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POSTGLACIAL CHANGES IN LEVEL OF LAND AND SEA

W.T. WARD[1]

ABSTRACT

Four postglacial high sea levels, separated by intervals of low water, are recognized at 7.5 ft, 4.5 ft, 3.0 ft and 1 ft above present mean sea level in East Gippsland, Victoria, Australia. Direct estimation of shoreline age is made impracticable by an absence of datable material in the stranded beach sediments, but a few dates are available for lagoonal beds. These dates, and correlations with New Zealand made possible by the common occurrence of similar sequences of coastal dunes resulting from changes in postglacial climate, suggest that the four stages of high sea level occurred about 4,700, 3,000, 1,500 and 750 calendar years ago. In particular the East Gippsland shoreline sequence is similar to that observed in the Firth of Thames, New Zealand.

The stranded shorelines are believed to result from combination of long-term land uplift with real changes in sea level.

This conclusion follows comparison of the Firth of Thames data with observations reported for 15 other localities in New Zealand, western Europe, North America, Africa and Oceania. Contradictory theses concerning postglacial sea-level changes in these localities are reconciled if it is assumed that each locality has been affected by earth movements. Such movements are already recognized in some areas affected by isostatic rebound or by mountain-building, and are presumed in others where shorelines appear excessively high or excessively low. To facilitate comparison, two simple models that relate shoreline elevation to implied rate of uplift are used. These models are based on the supposition that the earth movements actually experienced were continuous, or can be reasonably represented as small fluctuations about a regular long-term trend.

It is not yet possible to decide whether any of the localities studied has been stable in postglacial time. Earth movements may not have affected the Cook Islands, South Pacific, however. If this is so, it would seem that the sea gained its present level several thousand years ago. Subsequent fluctuations have been in response to global climatic changes. The highest level actually attained by the sea (5.5 ft) was reached briefly in Sub-boreal time.

STRANDED SHORES, EAST GIPPSLAND

Evidence of postglacial shorelines higher than present sea level is rarely observed on the exposed coasts of East Gippsland, Victoria. Wave action is vigorous, turbulent seas are common, and there is a tidal range of eight feet, factors which ensure that the beaches are frequently reformed. The waters of the Gippsland Lakes adjacent to the coast between Seaspray and Lakes Entrance are calm by contrast. These coastal lagoons (fig. 1), separated from the sea by a sandy barrier beach, were developed when the rising postglacial sea flooded into prior barrier-beach landforms that were stranded and eroded by the wind in the Late Pleistocene (W a r d in prep.). In postglacial times the lakes have always formed a quiet refuge, owing to nearly complete enclosure by the prior barrier.

Because natural outlets to the ocean were ephemeral, tide waters were generally excluded from the lakes and even now are severely restricted in access by the limited water connection cut through to the sea in 1888. No ocean waves reach to lake shores, and the short fetch limits the height and energy of waves formed on the enclosed waters.

[1] Division of Soils, Commonwealth Scientific and Industrial Research Organization, Cunningham Laboratory, St. Lucia, Queensland (Australia).

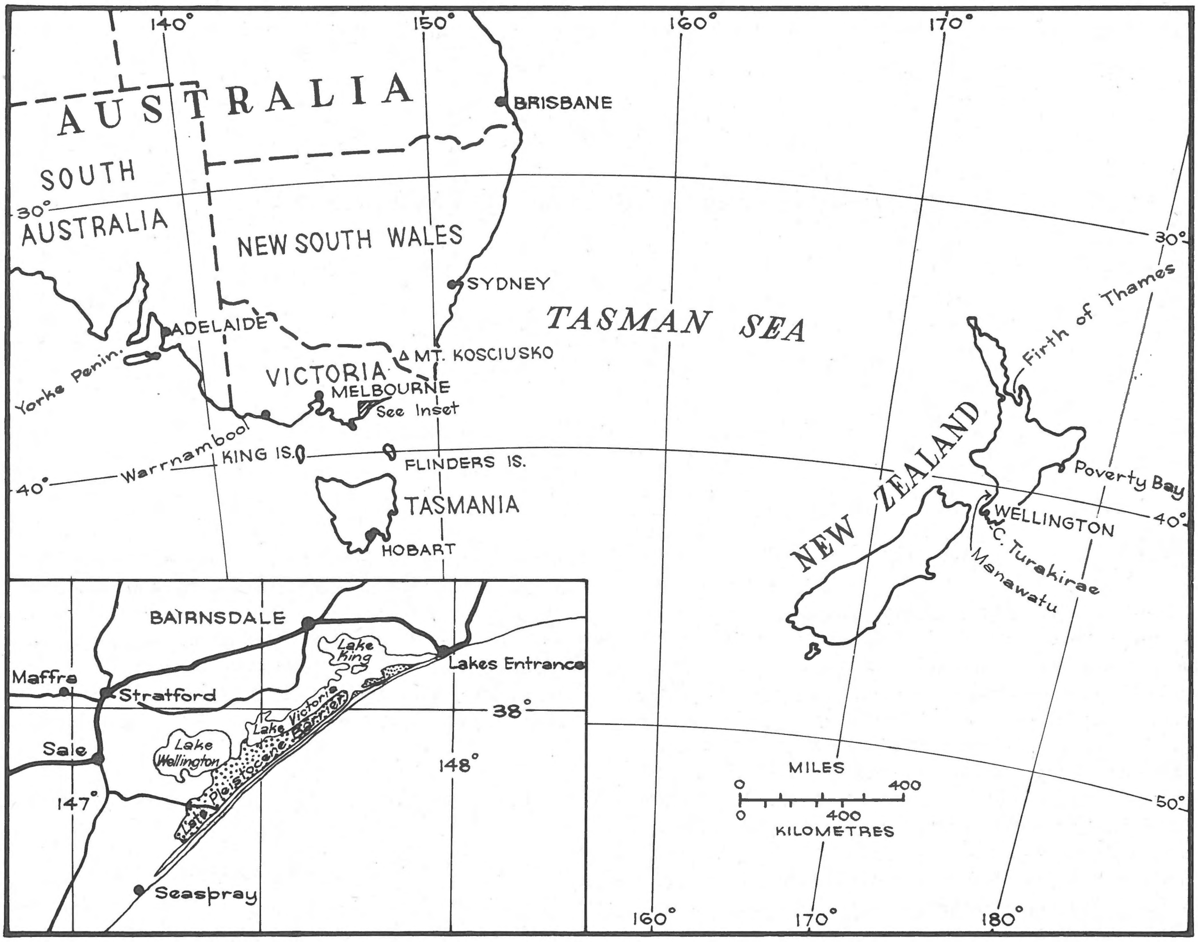

Fig. 1
Location of Gippsland Lakes, Victoria, Australia, and areas in New Zealand referred to in text.

Parity of mean lake water level and mean sea level has always been assured by intermittent surface water connections but is also effected by the permanent ground-water connection through the pervious sands of the ocean barrier. The lakes, in a word, form a natural stilling-well with respect to the sea, and are therefore of particular importance to an understanding of postglacial history. The changes in lake water level recorded by the beach ridges, dune sands, and stranded lagoon beds that border their shores clearly imply similar changes of sea level. The value of the record is further emphasized by the fact that all stranded shorelines would be within reach of ocean waves if the sea had free access to the lakes. It is not surprising, then, that a comparable record does not appear on the open coast.

Evidence for intermittent occupation of several levels will be reported in detail elsewhere. Briefly, four lake-water high stands are identified, with shorelines at 7.5 ft, 4.5 ft, 3.0 ft, and 1.0 ft above present mean water level. Exceptionally close estimates of shoreline height are possible because the beach ridges are well-formed, and occur on plains of very low gradient where a large shift in shoreline position accompanies a slight change in water level. The stranded ridges, which consist very largely of water-sorted sediments thrown to storm-wave limit, have the same form and evidently developed in the same way as the modern ridges at the present lake shores. Observed differences in elevation of comparable features in ancient and modern ridges, as for example the greatest heights of water-sorted sediments, can therefore be used to estimate former water levels. The values given by measurement with a dumpy level in seventeen localities around the lake shores, each with several ridges, were further checked by comparison with measured heights taken on the flat plains inland of the former beaches. Although these flats behind the beach ridges were not under water when the ridges were formed, their low elevation relative to the former shore shows that they were very close to high water level at that time, and relict ground-water stains in the soil suggest that the flats were then marshy plains. Other measures of former water level are provided by observations of stranded humate horizons (Hails and Hoyt, 1968) – fossil forms of the humus-iron accumulations that mark present ground-water level in this sandy terrain.

The 7.5 ft shore penetrates into areas of aeolian sand on which mature podzols are developed (Rotamah soils). These sands extend considerably below the present water line and therefore must have accumulated at a time of low sea level. Low places among the dune fields are now occupied by ponds and lagoons. The sands are believed to be Late Pleistocene in age, but younger than 42,500 years (Ward, in prep.). They provide evidence for a period of wind erosion which remodelled all areas of sand throughout the East Gippsland plains. These widespread effects imply not only an incidence of strong winds from the west but an absence of vegetation, such as might be induced by a severe climatic change.

A second episode of wind erosion, nearly as widespread as the first and also implying a general removal of the vegetative cover, is attested by erosional surfaces and contemporary sand dunes that partly mantle land surfaces formed during the +7.5 ft high water level. The soils on these yellow-brown aeolian sands (Lake Wellington association) are juvenile. Unlike their predecessors, they lack an A_2 horizon and the B horizon is indistinct. Wind erosion again occurred at a time of low water because the sands continue at depth beneath the present water table at the lake shores. Contemporary low water is also implied by the pattern of distribution, for large masses of Lake Wellington sands occur east of source areas now occupied by the lakes.

Weakly differentiated soils like those of Lake Wellington association are also developed on sediments related to the +7.5 ft shore. Subsequent shoreline deposits are darkened at the surface with organic matter and are leached of carbonate, but typical pedologic horizons are absent: the textural changes that do occur in places were formed when the parent sediments were deposited.

The +4.5 ft beaches rest in many localities on Lake Wellington sands. This stage of high water is represented widely on the shores of the Gippsland Lakes, and is commonly recorded by stranded lagoon sediments, particularly on the ocean barrier. A subsequent low water level is implied by erosion of 4.5 ft landforms at the open coast before deposition of foredunes recording the younger +3.0 ft high level. No deposits related to this low stand have been identified however.

The beach ridges formed since the +3.0 ft level give evidence for a general fall of the water surface to the present position. However, the occurrence in this fall of a small fluctuation is shown by partial submergence of some ridges and, finally, development of ridges implying a mean water level 1 ft above the present. At the sea coast this slight positive stand is identified with an erosional discontinuity in the foredune sequence.

In summary, the landforms and sediments adjacent to the Gippsland Lakes imply that the sea attained its present level perhaps several thousand years ago and since then has fluctuated about its present position. The record resembles that obtained by Schofield (1960) for the Firth of Thames in New Zealand, but is markedly different to results in other thoroughly studied localities for instance in Florida (Scholl and Stuiver, 1967; Scholl, Craighead and Stuiver, 1969) and The Netherlands (Jelgersma, 1966).

Chronology and correlation

No materials suited to radiocarbon analysis were found in any of the beach ridges, except the very youngest, and the few radiocarbon ages presently available in the area reported (Gill, 1966, 1970) cannot be confidently identified with particular shorelines. They show that the sea reached near its present level about 6,000 years ago, however, and indicate that the 4.5 ft level at Seaspray is younger than 4,510 ± 80 years B.P. Other ages reported from the Victorian coast indicate that sea level stood above its present position 6,000 years ago. At Warrnambool (Gill, 1967) a high stand of this age was followed by a withdrawal, proven by subaerial volcanic deposits from Tower Hill. These deposits were subsequently eroded by a high sea, dated between 3,750 and 5,000 years B.P. and thus shown to be contemporary with the Osborne high sea level in south-east South Australia (Blackburn, 1966).

The two episodes of wind erosion at times of low sea level apparently have analogues in King and Flinders islands, Bass Strait (Dimmock, 1957; Jennings, 1959, 1961), and in Tasmania (Nicolls, 1958, 1960). The oldest has the same field relations as the calcareous seif dunes of Yorke Peninsula, South Australia (Ward and Jessup, 1965; Jessup, 1968), which might therefore be correlatives. Climatic changes of widespread effect are implied, and support is given Galloway's (1965) view that the last glacial period in southern Australia was cold, arid, and windy. Galloway suggests that the immense system of longitudinal dunes across the heart of the Australian continent developed at this time.

Further afield, but at nearly the same latitude and in a similar climatic zone on the opposite shore of the Tasman Sea, four periods of sand dune formation are recognized by Cowie (1963, 1968) on the Manawatu coast of New Zealand, 1,500 miles east of Gippsland and similarly situated with respect to the prevailing westerly winds. The two youngest, named Waitarere and Motuiti, are believed to follow destruction of vegetation consequent on human occupation. The origin of the next oldest (Foxton) is unknown but relationships with dated volcanic ash beds indicate that these dunes developed about 2,000 to 4,000 years ago, in postglacial time (Cowie, 1963). The oldest sands (Koputaroa) are interbedded with the volcanic Aokautere ash which also occurs elsewhere as a bed within loess derived from floodplains formed during the last glacial age (Cowie, 1964a, b). Although Cowie does not report relationships of dunes and former sea levels, the Manawatu and Gippsland dune sand sequences appear to be similar, and provisional correlation of the Foxton dunes with Lake Wellington sands, and of the Koputaroa dunes with Rotamah sands is encouraged. The first pairing implies an age of 2,000 to 4,000 years for the Lake Wellington sediments. Vucetich and Pullar (1969) estimate Aokautere ash from radiocarbon datings to be about 20,000 years old, a time of near-maximum glacial extension (Suggate, 1965; Powers, 1970) that is also consistent with present late-glacial estimates for Rotamah sands.

Identification of Foxton dunes with Lake Wellington sands suggests that the +7.5 ft shoreline in Gippsland was formed 4,000 years ago, or even earlier. The shoreline can be identified with any of the dated materials in East Gippsland, therefore, and with either of the postglacial sea levels recognized at Warrnambool. However, the presence at Warrnambool of two distinct sea levels prevents exact identification. In terms of elevation this does not seem important because both of the shorelines in question, according to Gill's observations (1967), appear to have reached similar heights. It is therefore reasonable to conclude that the Lake Wellington sands mark a low sea level that followed a high stand which reached to +7.5 ft about 4,000 to 5,000 years ago. As the Gippsland record attests, a high level of +4.5 ft occurred soon afterwards.

The close similarity of these particular high and low sea levels to the sequence reported from the western coast of the Firth of Thames, New Zealand (Schofield, 1960, 1964, p. 365) supports the view that the stranded Gippsland shores record real changes in ocean level. This conclusion remains unchanged even when allowance is made for the slow epeirogenetic movements implied by the flights of elevated Pleistocene shorelines that occur in Gippsland (Ward, Ross and Colquhoun, 1971). Present observations therefore support without equivocation the "theory of an oscillating sea level after 6,000 B.P." (Jelgersma, 1966).

EFFECTS OF EARTH MOVEMENTS ON POSTGLACIAL SHORELINES

Studies of postglacial shores in different parts of the world provide three contradictory views of the history of postglacial sea-level change, namely (1) that the sea since the last glaciation has risen steadily to its present level, (2) that the sea gained its present level several thousand years ago and has subsequently remained very near that position, and (3) that the sea, since reaching its present position several thousand years ago, has experienced a number of large changes above and below the present position. These contrasting views, admirably summarised by Jelgersma (1966), have generated considerable discussion and no little heat. But the different opinions have each been promoted by different relationships observed in the field and are each well founded in fact, as the vigour of the debate would confirm, and thus a choice is not necessary between different schools of thought. Reflection suggests that if sufficient allowance is made for earth movements, as is proposed for Pleistocene shores (W a r d, R o s s, and C o l q u h o u n, 1971), major disagreements may be resolved.

Problems of postglacial correlation differ of course from questions of pleistocene succession because a practical radiometric method of age analysis is available. Radiocarbon determinations will ultimately resolve many present disputes. Nevertheless, it is believed that no useful purpose will be served by waiting now for further datings, for it is a common plaint that there are never enough analyses. For postglacial times sufficient observations are available for conjecture. Hypotheses based on present data may indeed inspire more critical work, and this is sufficient justification.

The heights apparently reached by the sea at particular times in different localities may be regarded as consisting principally of two parts, one representing the actual elevation of the past sea level relative to a chosen datum, e.g. present mean sea level, and the other the amount of land uplift or depression since experienced at the locality of measurement. If for practical purposes earth movements can be regarded as regular and continuing, shoreline elevations in different localities may be related by the model

$$Hx = Hy + kT \tag{1}$$

where Hx = observed level in locality 1; Hy = observed level in locality 2; k = rate of relative movement; T = age of sea level. Given values for any three variables, the fourth may be estimated. This model and its derivatives require no knowledge of the true position of sea level at time T. A simpler model that accepts former departures of sea level from the present as an unstated error is useful where rates of earth movement are high:

$$H = k'T \tag{2}$$

where H = observed height; k' = rate of movement, and T has the same meaning as before. This model may be used to estimate, for instance, the ages of several shorelines in a single locality where only one or a few shores are dated by radiometry.

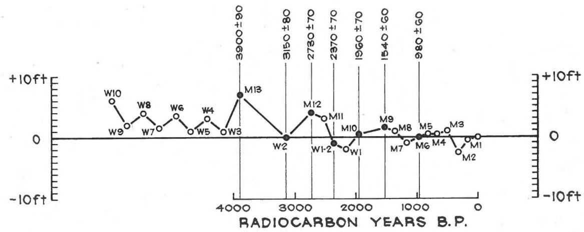

Fig. 2
Postglacial sea-level movements indicated by beach ridges, Firth of Thames, New Zealand (corrected data from S c h o f i e l d, 1960, 1964). Filled circles are levels dated by radiocarbon. Undated ridges (open circles) are plotted according to sequence of development; a uniform spacing relative to dated points is adopted. M and W indicate ridges observed on Miranda and Whakatiwai traverses respectively. Whakatiwai levels earlier than W2 are not dated but ages older than M13 are accepted for the first-formed at least, otherwise too little time is available for development of the Whakatiwai sequence.

Comparison of the Firth of Thames record with other elevated shoreline sequences

Comparison of the Firth of Thames record with the surveyed beach ridge sequence at Poverty Bay, New Zealand (P u l l a r and W a r r e n, 1968), using model 1, $Hx = Hy + kT$, is encouraged by the presence at Poverty Bay of well-dated volcanic ash beds which define the ages of several shores. The measured section at Poverty Bay (P u l l a r and W a r r e n, 1968, fig. 2) displays an apparent discontinuous fall of sea level from a height of about 25 ft attained since deposition of Waiohau ash about 11,250 B.P. Ash beds are indicated below the present 10 ft level at the Taruheru River, implying that the sea was below this level when the shore was in this position near the time of deposition of Waimihia Lapilli (3,400 ± 70 years B.P.). However, shell beds and logs cast up by the sea show that sea level was at the 10 ft level before deposition of the last of the members of Taupo subgroup around 2,800 B.P. This evident fluctuation parallels the shoreline trend at this time in the Firth of Thames (fig. 2) and suggests correlation of the +10 ft level at Poverty Bay with the twelfth shore of the Miranda traverse at +4 ft in the Firth of Thames. Emerged shell beds related to former high water mark indicate that mean sea level was near the present 2.5 ft level at Poverty Bay at deposition of Taupo Pumice (ca. 1800 B.P.). This level is in reasonable agreement with the elevation of sea-rafted

TABLE I
Dated sea levels identified at Poverty Bay and levels predicted for Poverty Bay from Firth of Thames data. $k = 2.20$ ft per thousand years. Elevations in feet.

Firth of Thames					Observed levels, Poverty Bay		
Measured level Shore	Height	Measured age	kT	Calculated equivalent level Poverty Bay	Estimated Height	Age Range, (years B.P.)	Ridge Group
					20-25	11,250-3,400	1
M13	7[1)]	3,900	9	16	19		
W2	0	3,150	7	7			
M12	4[1,2)]	2,730	6	10	10[1,2)]	3,400-ca.2,800	2
W1/2	−1	2,370	5	4	10, falling to 2.5	ca.2,800-ca.1,820	3
M10	.5	1,960	4.5	5			
M9	1.5[1)]	1,540	3.5	5	4	ca.1,820-ca.930	4
M6	0	980	2	2	3	ca.930-ca.300	5
					0	ca.300-0	6

[1)]Transgressive maxima.
[2)]These high stands are presumed equivalent as a basis for calculation according to the model $Hx = Hy + kT$, x – Poverty Bay, y – Firth of Thames.

Taupo Pumice boulders observed in the beach ridge sequence.

Estimates by the present author of other sea levels suggested by the Poverty Bay section are 19 ft, beneath Waimihia Lapilli 2 miles from the 1956 coast, and 20-25 ft further inland. These levels in shoreline Group 1 are implied by shell beds. Former levels of 0, 3, and 4 ft respectively seem indicated by mean elevations for ridges in Group 6 (0-300 years B.P.), 5 (300-930 years B.P.) and 4 (930-1,820 years B.P.).

These approximations relative to the Poverty Bay datum are compared in table I with elevations predicted for Poverty Bay from the dated Firth of Thames levels. The rate of relative movement is decided by accepting the Poverty Bay +10 ft level of 2,800 to 3,400 years B.P. as equal to the Firth of Thames +4 ft level, which has a radiocarbon age of 2,730 ± 70 years.

The predictions agree quite well with observations. It may therefore be concluded that the Poverty Bay record is in satisfactory accord with the sealevel trace determined by Schofield for the period since 4,000 years B.P. The differences in elevation are satisfactorily accounted for if long-continued uplift at a mean rate of 2.25 ft per thousand years is assumed. On this basis eruption of Taupo Pumice occurred at a time of low sea level, as Wellman (1962), Schofield (1967a), and Pullar (1968) believe on the basis of other data. The observations at Poverty Bay also provide evidence for an early high sea level that is reasonably correlated with the innermost ridges of Schofield's (1960) Whakatiwai traverse. Estimated ages based on model 1 range from 6,000 to 8,500 years B.P., suggesting that these beaches are contemporary with the earliest high sea level recorded in East Gippsland by radiocarbon dates and demonstrated at Warrnambool, Victoria, by the Pertobe Coquina (Gill, 1967).

Development of a beach ridge on a coast undergoing upheaval suggests a rate of sea-level rise equal to or greater than the rate of uplift. In both cases these are transgressive shores although in the field the former appears as a stillstand. It is reasonable to expect a relationship between the transgressive peaks evident in the Gippsland, Firth of Thames, and Poverty Bay data, therefore, and the elevated postglacial shorelines beside the river Forth in Scotland (Smith, 1968).

Differences in level of the carse clay lands between Aberfoyle and Kincardine record four shores, sloping very gently to the east, that were developed during the upheaval that resulted from removal of glacial ice from Scotland. Linear regressions fitted by Smith, (1968) to height measurements relate topographic surfaces and define shoreline elevation and slope. In

TABLE II

Estimated ages of displaced shorelines, River Forth. Data in columns 1-6 from Smith (1968). Y = shoreline elevation (ft); X = distance east of origin (km); b = slope of regression. Column 3 gives standard error of estimate of Y.

Shore-line (1)	No. of Points (2)	Standard Error of Estimate (3)	Standard Error of b (4)	Regression Equation (5)	Slope ft/ml (6)	Ages from radio-carbon analysis and pollen zonation	Estimated altimetric ages, B.P. Model 1	Model 2
PG1	50	0.8877	0.0165	Y = 50.06-0.2734X	0.4400	5,492-8,421	4,400-6,900	4,200-6,700
PG2	81	0.9200	0.0167	Y = 46.15-0.2344X	0.3772	3,020-4,925	3,800-5,900	3,900-6,200
PG3	56	0.6375	0.0496	Y = 35.99-0.1551X	0.2496		2,500-3,900	3,100-4,800
PG4	29	0.8239	0.1285	Y = 24.27-0.0418X	0.0673		700-1,100	2,100-3,300

other words, the regression equations describe shoreline elevations at all points near the river Forth and can therefore be used to obtain shoreline heights at two arbitrarily selected localities, x and y, for analysis by the model $Hx = Hy + kT$. Pollen analyses supplemented by a few radiocarbon dates suggest an age between 8,421 years and 5,492 years B.P. for the oldest shore, PG1. The next younger shore (PG2) is identified with pollen zone VIIb, dated between 4,925 and 3,020 years B.P. by Godwin (1960). These ages provide two measures of limiting values for k. Maximum and minimum ages or "altimetric ages" (Ward, Ross, and Colquhoun, 1971) based on these limiting values are given in table II. Mean values for greatest and least k are adopted. The observed age data and the calculations appear to confirm transgressive maxima at the times of high sea level recognised by Schofield (1960) and Gill (1967). Correlation of PG1 with the early Warrnambool shore is favoured, and of PG2 with Miranda 13 and the Gippsland +7.5 ft level. These identifications and the estimated ages suggest matching of PG3 with Miranda 12 but the calculated ages are not in good agreement. The lack of agreement in the age estimates for PG4 prevents correlation of this level and probably reflects the uncertainty of the regression, shown by the large standard error.

A sequence of three stranded shorelines recognized at Guam, Mariana Islands, allows another comparison with the Firth of Thames. The two highest postglacial levels at Guam are recorded by stranded coral platforms and shoreline notches 10 and 6 ft above present reef level (or 9 and 5 ft, respectively, above mean sea level) and a third "2-foot stand of the sea appears to be represented . . . by numerous truncated hummocks of reef rock slightly elevated above the general reef surface" (Tracey et al., 1964). Two radiocarbon dates, of 3,400 ± 250 years B.P. (Tracey et al., op. cit.) and 2,880 ± 110 years (Curray et al., 1970), provide ages for the 5 ft level. These

TABLE III

High sea levels identified at Guam and levels predicted for Guam from Firth of Thames data. k = .366 ft per thousand years. Elevations in feet.

Firth of Thames: Measured level – Shore	Height	Measured age	kT	Calculated equivalent level Guam	Observed levels, Guam: Height	Measured age (years B.P.)
W10	6	6,000[1]	2.2	8.2		
M13	7	3,900	1.4	8.4	9	
M12	4[2]	2,730	1	5	5[2]	3,400; 2,880
M9	1.5	1,540	.6	2.1	2	
M3	1	<980	.4	1.4		

[1] Age suggested by comparison of Firth of Thames with Poverty Bay.

[2] These high stands are presumed equivalent as a basis for calculation according to the model $Hx = Hy + kT$, x – Guam, y – Firth of Thames.

suggest equivalence of the 5 ft shoreline with M12, and levels predicted on this basis for Guam from the measured ages and elevations for other transgressive shores in the Firth of Thames are given in table III. The predictions are confirmed by observation and imply equivalence of the shores examined. If W10 is about 6,000 years old, as comparison with Poverty Bay and East Gippsland suggests, the 9 ft level observed at Guam may have been occupied twice by the sea.

Comparison with submergence curves

The evidence for a fluctuating sea level in post-glacial time in the areas noted above seems thoroughly contradicted by studies in many other localities. The Everglades coast of Florida, for instance, gives persuasive evidence and a wealth of radiometric data for a "more or less steady submergence" (Scholl and Stuiver, 1967) that has proceeded uninterruptedly from at least mid-Holocene times to the present. The observations are not so complete, however, that an absence of low-amplitude fluctuations can be affirmed.

Records of such marked contrast are simply explained by supposing regular earth movements to occur throughout the period of sea-level change. On coasts subject to slow upheaval high and low levels produced by moderate eustatic fluctuations are emphasized as the rate of change of water level alternately exceeds and is surpassed by the rate of uplift. On subsiding coasts peaks and troughs are suppressed, and the record shows a steadily rising water level varied only by changes in rate of transgression. Similarly, continuous but irregular sea-level fall is shown where rates of uplift are very high, as in Scandinavia (Schofield, 1964, fig. 1; compare Mörner, 1969a, b; Selli, 1962). Because evidence of the positions attained during low sea level on upheaved coasts is commonly effaced or hidden during subsequent rises of water level, observations of the trend of mean sea level there are not perfectly comparable with those from coasts subject to relative depression. For practical purposes this provision may be inconsequential and is neglected in the following comparison of the Florida submergence curve of Scholl, Craighead, and Stuiver (1969) with the Firth of Thames record of Schofield. The comparison uses model 1 to predict equivalents in Florida of the dated sea levels of the Schofield

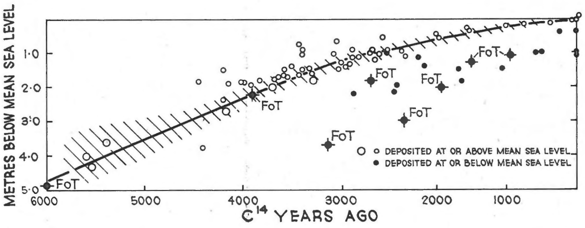

Fig. 3
Dated sea levels identified in the Firth of Thames (FoT) shown in relation to the submergence curve (full line) and supporting data for south Florida (after Scholl, Craighead and Stuiver, 1969).

curve. The relative rate of movement, k, is decided by setting the high sea level of Miranda 13 equal to the contemporary level, –2.25 metres, shown by the submergence curve for south Florida. For complete coverage the innermost Whakatiwai shore is given the age of 6,000 years suggested by comparison of the Firth of Thames with Poverty Bay, and the sea level in Florida at this time is decided by short extrapolation of the submergence curve. The results of the calculations are best expressed graphically and are shown in fig. 3, which reproduces the Florida curve and

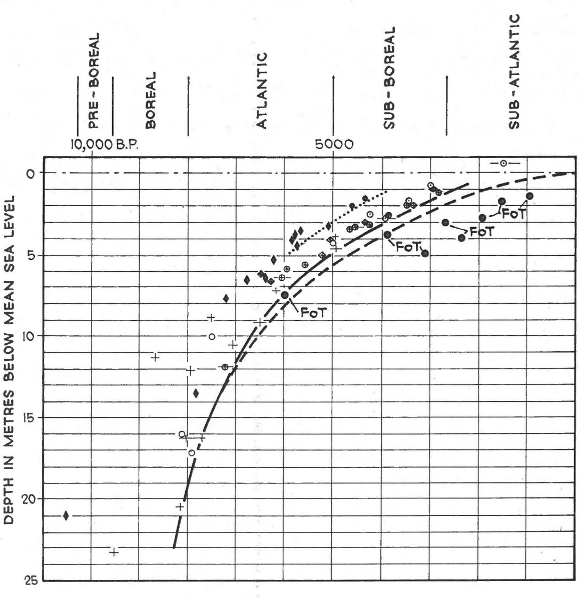

Fig. 4
Dated sea levels identified in the Firth of Thames (FoT) shown in relation to curves of relative changes in sea level in The Netherlands (after Jelgersma, 1966). The broken line shows former positions of mean sea level.

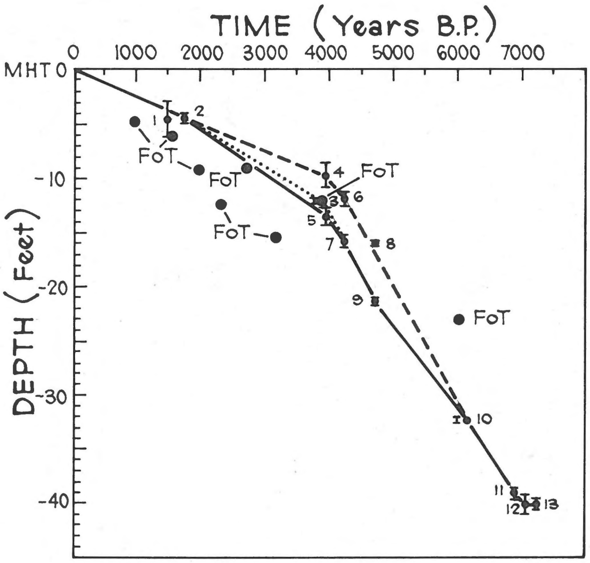

Fig. 5
Dated sea levels identified in the Firth of Thames (FoT) shown in relation to apparent changes of sea level in south-central Louisiana (after C o l e m a n and S m i t h, 1964). The solid line connects points of greatest depth for each known date; the broken line connects points of least depth. The dotted line is drawn through the points with smallest range in depth.

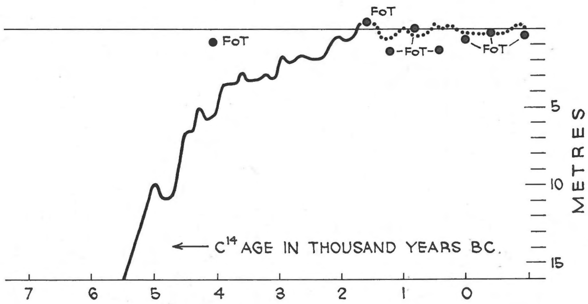

Fig. 6
Dated sea levels identified in the Firth of Thames (FoT) shown in relation to eustatic sea-level trace indicated by displaced shorelines of the Kattegat (after M ö r n e r, 1969a, b). k is determined by correlation (M ö r n e r, 1969b) of M13 with PTM-7; the dotted curve since 1,000 B.C. is suggested by preliminary examination of localities not yet closely investigated.

its supporting data.

The predicted levels lie generally below the submergence curve. Nevertheless they do not conflict in any significant way with the data for Florida. The plotted points for the Firth of Thames lie below points representing materials deposited at or above mean sea level in Florida and among or above those signifying materials deposited at or below sea level. Inasmuch as the observations are compatible, Schofield's sea-level curve is implicit in the Florida data, contrary to present opinion (S c h o l l and S t u i v e r, 1967). Calculations confirm that the submergence curve predicts as expected the general form of the Firth of Thames record. Similar results attend comparison of the Firth of Thames with The Netherlands (J e l g e r s m a, 1966), fig. 4, the Louisiana coast (C o l e m a n and S m i t h, 1964), fig. 5, and the Kattegatt Sea (M ö r n e r, 1969a, b), fig. 6. None of the Firth of Thames levels since 4,000 B.P. lies above the Coleman and Smith curve. Thus their view that sea level did not rise above its present position since 3,650 B.P. [their argument accepted] is not contradicted. For purposes of calculation, k is taken to be defined in these comparisons, as before, by the apparent differences in sea level at 3,900 B.P. when Miranda 13 was formed.

The several theses concerning the history of the postglacial sea-level rise are therefore reconciled if the occurrence of earth movements is accepted and given adequate recognition when the data from different localities are compared.

The positions shown for the Firth of Thames shores in figures 3-6 would be different, to a degree, and perhaps "improved" if other correlations were used to define k. However, further processing of the data would best await more critical study of the sea-level trace.

Conclusions summarised graphically

Present observations in different localities are shown in graphical form in fig. 7. This relates the various areas examined, and the following areas which are not discussed separately – Virginia, New Jersey, and Cape Cod (data from N e w m a n and R u s n a k, 1965), and Truk, Ponape and Kusaie (eastern Caroline Islands, B l o o m, 1970), to the transgressive shoreline sequence identified by S c h o f i e l d (1960). Shoreline height, calculated from $Hx = Hy + kT$ using the Firth of Thames height and age measurements, is plotted against various rates of uplift and depression relative to the Firth of Thames. An age of 6,000 years is accepted for W10. The peak

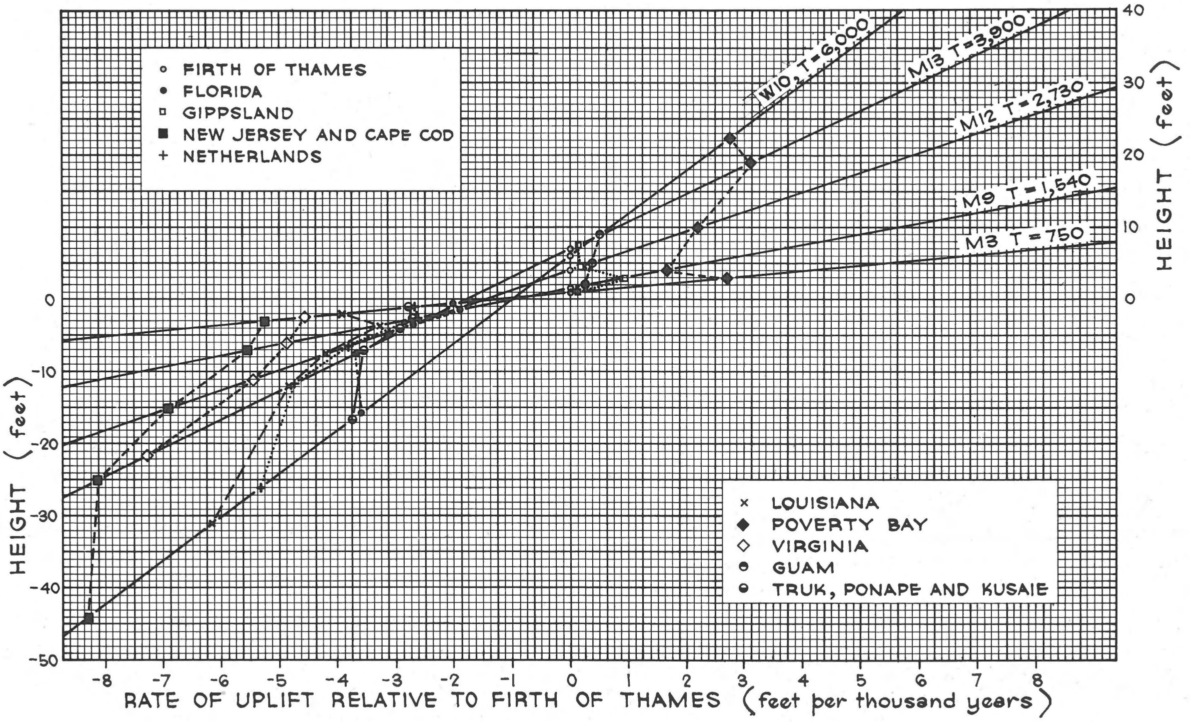

Fig. 7
Calculated positions of high shorelines observed in the Firth of Thames, allowing various rates of uplift ranging from $k = -8.5$ ft to $k = +8.5$ ft per thousand years relative to Firth of Thames datum. Ages for M9, M12, and M13 are given by radiocarbon analysis. The ages of M3 and W10 are estimated (see text). The plotted data points for other localities show the observed positions of sea level at these times.

of the last transgression in the Firth of Thames is younger than 980 years and is arbitrarily given an age of 750 years for purposes of calculation. Equivalent levels in other localities are identified from observed transgressive maxima in areas of relative uplift. For areas of relative subsidence the position of sea level shown by the submergence curves at the times indicated is accepted as best estimate. If rates of uplift were constant, and the data free of error, sea-level positions for each locality in fig. 7 would fall on a vertical line. The fact that higher rates of uplift are systematically implied by the elevations of older shorelines in all localities is evidence of a disturbing factor which in this case seems related to the disparity between years as measured by radiocarbon, and true sidereal time (Stuiver and Suess, 1966). Adjustment according to the formula given by Scholl, Craighead, and Stuiver (1969) produces the results given in fig. 8: the rates of uplift are more consistent. It is reasonable to conclude that the variations in k shown for each locality in fig. 8 result from errors in shoreline height estimation, especially in areas of relative subsidence where the mean curve may be a poor approximation; from imperfections in the formula relating radiocarbon years to sidereal time; from inexact dating; and from real variations in rates of earth movement. Indeed, the model appears to fit the existing data very well, when allowance is made for these obvious sources of error.

Further support seems given these correlations by observations from the chenier plain of south-western Louisiana (Gould and McFarlan, 1959), where relict shelly beaches and coastal marshes record an apparent stillstand since 3,000 B.P. In terms of the thesis presented here, any earth movements affecting the chenier plain have been balanced by long-term changes in sea level in this last interval of postglacial time. Ideally, any small changes of level that may be shown by field evidence in the short-term would be eustatic therefore, rather than tectonic in origin. Interpretation of the varied changes in position of the

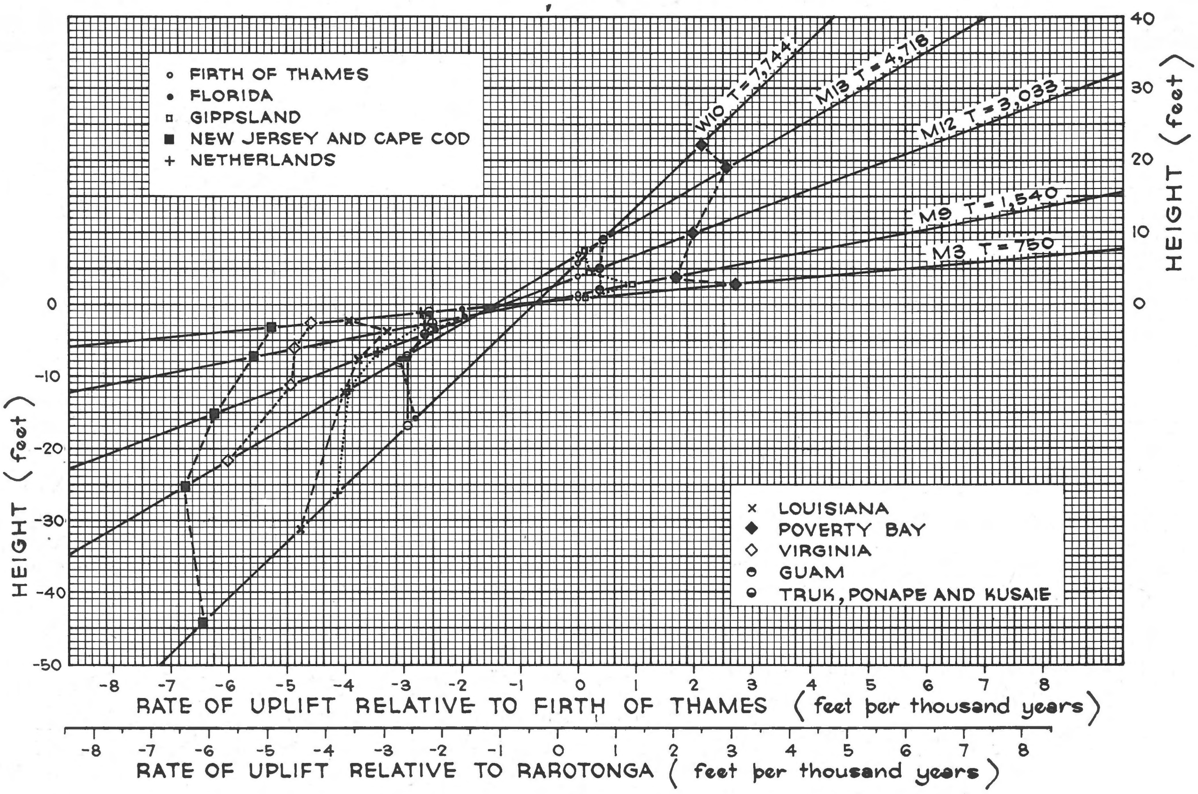

Fig. 8
Calculated positions of high shorelines observed in the Firth of Thames as for figure 7, except that radiocarbon ages were first converted to sidereal time. The observations agree reasonably well with a linear model.

shore is complicated, unfortunately, by possible compaction of marsh sediments, by the proximity of the Mississippi River, a major sediment source, and by the incidence of hurricanes, which frequently cause the chenier plain to be flooded by the sea.

Gould and McFarlan, following Fisk (1948), associate the changes in shoreline with changes in position of the distributaries of the Mississippi River. However, the coincidence in time of the major transgressive shorelines (Gould and McFarlan, 1959, plates 2 and 3), High Island-Little Chenier-Little Pecan Island Chenier (2,800 years B.P.), Oak Grove-Grand Chenier (1,600[2] years), and questionably the "modern" beach (650 years), with the latest high levels of the Firth of Thames strongly suggests a eustatic explanation. A similar coincidence marks the ages of high sea-level stages observed elsewhere. Thus ages equivalent to M12 and M9 are reported from Cat Island, Bahamas (Lind, 1969). In the Caroline and Marshall Islands radiocarbon ages of beach conglomerates form two separate groups ranging from 3,450 to 4,475 years B.P. and 2,500 to 3,000 B.P.: these ages, reported and discussed at length by Curray, Shepard, and Veeh (1970), suggest a relationship with M13 and M12. However, in reference to this area, Curray, Bloom, et al. (1968; see also Shepard et al., 1967) observe that "high sea-level stands suggested for about 2,800 B.P. for a few other localities of the world do not appear necessary here nor even compatible with our observations."

[2] 1,100 years of Gould and McFarlan. The younger dates are shown for the younger parts of these transgressive cheniers.

POSTGLACIAL UPLIFT AT CAPE TURAKIRAE, NEW ZEALAND

The absence of any real conflict in the postglacial records noted above favours recognition of the five episodes of high sea level shown in the Firth of

TABLE IV
Altimetric ages for beach ridges, Cape Turakirae.[1)]

Beach Ridge	Altimetric Age years B.P. Range	Mean	Radiocarbon Ages Eustatic Highs, Firth of Thames
A, modern ridge	–	–	
B, elevated in 1855	385-669	460	<980
C, ⩽1,800 B.P.	[set equal to 1,540]		1,540
D	2,577-3,068	2,822	2,730
E	3,174-3,984	3,551	3,900
F	4,327-4,407	4,366	6,000[2)]

[1)] The localities used for age estimation are those determined by the grid lines east of grid line 45 and points midway between them (see Wellman 1967, fig. 3).

[2)] Age suggested by comparison of Firth of Thames with Poverty Bay.

Thames as real eustatic events. Comparison with the five tilted postglacial shores described at Cape Turakirae, New Zealand, by W e l l m a n (1967) is therefore encouraged. Wellman reasons that the oldest beach at Cape Turakirae has an age of about 6,500 years B.P., and proposes that development of each of the beaches was terminated by sudden, catastrophic upheaval, as occurred with the youngest beach, raised beyond wave limit during a severe earthquake in 1855. The amount of each upheaval, he notes, appears to be "closely proportional to the length of time from the previous to the following uplift". These views notwithstanding, the Cape Turakirae shorelines seem to provide data that might be appropriately analysed by use of the model $H = k'T$, because the great elevations reached by the former shores (ca. 25 metres for the earliest) are proof of high rates of uplift. Shoreline height is therefore very largely a function of time. Although a shift in the axis of tilt occurred during development of the beach ridges, this happened so recently that its effects can be ignored.

A basis for age estimation is given by the observation that the third beach ridge, C, is the oldest that contains Taupo Pumice, erupted ca. 1,800 years B.P. If this ridge is accepted as equivalent to the stage of high sea level dated at 1,540 B.P. by Schofield, the ages in table IV result from calculation.

Because radiocarbon and sidereal years are equivalent for the period from the present to ca. 2,000 B.P., but not beyond that date, the calculations based

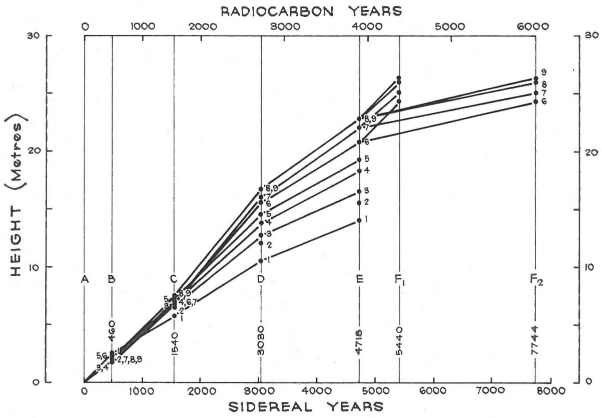

Fig. 9
Shoreline height for nine localities (1-9) at Cape Turakirae, New Zealand, plotted against shoreline age. Six shorelines (A-F) are recognized. F1 and F2 indicate alternative ages for shoreline F.

on 1,540 years give figures that should be compared with sidereal ages for older shorelines. For convenience the results are expressed in radiocarbon years in the table.

The calculated altimetric ages strongly imply that beach ridges D and E are in fact contemporary with the high eustatic levels indicated for the Firth of Thames. This suggests that F might record the earliest postglacial eustatic high, but the altimetric age is

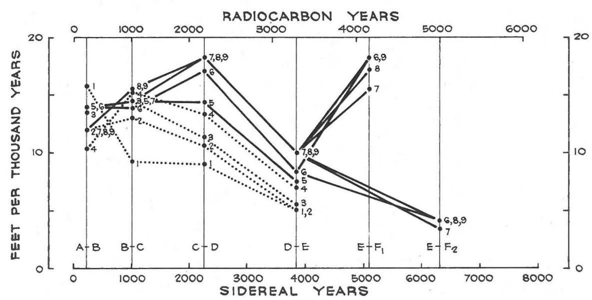

Fig. 10
Rates of uplift for nine localities (1-9) at Cape Turakirae, New Zealand, shown by dated shorelines. The observed rates are plotted at the midpoints of time intervals defined by successive beach ridges (A-F). E-F1 and E-F2 are alternatives depending on whether F has an age of 4,400 or 6,000 radiocarbon years. Western localities (1-4, broken lines) now have rates of uplift as great as eastern localities, (5-9, full lines).

much too low: either the correlation is unreal, and F is evidence for a separate stand of sea level about 4,400 years ago, or the rate of uplift is not regular. Graphs of height against time showing the two alternative explanations provide no basis for eliminating either (fig. 9). However, an examination of rates of uplift (fig. 10) suggests that equivalence of F with the ca. 6,000 year high stand is the better interpretation.

Identification of the Cape Turakirae tilted shores with eustatic high stands of sea level places emphasis on regular continuation of uplift in this area. Regularity in the long term can of course be accomplished by irregular short-term movements. It is probable that these were more frequent and of smaller amplitude than Wellman envisages, but it is unlikely that they were less catastrophic.

Given the validity of the present conclusions, the rates of uplift for the localities examined (feet per thousand years, fig. 10) indicate that the site of most active movement is moving west, in the direction of Wellington city. Uplift at the mouth of the Orongorongo River is now as rapid as rates that have prevailed for some 2,000 years at Cape Turakirae.

SUBMERGED SHORES, NIGER DELTA

The high rates of upheaval at Cape Turakirae are surpassed by rates of subsidence in the Niger delta (Allen and Wells, 1962), where submerged coral banks and thickets give evidence of apparent stillstands of sea level at ca. –20 ft, –120 ft, and –156 ft. Samples recovered from the two deepest banks have radiocarbon ages of 2,920 ± 100 years and 3,885 ± 125 years B.P. respectively. These indicate downward movement at a rate of 40 ft per thousand years (model 2), and thus an altimetric age of 500 years for the youngest thicket. In environments such as this, it is most likely that apparent stillstands indicate falls of sea level at rates comparable with downward land movement. The field observations therefore provide evidence of downward changes in ocean level. It would appear that these changes are those which terminated the high stands shown at 3,900 ± 90, 2,730 ± 70, and since 980 years B.P. in the Firth of Thames; the minor contradictions in the age analyses are satisfactorily accounted for by sampling error and errors inherent in the method.

RAROTONGA – A STABLE COAST?

Uplift at Cape Turakirae and subsidence of the Niger delta are both clearly shown by the field studies. Stable coasts, should they exist, lie between these extremes and they should provide a history of postglacial sea level that is uncomplicated by earth movements. A number of the localities discussed above, including East Gippsland (Ward and Jessup, 1965), have been suggested to be stable by field workers impressed by similarities in coastal stratigraphy and shoreline elevation over wide areas, and by a seeming absence of tectonic activity. Nevertheless, the relationships shown in fig. 8 imply that present evidence is insufficient to decide this question. Studies of Pleistocene shores (Ward, Ross, and Colquhoun, 1971) give reason to believe that Quaternary earth movements have not affected the southern Cook Islands, South Pacific, however. In this group the islands of Aitutaki, Manuae, Atiu, Takutea, Mitiaro and Mauke form a linear volcanic chain that rises from a deep, or moat, attributed to subsidence of the ocean floor; Rarotonga and Mangaia to the west, in contrast, lie at the crest of an arch-like crustal upwarp associated with this deep (Summerhayes, 1967; Hochstein, 1967). Quaternary shorelines are reported at the same levels on the islands of the Aitutaki – Mauke chain and on Rarotonga and Mangaia (Wood, 1967; Schofield, 1967b), and these observations provide clear evidence for no differential movement of deep and arch in Quaternary time. The possibility of uplifts or depression affecting all islands equally cannot be rejected but this seems unlikely in view of the moat and arch structure. It is significant, therefore, that high shorelines of possible postglacial age are identified at Rarotonga (Schofield, 1970). Unfortunately, accurate radiocarbon age analyses are frustrated by partial recrystallization of the samples examined. A minimum age of 2,030 years is provided for the lowest Rarotongan level at 3 ft. Schofield considers this stranded reef equivalent to the 2,730 old shore in the Firth of Thames, and suggests that the higher shore, at 6 ft, represents the 3,900 year old level. No date is yet available for this high bench, but its height correlates satisfactorily with the 3,900 year level, if movement of the Firth of Thames relative to Rarotonga is allowed. The implied rate of uplift for the Firth of Thames is 4 in. per thousand years. Removal of this secular trend from the Firth of

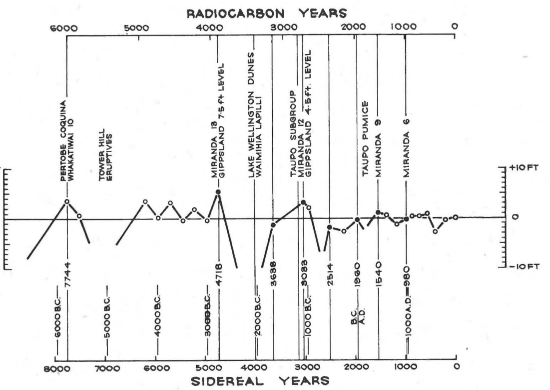

Fig. 11
Sea-level changes since 8,000 B.P. implied by Firth of Thames data, assuming Rarotonga to be stable. The low sea level at 7,000 B.P. is shown by volcanic ash at Warrnambool, Victoria; at 4,000 B.P. by Lake Wellington dune sands, East Gippsland, Victoria; and at 1,820 B.P. by Taupo Pumice, New Zealand. A further low stand after 2,800 B.P. and rapidly falling sea levels (ca. 40 ft per thousand years) at 4,600, 2,800, and ca. 500 B.P. are indicated by development of coral thickets, Niger delta. Filled circles are levels dated by radiocarbon. Undated levels (open circles) are arbitrarily positioned.

Thames data produces the eustatic sea-level trace shown in fig. 11. This eustatic record resembles that indicated by F a i r b r i d g e (1961) on the basis of a preliminary survey, and is comparable in phase, if not in amplitude, with that compiled by B l o c h (1965). It also provides support for F l e m m i n g's (1969) view that sea level in the last 2,000 years was within half a metre of its present position.

The changes shown by the sea-level trace are closely associated with climatic events. The low sea level of ca. 5,000-5,500 years B.P. demonstrated by Tower Hill eruptives at Warrnambool coincides with the widely reported period of glacial advances that terminated the Atlantic warm phase at 5,200 years B.P.; the submerged Neolithic stone circle at Er Lannig, Brittany (G u i l c h e r, 1969) may also give evidence for this interval of low water. Lowering and lowered sea levels attested by the distribution of Waimihia Lapilli at Poverty Bay and by coral thickets in the Niger delta are contemporary with the arid, windy conditions that produced the Lake Wellington sands in Gippsland, and with initiation of periglacial mass movement on Mount Kosciusko (C o s t i n, T h o m, W i m b u s h, and S t u i v e r, 1967). The later regression at 2,600 to 2,800 B.P. coincides with advancing glaciers and lowering timberlines in northern and southern hemispheres (L a m a r c h e and M o o n e y, 1967; P o r t e r and D e n t o n, 1967; M e r c e r, 1968; C u r r y, 1969), and is probably also contemporary with the recent period of deep-sea cooling noted by G r i g g s, K u l m, D u n c a n, and F o w l e r (1970).

Although this review recognizes a common pattern in studies of postglacial shorelines, a need for further critical examination of coastal records is evident. More careful measurements of former sea levels are required, and accurate and comprehensive dates are needed for adequate description of significant sections.

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