillations of the sea surface by waves, tides, and occasional tsunami and storm surges. Exact height measurement should be made but this is not always possible, especially on a coast such as that of Queensland where bench marks and spot heights are rare. However, the relatively close network of tidal stations may allow heights to be related to tidal datum with confidence. Although some error may still be incorporated in the heights quoted, this is unlikely to be significant compared to the total height range of the data.

Error may also be associated with the radiocarbon dating technique. Variation may be produced by the non-uniform distribution of the amount of ^{14}C isotope in ocean waters and by geomagnetic and biomagnetic modulation of the production of radiocarbon in the Earth's atmosphere. Problems may be especially related to recrystallization of marine carbonates (see Thom 1973). In the majority of results quoted, however, the dated materials were highly aragonitic and stratigraphic cross checking was possible by obtaining a number of dates at each site.

A more serious error may be caused by misinterpretation of the evidence. Failure to recognize the height variation of shore platforms related to exposure conditions, compaction of peats or the high nature of storm beaches are obvious examples. In the region of the Great Barrier Reef shore platform evidence has not been utilized in spite of the widespread quotation in the literature of raised platforms (see, for example, Hedley 1925; Stanley 1928). Detailed examination of platforms in the Whitsunday area indicated that the majority of such features are high tide, near horizontal 'water layer weathering' type phenomena in which height variations of up to 1.5 m may exist along short stretches of coast. A major control is the height at which wet season spring lines emerge onto the coast, a factor related to the spacing of fracture zones and joints in the volcanic and granitic rocks. Problems may exist in the utilization of beach-rock which may be confused with other cemented materials (dune calcarenite, reef-rock, phosphatic cay sandstone, humic sandrock) but in general, beach bedding and a horizontal upper surface of cementation may be recognized in the sites utilized and the relation of the maximum elevation of the upper surface of cementation with m.h.w.s. appears firmly established. Corals also may be related to specific tidal levels though enclosure of reef flat waters behind shingle ramparts or algal rims may raise the levels of moated corals above those of their open water counterparts. A conservative estimate of the amount of exposure of raised corals has been made by comparing them with the highest level at which similar species are growing today, even where these may be moated.

2. *Real spatial variations in the level of ocean surface*

Even allowing for variations produced by waves and tides, it should be recognized that the ocean surface is non-horizontal; variations of up to 2 m occur with factors such as temperature and salinity (Fairbridge 1966), and significant slopes are associated with ocean currents as the result of centrifugal and Coriolis forces (see, for example, Hamon 1958). Tidal range may also change through time, an important factor when evidence utilized is related to tidal extremes (e.g. beach-rock and coral) and not to mean sea level. Changes have undoubtedly taken place in the last 6000 years in the configuration of the Great Barrier Reef, but no estimate can be made of the effect that this would have on tides along the Queensland coast. This may be an important factor on the south central coast where tidal ranges vary from about 3 m near Bowen to almost 10 m at Broad Sound. Also important along the coast are the meteorological influences on sea level. Storm surges up to 6 m have been recorded (Hopley 1974*b*) and many shingle ridges and other features on reef islands undoubtedly owe their origin to these short-lived events.

3. *Movements of the land*

Tectonic dislocation of the shorelines of eastern Queensland is an obvious cause of variation, particularly as the sharp dislocations coincide with major structural breaks and changes in the alignment of the coastline (e.g. the northern end of the Whitsunday Passage is a highly fractured zone of horst–graben structures (Hopley 1975)). Even more convincing is the apparent relation between the basement structure of eastern Queensland and the highs and lows in Holocene shoreline heights. The high shorelines near Townsville, for example, correspond with the major granitic axis of uplift, the lack of high evidence in the Cumberland Islands with the Tertiary Hillsborough Basin, the eastern side of Broad Sound with the northern limb of the south coast structural high; and the Coolum area of no higher shorelines with the Mesozoic Maryborough Basin (Hopley 1974*a*).

However, eastern Queensland is not recognized as a zone of high seismicity and the rates of tectonic deformation required to warp the Holocene shorelines are more compatible with a plate edge rather than mid-plate situation. Further, the heights of the Pleistocene shorelines appear to contradict any form of tectonic dislocation though it is possible that the inner barrier shorelines are interstadial levels uplifted to their present height (see Hopley 1974*a*). However, the coincidence in height of shorelines of differing ages and complete lack of higher and older shorelines in the areas of apparent uplift appears to militate against this explanation.

Isostatic warping may be more acceptable. Movements of hundreds of metres have long been recognized to be associated with the major Pleistocene ice sheets of the northern hemisphere.

More recently it has been calculated that the load applied to continental shelves by the Holocene transgression is sufficient to produce a response (Bloom 1967; Walcott 1972; Chappell 1974). As the nature of response depends on the morphology of the ocean basins, the shape of the continental shelf and the strength of crustal materials, geographical variation in the amount, pattern and time of isostatic warping may be expected. Such an explanation contributes much towards explaining the discrepancies along the Queensland coast. Notably, the evidence for higher shorelines comes from the high continental islands generally within 15 km of the mainland, the area in which Chappell (1974), at least, considers the most likely for upwarping. Further, the presence of three islands at varying distances up to 30 km off the coast of Bowen, all retaining evidence of three higher shorelines, has allowed the identification of greater slopes on shorelines normal to the coast than exist parallel to it, a situation which again might be expected from hydro-isostatic response models. As shelf morphology and structure are important determinants of hydro-isostatic response, it is not surprising that a correspondence exists between the pattern of shorelines and major structural regions. Apparently, however, much of the stress imposed on the shelf area has been released along pre-existing weaknesses. Sissons (1972) has described a similar but smaller dislocation in glacio-isostatically warped shorelines where they cross older fault lines in eastern Scotland. If a hydro-isostatic deformation is accepted, then Pleistocene shorelines may have undergone a similar amount of warping during the glacial low sea levels when the load was removed from the shelf. Only with the reapplication of the load are these shorelines resuming a near-horizontal disposition.

Local sediment loading may explain the lower elevations of Holocene shorelines in the Burdekin delta and the down-warping of the last interglacial surface beneath the present delta (Hopley 1970). Over 150 m of deltaic sediments are recorded in the delta, with up to 30 m of Holocene deposits along its eastern edge.

The northern Great Barrier Reef in the light of the discussion

The apparent explanation of discrepancies in Holocene shorelines along the Queensland coast by hydro-isostasy, possibly aided by temporal variations in oceanic factors such as tides, can only be confirmed by detailed study of the whole of the shelf area. In this respect the Great Barrier Reef offers a unique opportunity because, especially north of Cairns in the area of the 1973 Expedition, gauges in the form of coral reefs exist up to the very edge of the continental shelf. The reefs closest to the mainland may display both the longest record of Holocene sea levels at or close to their present level and any evidence related to higher sea levels of this period. Maximum subsidence on the outer edge of the shelf should produce the youngest reef surfaces here. From the literature, however, Raine Island, detached on the outer edge of the shelf and with recorded raised features, appears anomalous.

A multidisciplinary approach to this area of the Reef may provide answers to the sea level problem, which may in turn help in explaining the variable morphology of the Great Barrier Reefs, as for example, the decreasing degree of development of reef flats outwards across the shelf. Variable rates of reef growth, and the nature of the underlying karst surface over which the Holocene veneer has formed, should however, be combined with explanations of variable sea level curves in providing answers to Great Barrier Reef problems.

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