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Holocene sea level change: an interpretation

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Interpretation of factors responsible for land–sea level change in areas such as the Great Barrier Reef involve an appreciation of not only the field evidence purporting to show change, but also the theoretical models which attempt to explain depth variations in shorelines of a given age. Relative movements in sea level in Holocene time may result from a number of factors operating either external to the study area (e.g. glacio-eustatic, and broad-scale hydro-isostatic deformation of the globe resulting from the last deglaciation and sea level rise), or those whose effects are essentially local (e.g. changes in circulation and tidal levels within partially enclosed water bodies induced by sedimentation or biogenic reef growth, meteorological changes affecting the magnitude and frequency of storminess, regional flexures and/or faulting, and hydro-isostatic deformation of shelves and adjacent coasts accompanying the Postglacial Transgression). In this paper, data from the northern Great Barrier Reef Province are evaluated in relation to various causes of sea level change. Emphasis is placed on explaining variations in relative sea level position by hydro-isostatic theory. Deflexion in the ocean margin 'hinge zone' varies with continental shelf geometry and rigidity of the underlying lithosphere. The fact that the oceanic crust meets the continental crust quite abruptly east of the study areas, dictates that moderately strong flexures occur, and that variations in Holocene hydro-isostatic flexure in the Great Barrier Reef Province are partly explainable in these terms.

Introduction – identifying datum in reefal materials

Interpretation of factors responsible for land–sea level change in areas such as the Great Barrier Reef involves an appreciation of not only the evidence purporting to show change, but also the theoretical models which attempt to explain depth variations in shorelines of a given age. Relative movements in sea level in Holocene time may result from a number of factors operating either external to the study area, or whose effects are essentially local.

It is quite clear that many time–depth curves which have been used to show changes in sea level in Holocene times vary markedly from place to place, and even between areas remote from glacio-isostatic effects there are pronounced differences. Before seeking to explain these, it is necessary (i) to reach agreement about the most useful datum from which measurements of sea level changes should be made, and (ii) critically evaluate the geomorphic and stratigraphic elements upon which interpretations of palaeo sea levels are based. Once a particular facies unit is well dated and its height/depth relations to the chosen modern datum are established, estimates of its associated palaeo-datum can be made, as long as certain factors are borne in mind. For coral reef environments, these include the following.

The geometry of reefs and reef islands during Holocene times has changed, so that relations of certain zones to datum has altered. For example, upward growth of a barrier crest may have lagged behind sea level rise during the postglacial transgression, with the crest becoming stable at some stage during the last 6000 years when relative sea level changes have been minor. In such cases, the changing relation between the particular reef zone and datum should be recognized from close examination of composition and structure (see, for example, Chappell & Polach 1976). In other situations, such as on reef flats, false interpretation might stem from past temporary super-elevation, above m.l.w.s., of shallow coral meadows or microatolls as a result of moating. Only careful examination of the plan-view reef flat structure will reveal this. Finally, high-tide beach and supratidal storm deposits are also susceptible to changing reef geometry, among other factors. The height and horizontal depth to which these are built is affected by the degree of retardation of storm waves across the developing reef flat, as well as by variations in the productivities of different reef faunas. Especially in a very broad region of reefs such as the Great Barrier Reef Province, the sweep of storm waves is likely to have declined as reef crests, intertidal flats and supratidal islands have achieved their present forms during later Holocene times. Thus Neumann (1972) has suggested the existence of a Holocene 'high energy interval', during which 'deposits dating back to this early high energy window still rest where they were emplaced – a few feet higher than those of the more protected present coast – not because they were deposited during a higher stand of the sea, but during an interval of higher energy when the new coast was less protected' (Neumann 1972, p. 42).

The second factor which would influence environment of reef growth and sedimentation is more problematic: the possibility of changing storminess in the last 6000 years or so. Significant climatic changes in higher latitudes have been interpreted from glacial and other evidence elsewhere in the world (Denton & Karlen 1973; National Academy of Sciences 1975). Such changes may also have had an effect on patterns of storminess affecting Australian coasts, as Thom (in preparation) infers from dated pulses of transgressive dune formation on the New South Wales coast. Consequently, there is a possibility that storminess within the Great Barrier Reef Province may have varied in Holocene times, with concomitant variations in patterns of supratidal storm ridge and rampart formation. However, storm rampart deposits on the low wooded islands are not adequate evidence themselves of relatively stormy epochs, as their construction depends in part on reef geometry, as mentioned above, and on productivity of shallow-water branching corals. In any case, such ramparts may reflect the least frequent, large, events within a magnitude–frequency distribution of storms which might have remained constant in Holocene times. Storminess history might be investigated by mapping and dating a large number of the large blocks of forereef and buttress-zone material, ripped out during major storms, which lie scattered on patch reef flats.

The foregoing remarks indicate that many reefal facies may have varied in their relation to datum in Holocene times. Bearing these points in mind, and before proceeding to identify the course of relative sea level change for a particular site, the datum itself must be chosen. In coral reef environments it is tidal extremes rather than mean sea level which can most easily be related to particular facies, especially spring tide low water level which delimits the top of the reef buttress zone and which regulates the upper growth limit of many corals of the outer reef flat. The high tide level may, in certain circumstances, be recognized from sedimentary structures preserved from ancient intertidal beaches. Care must be taken, however, when comparing time variations of ancient low water level datum from different places, because the tidal range may have varied. While this is probably negligible for outer shelf and deep ocean positions, in Holocene times, it can be significant for major bays and archipelagic regions

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where the coastal and bottom geometries may have changed during and since the Postglacial Transgression. It is possible that tidal range may have altered within some inner regions of the Great Barrier Reef, a possibility which can be tested only by very careful examination of the shallow three-dimensional structure of the largest reef islands.

Causes of difference between curves of Holocene datum changes

Given agreement about the interpretation of the evidence for palaeo-datum positions, it is possible to examine the proposition that these palaeo sea levels represent any or all of: (i) tectonic movements; (ii) isostatic movements; (iii) true eustatic changes resulting from ice volume changes. Before anything positive can be said about oscillations or trends in sea level due to changes in ice volume over the last 6000 years, it is important to examine the first two factors which can be responsible for regional variation of apparent sea level histories. Such variations on the Queensland shelf and coast may be explained by hydro-isostatic effects (Chappell 1974), or by tectonic movements (Hopley 1974), or by a combination of both. In this paper, an attempt will be made to apply hydro-isostatic theory developed by Walcott (1972) and Chappell (1974) to the northern Great Barrier Reef province, in order to see if the different elevations of palaeo sea levels can be attributed to isostatic movements.

In most studies of sea level change, the hydro-isostatic factor is generally neglected. Hydro-isostatic depression of ocean basins and flexure of their margins is a consequence of the post-glacial increase of ocean volume. There are two mechanisms of load compensation: (i) instantaneous elastic adjustment of the broadest-scale Earth figure; and (ii) progressive slow creep of the figures. For the last 600 years, glacial volume changes are minor and the elastic effect is insignificant for deformation at ocean margins. However, continuing isostatic creep causes significant flexure near ocean margins in the last 6000 years (Walcott 1972; Chappell 1974). The exact pattern of flexure may be calculated for a given rheological model of the upper Earth, and a given history of ocean volume change. Theory and methods of calculation for simpler cases have recently been presented by Chappell (1974).

The creeping flexure of the ocean floors and margins involves deep flow in the upper mantle (asthenosphere) in compensation for the surface redistribution of the load. Physical constants pertaining to this flow have been estimated by many geophysicists for deformations ranging in size from glacial-lake Bonneville, through postglacial rebound of Pleistocene glaciated regions, to the Earth's equatorial bulge (see review by Walcott 1973). During and following deglaciation, the ocean basins subside gradually while the continents rise. Somewhere near the margins between the two is a relatively stable zone, the hinge zone. Strong flexure near this hinge affects apparent or relative sea level changes in coastal and continental shelf regions.

The mean course of ocean basin subsidence by the creep mode of compensation, as well as mean updoming of continents, can be calculated for a given history of glacial ice melt, and a reasonably realistic model of the Earth's rheology. Assuming a simple deglaciation of curve, these calculations show ocean basins subsiding towards the centre of the Earth *ca.* 8 m in the last 6000 years, while the mean continental surfaces rise *ca.* 16 m. The latter result is consistent with modern geodesic relevelling rates determined by Hicks (1972) for continental U.S.A.

The effect of ocean floor subsidence on sea level change recorded near ocean margins must be compounded with the hydro-isostatic flexural movement of the margins themselves. These can similarly be calculated, given appropriate rheological models for the marginal zones. In figure 1, three cases of isobase deformation are depicted for different upper Earth models, continental lithosphere, ocean (less rigid) lithosphere (from Chappell 1974), and an oceanic–continental transition case. The results for the transitional case are preliminary and *must* be treated with caution.

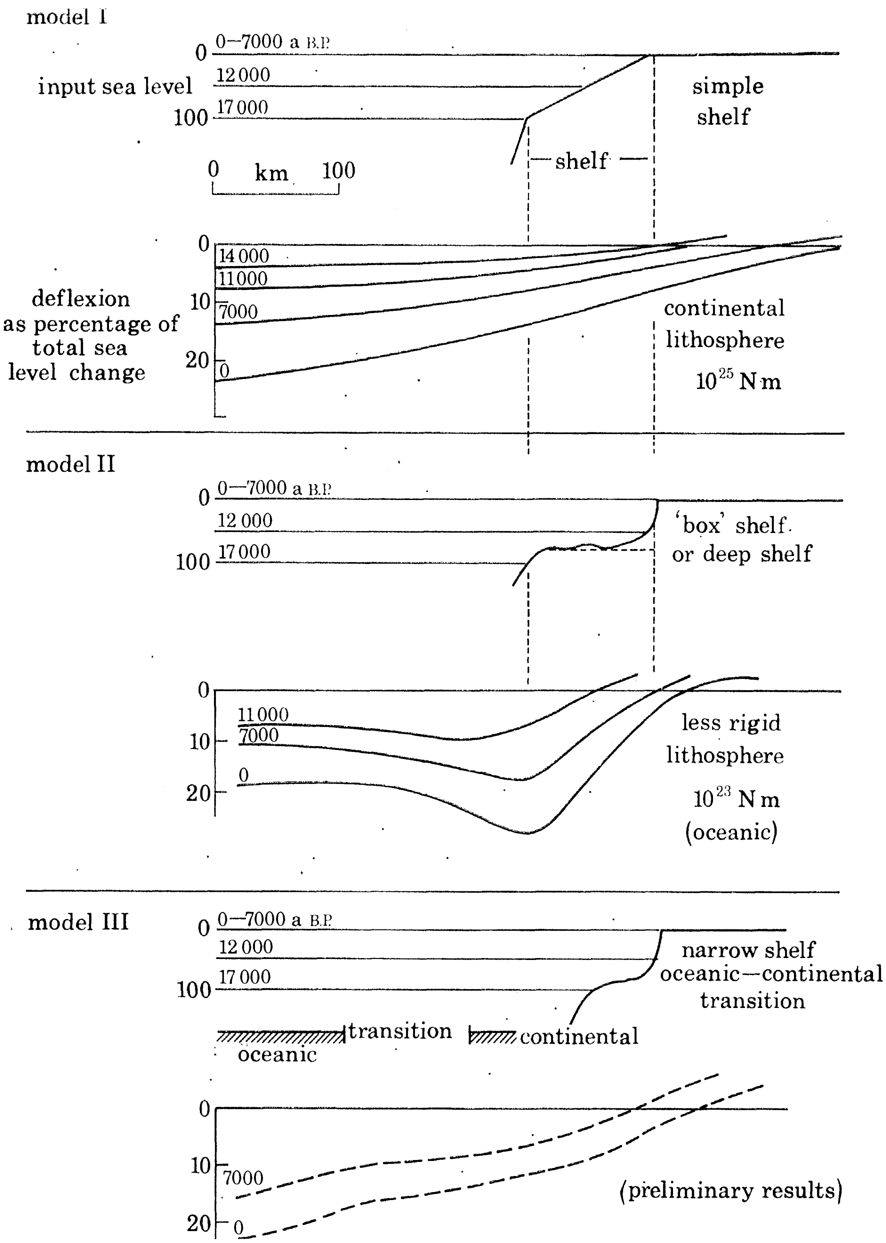

FIGURE 1. Hydro-isostatic deformation of continental margins possessing different rheological properties. Isobase divergence is strongest in the case of a deep shelf with an 'oceanic' (or less rigid) lithosphere.

Two main points arise from figure 1. First, divergence of isobases from the ocean margin to the coast increases with time. Divergence is strongest in the extreme case of ocean lithosphere and box shelf geometry, and weaker in those cases of rigid lithosphere and narrow planar shelf. It also appears that divergence is weak in the transitional model case, indicating limited deformation of outer and inner shelf perhaps because the rate of continental lithosphere bending is dependent on movement in the oceanic crust. The second point is that the hinge or crossover from subsidence to uplift migrates inland with time. This means that all points near the coast are effectively subsiding. If the shelf and near-coastal subsidence equals the mean subsidence of ocean basins, then there is no apparent sea level change for the last 6000 years

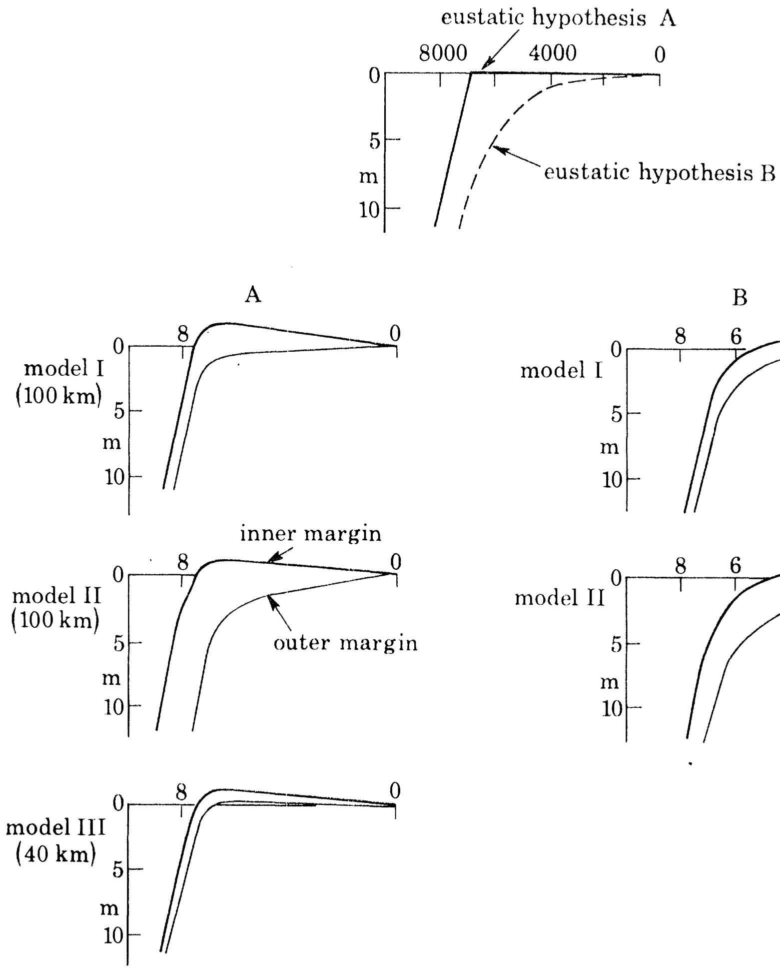

FIGURE 2. Relative sea level curves for inner and outer margins of continental shelves, for two ice-melt (eustatic change) hypotheses. Three rheological models are depicted: I, continental lithosphere; II, oceanic lithosphere; III, continental–oceanic transition lithosphere. Curves are derived for continental shelf widths of 100 km in the case of models I and II, and 40 km in the case of model III.

(assuming zero ice volume change). If near coastal subsidence is less than that of the mean ocean basin, net shoreline emergence should be apparent over the last 6000 years. However, if the shelf is subsiding at a rate which exceeds the mean ocean floor (e.g. the case of ocean lithosphere and wide shelf), then shelf submergence will have occurred over this period. For a given ocean volume history, shelf geometry, and Earth structure, apparent sea level curves can be constructed for both outer and inner margins of the continental shelf, by methods given in Chappell (1974, fig. 7).

The exact course of glacio-eustatism has been extensively debated, principally because of difference between Holocene sea level curves from different places. Let us examine two eustatic hypotheses on hydro-isostatic terms. Eustatic hypothesis A views the ice-melt contribution to

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sea level change as effectively ceasing about 7000 years ago (cf. Bloom 1971). The apparent courses of sea level, given a broad, sloping shelf and a continental lithosphere, are shown in figure 2, column A, as model I. At the coast (inner shelf margin) sea level falls from a high 6000 years ago to the present time, but at the outer margin it is continually rising. In model II an oceanic lithosphere in invoked. The degree of downward deflexion of the shelf edge increases in this case resulting in a much lower position of the 6000 a B.P. shoreline on the outer margin, and a fractionally lower but still positive position at the coast. If the shelf width is narrowed, and an oceanic–continental crustal transition model applied to hypothesis A, then preliminary results suggest close parallelism in the apparent sea level curves for both outer and inner shelf sites. In this case (model III), the 6000 a B.P. shoreline is only fractionally raised (to 1 m) above present. At this stage there may be some question as to whether we can achieve such a resolution on the elevation of shorelines using this particular model.

Eustatic hypothesis B, as shown in figure 2, column B, involves progressively declining addition of water from ice sources to the oceans, a possibility which Bloom (1971) regards as being relevant if one considers the potential contribution of the West Antarctic ice sheet to sea level over the last 7000 years. The effect of applying this hypothesis to rheological models I and II is (i) to displace towards the present the moment when apparent sea level on the inner shelf margin reached its present position; (ii) to decrease the difference between inner and outer shelf deformation. In the case of model III (not shown in column B), the degree of elevation above present sea level and the difference between apparent sea level for the two sites is negligible.

If eustatic hypothesis A is applied to the Queensland continental shelf between latitudes 14 and 20° S, and assuming the flexural rigidity of the shelf approximates a continental lithosphere (model I), then variations in the distribution of a 6000 a B.P. shoreline can be estimated (figure 3). Now the main variables which affect the course of sea level change from place to place are shelf width and depth. Towards the north where the shelf width is narrow, the elevation of the inner margin of a 6000 a B.P. datum is 0.5–1.0 m. South of Cairns this increases to 1.0–1.5 m. Under the same conditions on the outer margin, the 6000 a B.P. datum would be at or a little above the present datum level where the shelf is at its narrowest, from Cooktown to Cape Melville, but is deflected downwards as the shelf widens (values in bold type at outer shelf margin in figure 3). If the somewhat unreal case of an oceanic lithosphere (model II) is assumed beneath the north Queensland shelf, the pattern changes. At the outer margin the 6000 a B.P. datum would lie at a greater depth (values in parentheses in figure 3). The elevation of inner margin shorelines would be lowered only slightly.

The effect of employing eustatic hypothesis B on the Queensland shelf would be to lower even further the elevation of 6000 a B.P. shoreline on the shelf outer margin. It would occur below present sea level on the inner margin or coast sites. It is of interest to note that the shoreline which would achieve maximum elevation (*ca.* 1.0 m) at the inner margin under this eustatic hypothesis would date between 3000 and 4000 years ago.

In summary, various hydro-isostatic models as applied to the northern Great Barrier Reef Province suggest that the 6000 a B.P. shoreline should be elevated the highest relative to present sea level by the order of 1–2 m, under eustatic hypothesis A. But if hypothesis B is applied, then this shoreline should lie below present sea level, and the 3000–4000 a B.P. shoreline should be the highest (*ca.* 1 m). When these conclusions are confronted with the field evidence (McLean, Stoddart, Hopley & Polach 1978, this volume) certain discrepancies emerge:

(i) where it has been recognized, the 6000 a B.P. low water datum lies 0–0.5 m above present;

(ii) the highest raised or elevated deposits which possibly could be attributed to higher relative sea levels by McLean were deposited 3000–4000 years ago (+1 to 1.2 m).

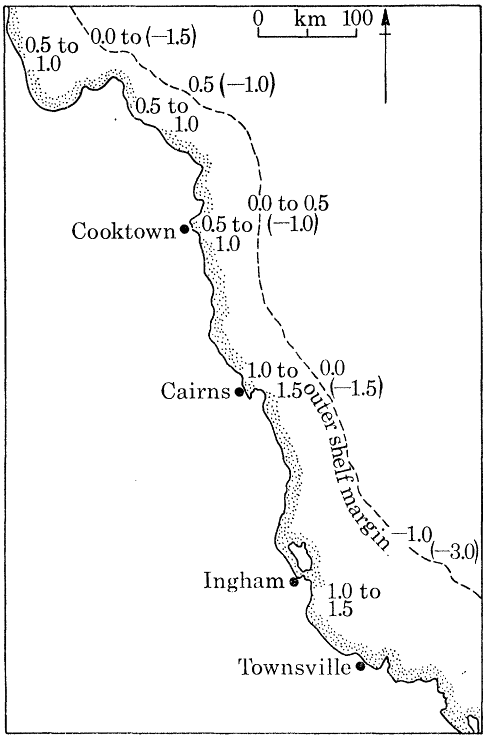

FIGURE 3. Preliminary estimates of elevations of a hypothetical 6000 a B.P. shoreline datum on the north Queensland coast applying eustatic hypothesis A (figure 2), and assuming no tectonic movements. The portion of this shoreline as shown here would be only dependent on glacio-eustatic and hydro-isostatic factors. At the outer margin figures not in parentheses represent a continental lithosphere shelf (model I); parenthetical figures represent the elevation of the 6000 a B.P. shoreline assuming an oceanic lithosphere shelf.

Thus, it appears that some compromise between eustatic hypothesis is called for. More exact resolution will be possible when apparent palaeo-datum curves for several Great Barrier Reef sites are agreed upon, and when hydro-isostatic calculations are completed for the oceanic–continental transitional model.

There are two significant consequences to the understanding of hydro-isostasy in relation to areas such as the Great Barrier Reef. First, for students of late Quaternary sea level changes, differences between sites are to be expected and are at least partly explainable in these terms. Secondly, hydro-isostatic flexures cause the relative rates of sea level change over the last 6000 years to differ substantially between inner and outer zones of shelves, and this surely is an ecological factor of some importance with a strong potential influence on the nature of reef development.

In conclusion, it is now possible to view an apparent or relative sea level curve for any particular stretch of coast as being the product of several factors or mechanisms. The contribution of each factor changes with time. For instance, between 6000 and 9000 years ago, glacio-eustasy accounted for up to 80 % of observed sea level change; over the last 3000 years this factor was probably responsible for no more than 10 % or 10 cm of observed change, while hydro-isostasy becomes relatively more important. This principle is summarized in figure 4. The exact proportions for the case of the northern Great Barrier Reef cannot yet be stated, and the course of sea level shown here is no more than a first approximation derived from somewhat ambiguous evidence at and above present sea level (McLean *et al.* 1978, this volume), and below present sea level (Thom, Orme & Polach 1978, this volume).

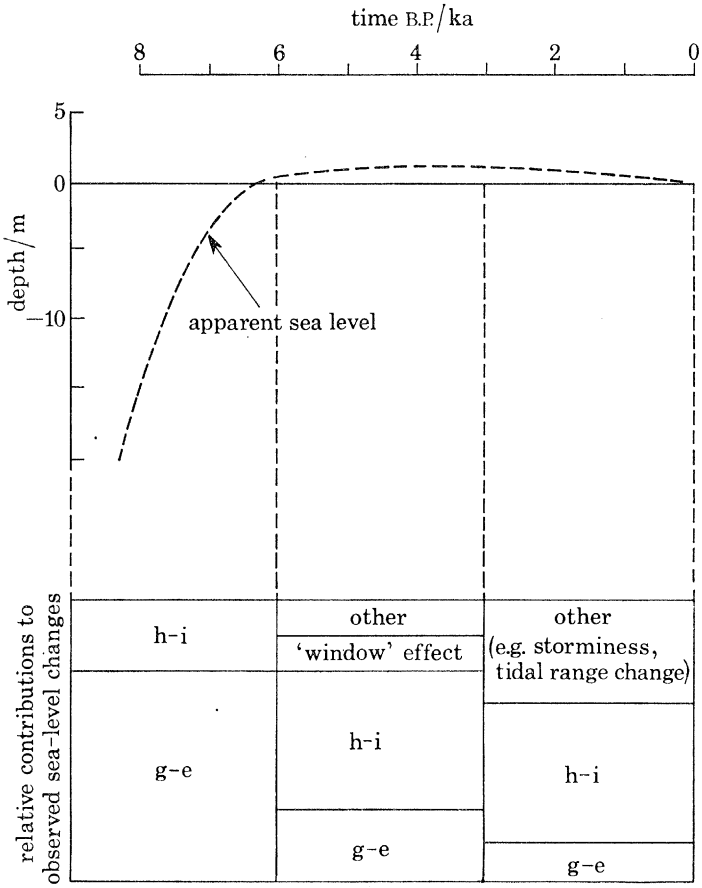

Figure 4. The approximate position of apparent or relative sea level over the past 8000 years based on evidence from 'low wooded' islands of the northern Great Barrier Reef Province. The relative contribution of a variety of factors or mechanisms responsible for change is indicated as changing with time: h–i, hydro-isostasy; g–e, glacio-eustasy. The exact degree of explanation by each factor is unknown.

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