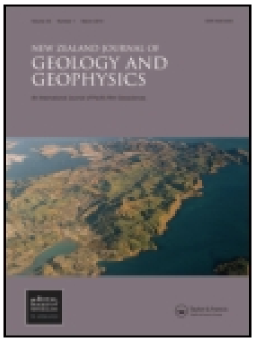

New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: https://www.tandfonline.com/loi/tnzg20

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To cite this article: J. C. Schofield (1960) Sea level fluctuations during the last 4,000 years as recorded by a chenier plain, firth of thames, new zealand, New Zealand Journal of Geology and Geophysics, 3:3, 467-485, DOI: 10.1080/00288306.1960.10422089

To link to this article: https://doi.org/10.1080/00288306.1960.10422089

Published online: 17 Jan 2012.

SEA LEVEL FLUCTUATIONS DURING THE LAST 4,000 YEARS AS RECORDED BY A CHENIER PLAIN, FIRTH OF THAMES, NEW ZEALAND

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(Received for publication, 27 October 1959)

Summary

Constructional and erosional morphologies of beach ridges and intertidal flats of a chenier plain in the Firth of Thames are illustrated and discussed. These are used to determine a sequence of past sea levels.

Radiocarbon ages for seven samples of shell permit the drawing of a reasonably accurate time - sea-level curve which correlates favourably with transgressional periods recorded along the European coast and possibly with changes in the European climate. Neglecting minor fluctuations, sea level fell 7 ft from 2,000 years B.C. to about the beginning of the Christian era and has remained relatively stable since. The sea level minimum recorded during this period is 2 ft below present level. The present rise of sea level is locally 8–9 in. per century and may well be only another minor fluctuation in an otherwise stable sea.

INTRODUCTION

The Quaternary consists of two unequal divisions, the longer Pleistocene and the shorter Holocene which includes the present day. The Holocene sediments have been somewhat neglected but their study and interpretation is important in river control and coastal protection and where reclamation of large tracts of the sea bed is envisaged.

Inseparable from the study of Holocene sediments is the study of constructional landforms. This has been neglected until recently, as geomorphology has been concerned mainly with erosional landscapes. This is understandable, for study of constructional landforms demands a high degree of topographic detail and accuracy in levels. With such information, the older landforms can be interpreted in terms of modern ones and any slight deviations due to crustal deformation or compaction can be determined.

One of the most recently described constructional landforms is the "chenier plain" named by Price (1955) which includes stranded breach ridges called "cheniers" in Louisiana by Russell and Howe (1935). Brouwer (1953) had described a "chenier plain" in detail but gave it no overall name. He also abandoned the local name of "rits" – "a neutral term simply indicating that the ridges rise above the level of the swampy country" – for the English term "spit" and included the Surinam coastal plain in Shephard's (1952) "barrier" group. Price's terminology of chenier plain is adopted as it is suitably descriptive of a geomorphic unit that differs from other coastal plains. His description is as follows (1955, p. 75) "Shallow-based, *perched,* sandy ridges resting on clay . . . along a marshy or swampy, seaward facing, tidal shore, with other beach ridges stranded in the marsh behind, form a belted marsh-and-ridge plain, here called the chenier plain, . . . Cheniers differ from other beach ridges, including those of barrier islands, in that they commonly rest on the marsh clay with their bases near sea level . . . whereas *normal* beach ridges and barriers have deep shorefaces extending from 15 to 55 ft below sea.

The cheniers run parallel with or at small angles to the general shoreline direction. One chenier may truncate others, recording a shoreline revision".

Several factors have combined to make the chenier plain of the Firth of Thames (fig. 1) a fruitful area for study of sea level fluctuations during the

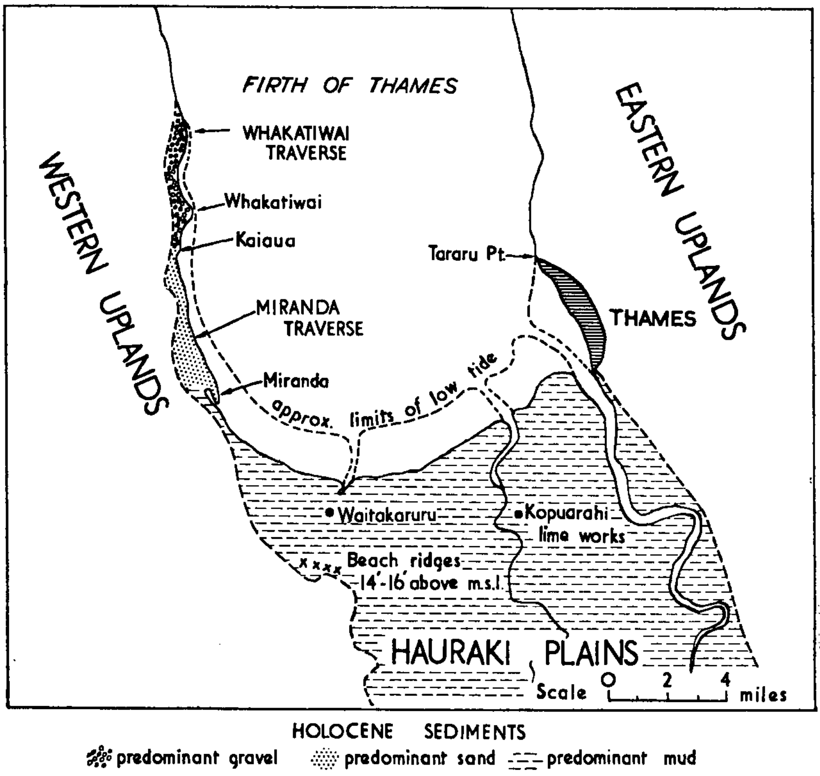

FIG. 1—Locality plan (Firth of Thames lies 35 miles south-east of Auckland, New Zealand). The chenier plain is mainly restricted to coastal strip north of Miranda. Isolated cheniers also exist south of Waitakaruru. The Hauraki Plains, within figure, are stranded estuarine mud flats.

last few thousand years. First, although open to the sea, the length and direction of the Firth of Thames protects the western and southern shores from violent seas and winds. Secondly, the prevailing wind is from the west and thus no covering dunes have been formed. Thirdly, the northern portion of New Zealand has been considered tectonically stable since about the end of the Miocene (Marwick, 1948; Gage, 1953; Eiby, 1955; Schofield, 1958).

GENERAL SETTING

The chenier plain of the western shore of the Firth of Thames commences north of Whakatiwai and continues south to Waitakaruru (fig. 1). Isolated cheniers exist south of Waitakaruru but are better developed north of Miranda. The northernmost sediments are gravels with a sandy and shelly matrix, the gravel becoming progressively smaller southwards before being replaced by a predominance of shell and sand south of Kaiaua. Here too, mud flats, behind the present and between the older cheniers, begin to appear. Further south the modern chenier of shell and sand continues as far as Miranda. South of Miranda the modern shore and most of the prograded sediments of the hinterland consist of mud.

The gravel foreshore slopes steeply down to mud flats exposed at low tide (fig. 2). These flats become wider southwards and their inland edge rises to progressively higher levels in the foreshore sequence until along the southern shore of the Firth of Thames it approaches high water mark.

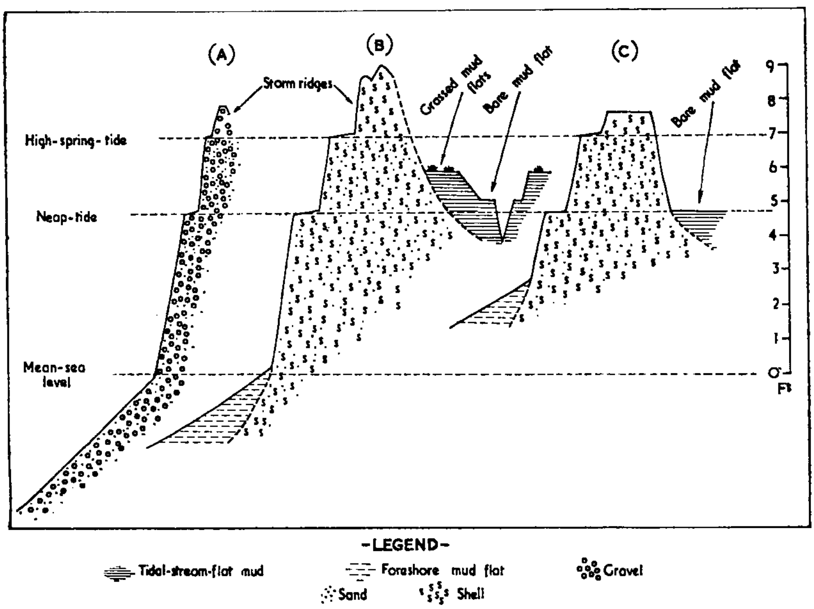

FIG. 2—Diagrammatic cross sections across modern cheniers: (a) gravel beach; (b) shell and sand beach; (c) shell and sand beach at eroded portion of coast line. (Vertical scale is much exaggerated.)

MORPHOLOGY

Broad morphological descriptions and mode of origin of chenier plains are given by Brouwer (1953) and Price (1955) but there are minor morphological details of importance in sea level interpretation present in the Firth of Thames.

These minor morphological details, found on the modern shore and often preserved on stranded cheniers are of two types: (A) constructional details related to high tides and storms; and (B) erosional details related to a rising sea level.

(A) *Constructional Morphology*

Modern foreshore profiles in areas of gravel, and sand with shells are shown in figs. 2 and 3. Their morphology shows that, under favourable conditions, there are three criteria that can be used in interpreting the older cheniers in terms of past sea levels: heights of (a) storm ridges, (b) high-spring-tide wash benches (figs. 3 and 4) and (c) tidal stream flats.

Storm Ridges: The maximum heights of storm ridges formed of gravel average 1 ft above high-spring-tide level. Levels along half a mile of the present storm ridge showed a variation of 8 in. Similar variations of 6 to 9 in. were found on the older gravel ridges, the means of these levels being those recorded in fig. 5. The gravel storm ridge consists of gravel without a sandy matrix. This is termed free gravel to distinguish it from that below containing a sandy matrix.

Storm ridges built of shells, where coastal sediments are principally shell and sand, reach higher levels of 1 ft 6 in. to 2 ft above high-spring-tide level. Like the gravel storm ridges a shelly storm ridge is mainly free of sandy matrix.

These observations agree with storm tide-levels recorded at Tararu Pt which was on the opposite coast of the Firth of Thames (fig. 1). Records between 28 September 1922 and 3 December 1923 show that storm tides at Tararu Pt are normally 1·05 ft higher, but that extraordinary storm tides were 3·55 ft higher than normal high-spring-tide level.

High-spring-tide Wash Benches: The average high-tide level recorded by Tararu Pt gauge was 2·05 ft below high-spring-tide level. Wash benches of the lower high-tides are temporary features whereas high spring-tide is always represented along the present sand and shell foreshore by a distinct bench, 2–4 ft wide.

Except for 2–4 in. of free shell, the sediment below the high-spring-tide wash bench consists of compacted shell or gravel with a matrix of sand.

On gravel foreshores, high-tide wash benches are commonly absent and where present are only a few inches wide.

Tidal-stream Flats: Behind the modern shell and sand chenier, tidal-stream flats consist of bare mud and marshy tracts that rise to levels between 1·75 and 2 ft below high-spring-tide level, i.e. to average high-tide level. (Similar relationships were noticed along the Dutch Coast by van Straaten (1951).) These marshy mud flats pass laterally into grassed mud-flats below which they lie at a lower level of approximately 0·75 ft.

(B) *Erosional Morphologies*

Present Coastal Changes: Some parts of the Thames chenier plain are being eroded. At least one portion, the southern extension of the modern shell chenier near Miranda, is being prograded, whereas other portions may be stationary.

Present-day erosion is shown by shallow cliffing within previously formed cheniers and even within the tidal mud flats where these are unprotected by cheniers. The region of greatest erosion lies half way between Miranda and Kaiaua. Because of erosion the road at this locality had to be shifted

FIG. 3—(a) Shore of shells and sand, east of ridge 7 (fig. 6 (a)) taken at about mean tide. "a" equals slope from current high-tide wash bench ("b") down to mudflats (not exposed). "e" equals high-spring-tide wash bench surmounted by storm ridge ("d"). Both "b" and "c" are delineated by a line of flotsam at inner edges.

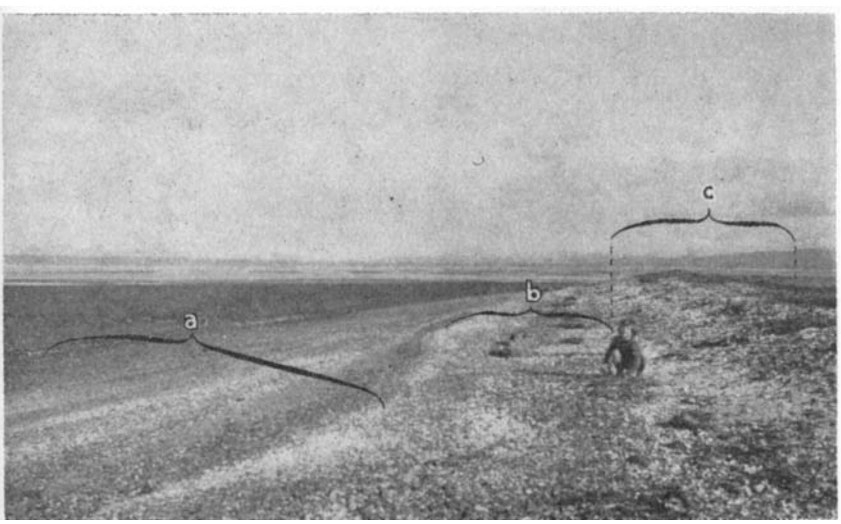

FIG. 3—(b) Shore in gravel, sand and shells just south of mouth to Whakatiwai Stream. Taken at about low tide level. "a" equals slope between low tide flats (locally gravel) and high-spring-tide wash bench ("b"). "c" equals storm ridge.

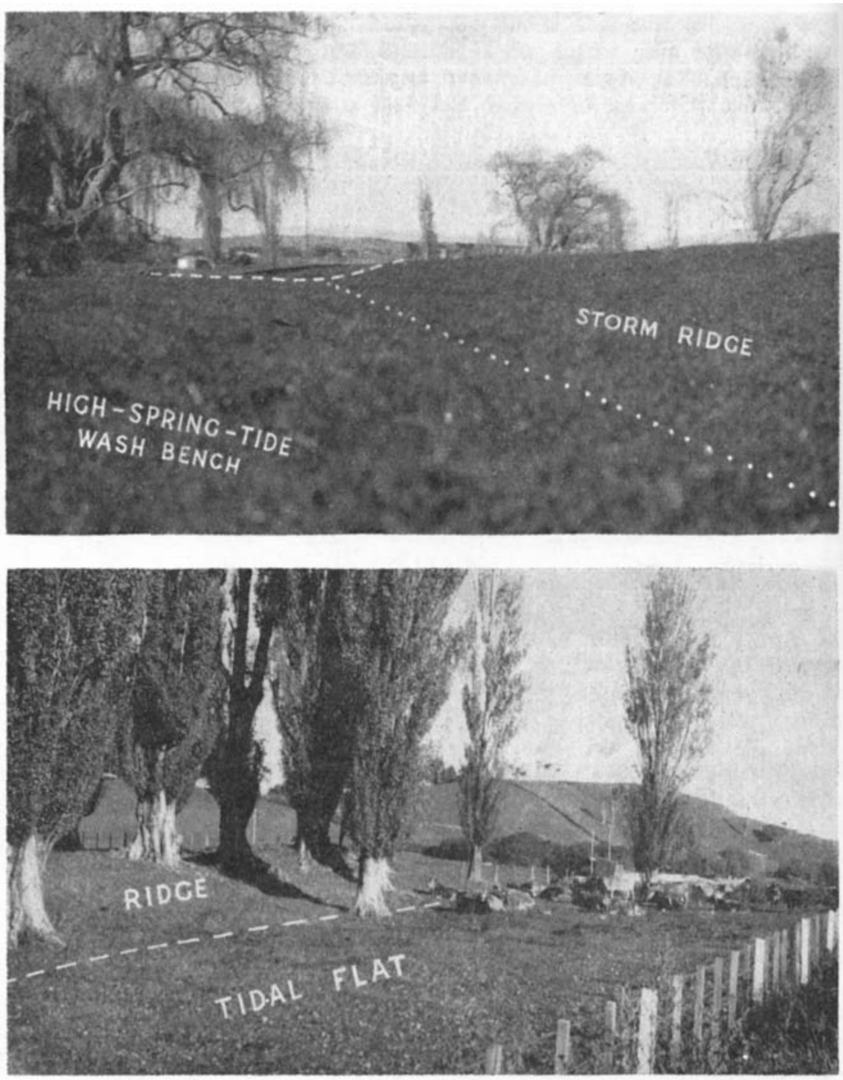

FIG. 4—(a) View south along shell and sand chenier No. 13 (fig. 6 (a)). (b) An isolated shell and sand chenier south of Waitakaruru (fig. 1), principally showing steep foreshore.

inland during 1934. The road is again being eroded and inspection of road construction plans show that over the last 23 years the coast has receded an average of 4 ch. along a stretch 30 ch. long. Now at the same locality, shell beds including some decaying shell fish are accumulating approximately along the earlier 1934 coast line.

Past Coastal Erosion: Truncation of cheniers north of Whakatiwai (fig. 5) show periods of coastal revision at intervals between W8 and W7 and between W4 and W3.*

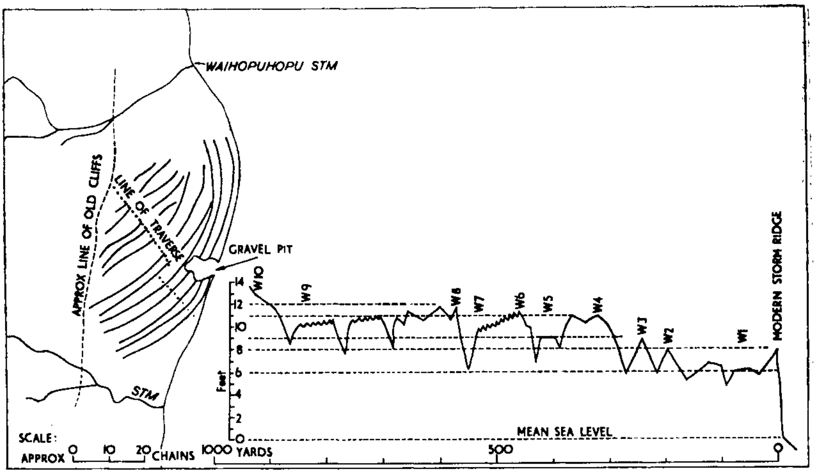

FIG. 5—Distribution of, and section across, gravel cheniers north of Whakatiwai.

From M11 onwards each chenier of the Miranda area is itself a complex of divergent beach ridges (see discussion in next section) but neglecting this fact truncated cheniers are not so marked in the Miranda area. However, the chenier pattern of this area (fig. 6 (a)) shows a possible shore line revision between M12 and M11. Up to the time when M12 was formed the cheniers extended southwards to the cliffed margin of the hinterland. Thereafter conditions appear to have changed; the southern extension of the cheniers failed to reach the hinterland but almost without exception their southern ends extended further southwards as each successive chenier was formed.

CHENIER FORMATION

Brouwer (1953, p. 229) described in broad outlines how the curved ends of the spit-like ridges show that they have been formed by beach drift: "Nothing indicates that the ridges originated as offshore bars and moved landwards only afterwards".

The gravel cheniers of the Firth of Thames are simple ridges parallel to the present coast. They also parallel each other except for those formed during two periods of erosion that coincided with maximum sea-transgressions (similar relationships are also noted by Brouwer). On the other hand most of the shell and sand cheniers are a complex of a number of smaller ridges. Each has a steep foreshore slope that faces its full length (fig. 4b) but land-

*M1, etc., W1, etc., refer to stations on Miranda Traverse and Whakatiwai Traverse respectively.

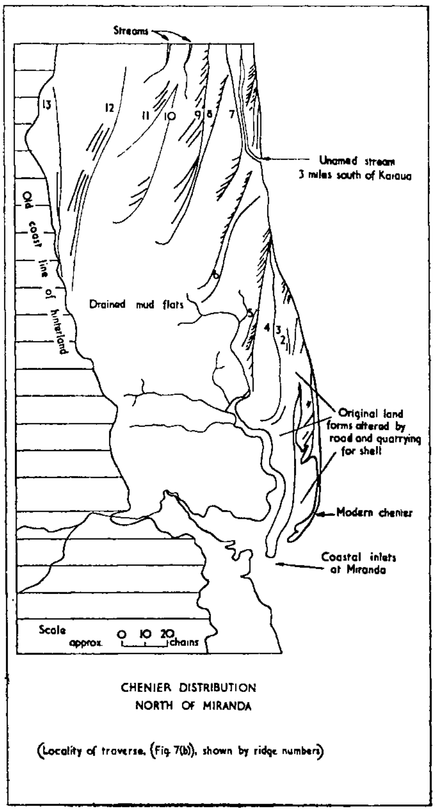

FIG. 6 (a)—Distribution of shell and sand cheniers north of Miranda.

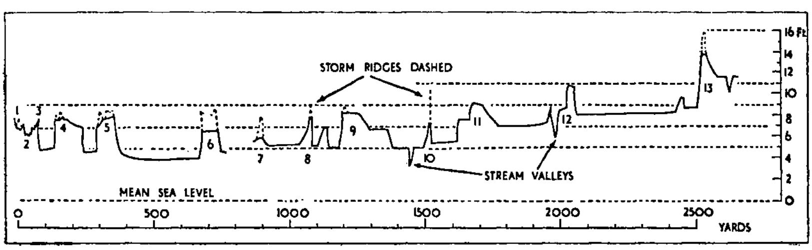

FIG. 6 (b)—Topographic section across shell and sand cheniers north of Miranda. (Numbers of cheniers correspond to position of numbers given on fig. 6 (a)).

wards many minor ridges diverge from the main trend (fig. 6 (a)). Within some cheniers these minor divergent ridges tend gradually to become parallel to the main trend as the southern end is approached. They are interpreted as being successive curved ends of a chenier growing across a tidal mud flat for they slope landwards and like the growing end of the present day chenier their crests rise from about mean high-tide level to storm-ridge height.

Each complex ridge (fig. 7a) has two possible modes of origin. Firstly it may have been a number of closely packed parallel ridges (fig. 7c) formed during fall of sea level. During a subsequent rise of sea level the up-current ends of this multiple ridge may have been eroded to produce the present complex form. Secondly each complex could have been produced during a

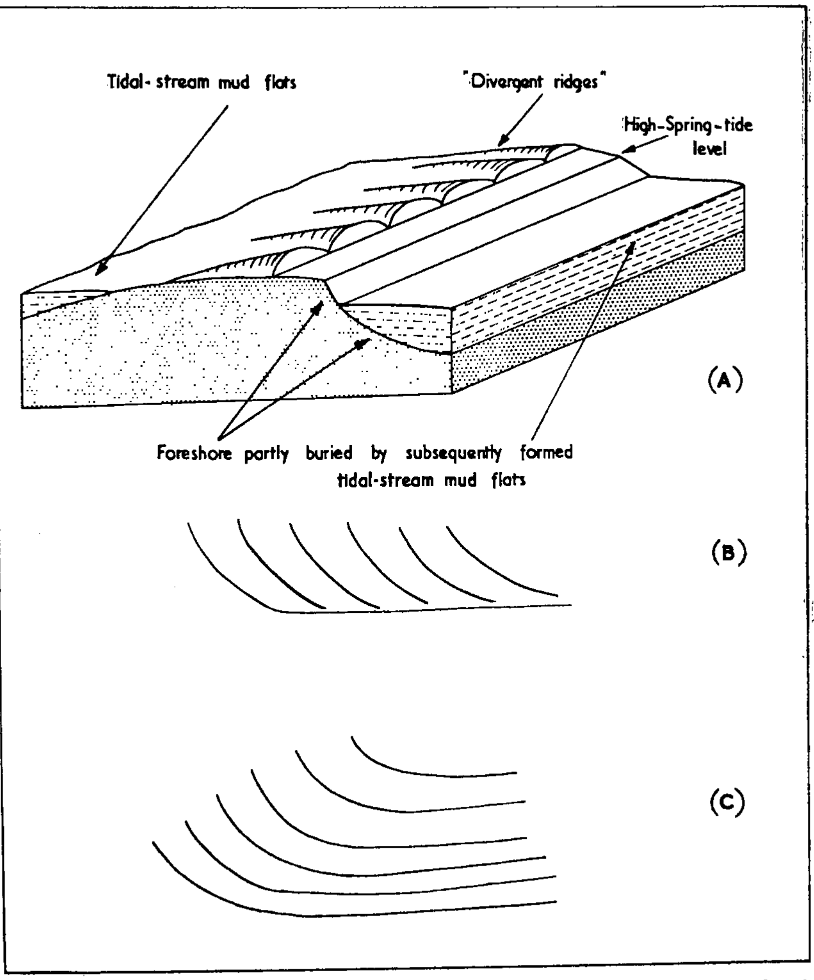

FIG. 7—(a) Diagrammatic representation of part of chenier 9 (fig. 6 (a)) showing its composite nature of many divergent ridges and their erosion. It also shows relationships to concurrently formed tidal-stream mud flats (behind) and subsequently formed mud flats. (b) Theoretical plan view of a composite chenier formed during rising sea-level (erosional period) or sea-level standstill. (c) Theoretical plan view of composite chenier formed during a falling sea level (period of aggradation).

stable or rising sea-level, each curved end of the chenier being attached to its predecessor (fig. 7b). Unfortunately it is not possible to determine changing or stationary sea level from the divergent ridges because no high tide wash benches have been found associated, and hence any interpretations of sea level may be inaccurate, especially as the growing end of a chenier rises from about mean-high-tide to storm-ridge level.

PAST SEA LEVELS

To determine past sea levels two traverses (figs. 5 and 6 (b)) have been made; one, 900 yd long across the gravel cheniers north of Whakatiwai – the Whakatiwai travese (W) – and another nearly 3,000 yd long across the shell and sand cheniers together with their intervening mud flats north of Miranda – the Miranda (M) traverse.

Past Sea Levels Shown by the Whakatiwai Traverse: In the absence of other criteria it has been necessary to assume that each of the gravel ridges reached storm ridge level and that these storm ridges were built to levels above high spring tide as high as today's storm ridge.

The record may not be complete, not only because a rapid rise of sea level may have caused erosion but also because successively higher ridges may have buried older lower ones. Thus in a period of fluctuating sea level lowest sea levels may not be represented. If sea levels were much lower than those represented by ridges W9, W7, W5, and W1 (fig. 5) then the rise to subsequent high sea levels must have been rapid at first – to bury or erode away lower storm ridges – and then less rapid. The latter stage is represented by progradation in the form of tightly packed ridges rising up to a maximum level, e.g., the long slope between W7 and W6 (fig. 5).

Past Sea Levels Shown by Miranda Traverse: Table 1 shows the sea levels obtained by comparing the past storm-ridge, high-spring-tide, and tidal-stream-flat levels with their modern counterparts. Storm ridges may have been built to higher or lower levels in the past, and the interpretation of high-spring-tide levels to within a few inches either way are impossible; thus the differences of sea level shown by these two criteria are to be expected.

TABLE 1—Past Sea Levels as shown by the Miranda Traverse

Ridge	Storm Ridge	Sea Level on Basis of High Spring Tide	Tidal-stream Flat	Accepted Sea Level
	ft	ft	ft	ft
(1)	− 1·25	− 0·25	......	− 0·25
(2)	− 2·45	......	......	− 2·50
(3)	......	+ 0·85	+ 0·7	+ 1·00
(4)	− 0·55	+ 0·65	+ 0·25	+ 0·5
(5)	− 0·2	+ 0·50	− 0·5	0·0
(6)	− 0·1	+ 0·1	+ 0·25	+ 0·5
(7)	− 0·8	− 0·8	......	− 1·0
(8)	+ 0·4	+ 1·0	+ 0·5	+ 1·0
(9)	+ 0·0	+ 1·4	+ 0·4	+ 1·5
(10)	+ 1·6	+ 0·4	+ 0·7	+ 0·5
(11)	......	+ 3·0	+ 2·5	+ 3·0
(12)	......	+ 3·9	+ 3·9	+ 4·0
(13)	+ 7·1	+ 6·9	+ 6·9	+ 7·0

Despite the fluctuation of past sea levels and the fact that sea level is rising today each successive high stand has been lower than the one preceding it.

DISCUSSION

Before accepting the evidence of these beach ridges directly in terms of past sea levels the effects of tectonic movements, compaction, wind changes, and the effect of equilibrium or non-equilibrium between sea level and sea floor must be considered.

Tectonic Movement: The northernmost portion of the North Island, including the area under discussion, has been considered relatively stable since about the late Miocene (Marwick, 1948; Gage, 1953; Eiby, 1955). However, although agreeing in general, Schofield (1958) has found that some tectonic movements of Pleistocene age have occurred 20 miles to the west of the Firth of Thames, but these movements were local and associated with volcanism. No Late Quaternary Volcanism has occurred within 30 miles of Miranda and it is doubtful if any crustal movements would not be revealed by tilting in some degree transverse to the coast. The chief evidence in favour of stability rests in the similarity of heights of sea level inferred from the oldest cheniers north of Whakatiwai, near Miranda and south of Waitakaruru, a total distance of 15 miles.

Compaction: According to Wiggers (1954) the compaction of sediments older than the Holocene "can be left out of consideration". Bennema *et al.* (1954) state that compaction of marine sands of Holocene age is negligible but that the maximum compaction of 85–90 per cent is reached in peaty mud soils. Clay soils with 30–35 per cent lutum (particles less than 2μ) compact 50% during 100 years after reclamation – with 20% lutum the compaction is 25%.

Although the beach ridges may have been deposited on a tidal mud flat, they themselves are formed of shells and sand. Thus assuming, that their weight compacted the underlying mud while they were being formed, any compaction since their formation is likely to be small.

Wind Changes: Although changes in prevailing wind direction could cause local changes in storm and high-spring-tide levels the absence of dunes on the chenier plain of the western coast of the Firth of Thames and absence of any similar plain on the eastern coast of the firth imply a westerly prevailing wind throughout the period under consideration.

State of Equilibrium: Bartrum (1948) pointed out that an apparent drop of sea level, as shown by stranded beach-ridges, may be due to a state of non-equilibrium between sea level and sea floor, i.e., sea level could remain the same but as the sea floor was gradually built up to wave-base over continually widening areas, wave-power and thus storm ridge heights could gradually fall. However, this argument applies only to one part of a beach ridge, i.e., the storm-ridge, and where sea levels can be computed from consideration of other evidence it does not apply.

Nevertheless during equilibrium between sea level and sea floor, excess sediments will be either transported further seaward or will be tossed ashore in the process of progradation. If sea level should fall at a faster rate than the rate at which equilibrium can be maintained, there would be a marked increase in sedimentary supply and hence rates of progradation could increase. The power of waves would be decreased and thus, theoretically, storm ridges might be built to a lower height above high-spring-tide level than during a period of equilibrium. Conversely if sea level rose faster than the rate at which equilibrium could be maintained, the coast line could remain stationary or be eroded, depending on the rapidity of rise, and storm ridges might be built to a greater height above high-spring-tide level. Thus progradation during a fall of sea level could well have alternated with a static or eroded coastline during rise of sea level.

From the above considerations it appears that none of these factors seriously invalidate the interpretation of past sea levels. The only two factors not entirely dismissed are compaction and tectonic movement. Effects of the former appear to have been negligent because of correlation of the early parts of both traverses formed in two different lithological and morphological areas (see section on "Age"). Effects of the latter are also ruled out unless conditions of a slow regional rise combined with fluctuating sea level have operated.

AGE

Seven samples of shell were collected for radiocarbon dating. Five of these came from some of the older cheniers within the Miranda section and two from cheniers within the Whakatiwai section. All samples were cleansed thoroughly, and as older shells, derived by erosion and re-transportation could be present, only the least worn were chosen. Their ages (Ferguson and Rafter, pers. comm.) are shown in table 2.

TABLE 2—Radiocarbon Ages and Related Sea Levels

Sample	Age in Years B.P.	Sea Level (ft)	Traverse and Chenier No.	
N48/590	980 ± 60	0·0	Miranda	M6
N48/591	1540 ± 60	+ 1·5	Miranda	M9
N48/592	1960 ± 70	+ 0·5	Miranda	M10
N48/585	2370 ± 70	− 1·0	Whakatiwai between W1 and W2	
N48/586	2730 ± 70	0·0	Whakatiwai	W2
N48/593	3150 ± 80	+ 4·0	Miranda	M12
N48/594	3900 ± 90	+ 7·0	Miranda	M13

It would appear from these ages that there has been very little progradation, if any, in the Whakatiwai gravel section since 2,300 years ago.

On the basis of similar sea levels represented, M13 and M12 are correlated respectively with W10 and W8, later sea levels represented by the Whakatiwai traverse being inserted between M12 and M11 (fig. 8 (d)). The missing part of the Miranda section is probably due to a period of erosion, and inspection of the chenier distribution in the vicinity of Miranda (fig. 6 (a)) shows that an erosional period probably preceded M11 and followed sometime after the deposition of M12. The spacings of undated sea levels in fig. 8 (d) is based on assumed equal rates of progradation between those dated.

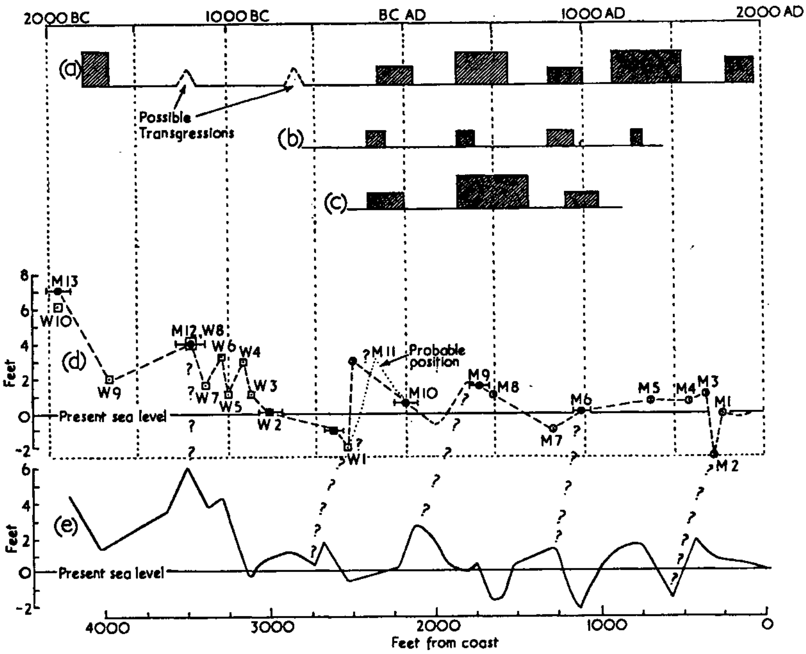

FIG. 8—Transgressional periods along (a) the Dutch coast (Bennema, 1954), (b) north-west coast of Holland (Bakker, 1954), and (c) Flemish coast (Tavernier and Moormann, 1954) compared with (d) the sea level-time curve of the Firth of Thames chenier plain (prefixes M and W denote control points from the Miranda and Whakatiwai traverses respectively; filled-in control points are those dated by radiocarbon analyses—the ranges for each date being denoted by lateral extensions). (e) is section across Seven Mile beach ridges, Tasmania (Davies, 1958).

The strict placing of M11 by this method would mean an extraordinary rapid rise in sea level of 5 ft* in less than 50 years and M11 is more happily placed if considered to be 100 years younger (fig. 8 (d)).

There are thus two possible sources of error in the ages given to the sea level fluctuations: (a) the radiocarbon dates may be slightly too old through contamination by shells from resorted older deposits; and (b) periods of progradation were probably interspersed with periods of erosion so that assumed constant rates of progradation may be in error. As to the reliability of shells for radiocarbon dating "shells are gaining in stature as more

*This 5 ft rise is the single greatest rise recorded by any of the minor fluctuations. Even with M11 at its "probable position" (fig. 8 (d)) the rate of sea level rise would have been 3 ft per century and there may be some connection between this rapid, relatively excessive rise, and the age of the Kopuarahi shell bed. The latter lies on the Hauraki Plains, is not a chenier, and is being worked by the Kopuarahi Lime Works (fig. 1), and according to radiocarbon dating its age is 2,270 ± 70 years B.P. (NZ ^{14}C No. 45, Ferguson and Rafter, 1957). Its meaning in terms of past sea level is not known, but it need not have been deposited by a sea level greater than 3 ft above the present.

[radiocarbon] dates accumulate" (Olson and Broecker, 1959). This certainly appears true for the dates given in table 2 as is shown by the correlations with the archeologically dated, Dutch sea transgressions (see next section).

CORRELATION

Despite the possible errors in dating there is a very good correlation with periods of transgression recorded along the coast of Holland by two independent observers (figs. 8 (a) and (b)) and along the Flemish Coast by another (fig. 8 (c)). According to Bennema (1954) these "transgressional phases are very likely characterised by slight rises in sea level and possibly by the occurrence of relatively frequent storm urges". No sea levels above the present are recorded for these European periods of transgression. Indeed the consensus of opinion was that, for the Netherlands, there has been a continuous rise of sea level during the Holocene (Pannekoek, 1955) with superposition of small oscillations. However, Quaternary tectonic subsidence of the Netherlands (Pannekoek, 1954) is still continuing (Edelman, 1954) and is no doubt the reason why there has been a more or less continuous local rise of sea level.

No other sequences of beach ridges appear to have been dated. The more recent portion of the East-Suriname sequence (Brouwer 1953) shows a general fall in a series of fluctuations from an apparent positive sea level of 7·5 m (24 ft). The amount of progradation in this sequence is 4–6 times that within the Firth of Thames and is interrupted by several periods of erosion. Thus the more recent portion of the East-Suriname sequence may extend further back in time, or alternatively the region has been relatively uplifted – a possibility described by Brouwer (1953).

The only other surveyed sequences of ridges known to the author are sand ridges near Hobart, Tasmania. Two sequences are described by Davies (1958) the longest being at Seven Mile Beach. These are not dated, nor is there clear evidence that their heights could represent relative positions of past sea levels. Nevertheless on the assumptions (a) that their relative heights do represent past sea levels and (b) that rates of progradation have been constant, a sea level curve has been plotted for the Seven Mile Beach sequence (fig. 8 (e)). With slight time adjustments this curve would correlate reasonably well with the Firth of Thames curve (fig. 8 (d)).

Since the above was written and since the block for fig. 8 was prepared, Dr Maxwell Gage has kindly drawn my attention to a publication by Fairbridge (1958). Fairbridge has assembled a graph of sea level oscillations of the last 12,000 years from both published and unpublished radiocarbon dates received from all parts of the earth. His "highs" of 2–3 ft (about 1,000–1,200 B.P.), 5–6 ft (about 2,300 B.P.) and 10 ft (3,400–3,900 B.P.) compare favourably with the Firth of Thames "highs" at 0 ft (980 $\pm$ 60 B.P.), 3 ft (about 2,200 $\pm$ 100 B.P.) and 7 ft (3,900 $\pm$ 90 B.P.). In all cases the Firth of Thames "highs" are 2–3 ft lower than those quoted by Fairbridge. There are important differences between the two graphs which are undoubtedly due to lack of information in both cases. Fairbridge shows several periods of low sea level not recorded within the Firth of Thames graph possibly because the evidence has been buried by tidal-stream flats formed during subsequent high sea levels. These are levels of — 2 m (3,300 ± 240 B.P.), — 3 m (2,400–2,800 B.P.) and — 3 m (about 2,000 B.P.). On the other hand the Firth of Thames graph shows two additional "highs" of 1·5 ft (1,540 ± 60 B.P.) and 4 ft (3,150 ± 80 B.P.) that are not recorded by Fairbridge (1958).

RATES OF SEA LEVEL FLUCTUATION

After studying many tide gauge records throughout the world, and neglecting those from tectonically unstable areas, Gutenberg (1941) concluded "that sea level generally is rising at an average rate of 10 cm per century". Kuenen (1954) finds "no grounds for doubting the validity of Gutenberg's conclusion". Valentine* (1952) amplifying Gutenberg's results, finds that sea level is rising 10–20 cm per century, being more rapid during the last few decades than around 1900. Caileux* (1952) also concludes that sea level rise has been more rapid of latter years and may be 15 cm per century for the last 20 years. The nearest reliable tidal gauge to the Firth of Thames for which full records have been kept since the turn of the century is at Auckland. This shows (fig. 9) that sea rise at Auckland has been an

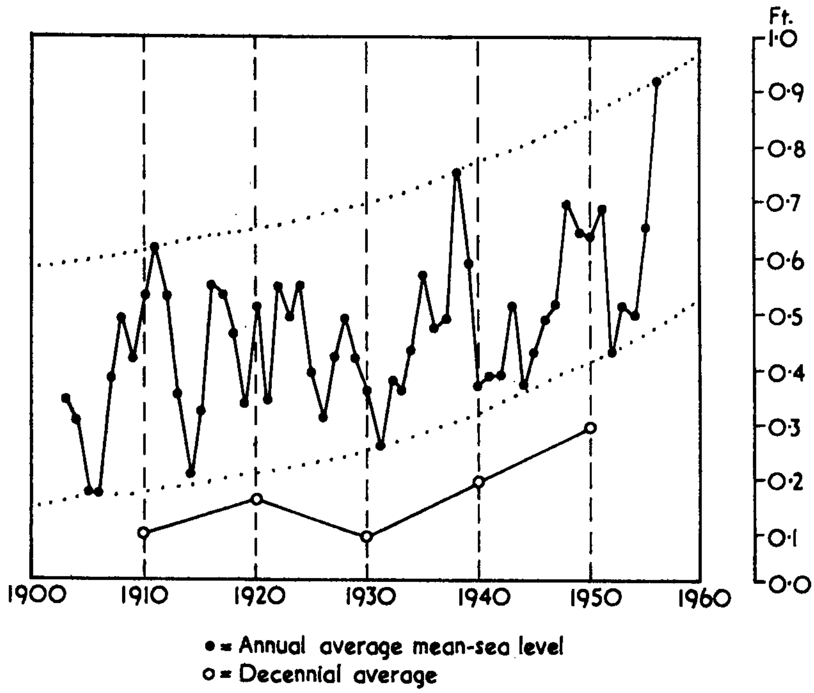

FIG. 9—Tidal records of the Queen's Wharf gauge, Auckland. Published by kind permission of the Chief Engineer, Auckland Harbour Board.

*Not seen, quoted from Kuenen (1954).

average of approximately 0·3 ft (10 cm) per century from about 1900 to 1930 and increased to 0·75 ft (20–25 cm) per century from 1930 to 1956. These figures agree remarkably well with the generalised figures given above and is an added reason to those given earlier for suspecting tectonic stability for the Firth of Thames.

Although sea level has doubled its rate of rise within the second quarter of the present century it is not as great as it was between 14,000 and 6,000 years ago when it appears to have been "approximately 3·0 ft per century" (Godwin *et al.* 1958). The latter figure is based on relatively few stations and can only be an average rate of rise. Actual rates of rise were most likely greater during some periods and less during others. Similarly, lack of sufficient datings for the sea level fluctuations recorded by the chenier plain of the Firth of Thames create uncertainty as to the rates of sea-level changes. However, the maximum rate of change recorded by these minor fluctuations since 4,000 years ago appears to be about 7 ft per century. Neglecting minor fluctuations, sea level fell 7 ft from 2,000 years B.C. to about the beginning of the Christian era (0·35 ft (10 cm) per century) and has remained relatively stable since then. The present rise of sea level may well be only another minor fluctuation in an otherwise fairly stable sea.

CAUSE OF SEA LEVEL FLUCTUATIONS

The almost universally accepted hypothesis of glacially controlled eustatism during the Pleistocene appears applicable to the Holocene as is demonstrated by the present recession of glaciers "in practically every glacier district of the world" (Thorarinsson, 1940) and present rise in sea level (see above). Not only could a rise of temperature release water from a glaciated region and thus raise sea level but warmer ocean waters would expand and thus also raise their own level. According to Brooks (1950) a rise of 5°F in the temperature of the ocean waters would raise sea level by 5 ft. Although it may require some time to alter all the oceanic water by an average of 5°F, the effects of slight differences in the average oceanic temperature may be an important factor.

Sprigg (1952), following Zeuner, believes that "sea level variations of the Pleistocene were dominated by events occurring in the northern hemisphere". Thus as the Holocene glacial events appear related to climate (Willett, 1951), there may be some correlation of the European climatic changes with the sea level changes recorded in the Firth of Thames. Some evidence for this is shown by fig. 10. The rainy periods and droughts of central and southeast Europe (Gams and Nordhagen, 1923, not seen, quoted from Bennema (1954)), correspond with low and high sea levels respectively. This could be due to increased glaciation during the wet periods (Suggate, 1952). On the other hand there is little correlation with Brooks' (1950) generalised rainfall curve for the north temperate zone. There are broad correlations with Brooks' (1950) temperature curve for Europe, e.g., (a) the relatively large drop of both sea level and temperature from about 1,000 years B.C. to 400 years B.C., (b) the comparatively low sea level and temperature of the latter date, and (c) the minor temperature and sea-level changes from the beginning of the Christian era onwards.

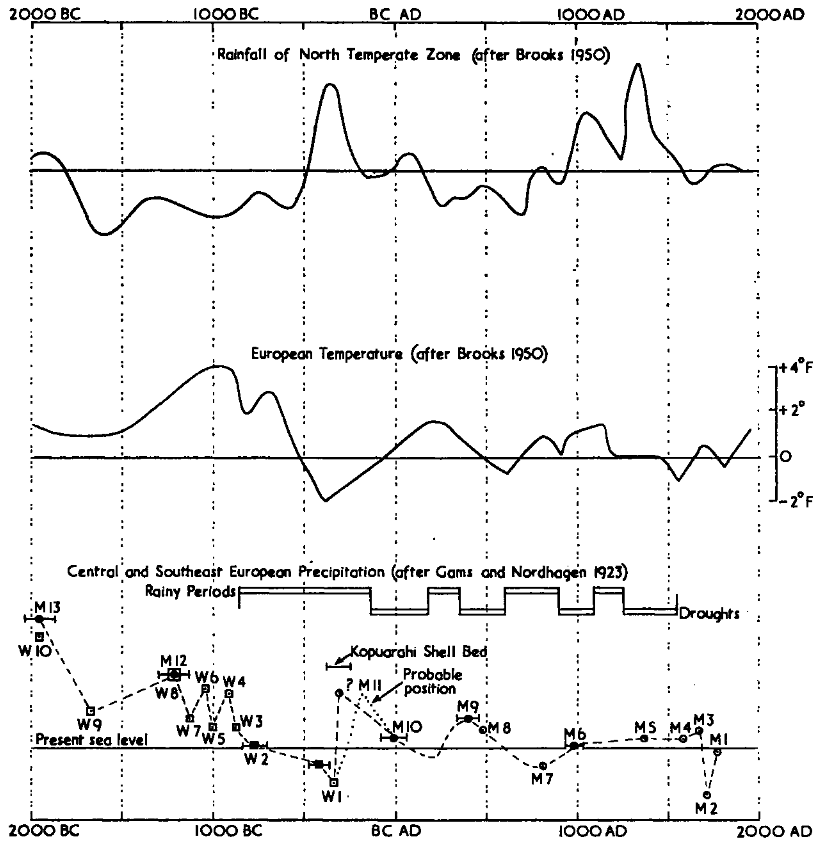

FIG. 10—Comparison of the Firth of Thames sea level time curve with European climatic fluctuations.

Thus it may be concluded that climatic changes may have been the prime cause of Holocene changes in sea level but they are not proven to have been. Tectonic pulsations, as appear in the isostatic dome of northern Europe (Florin, 1944; Post, 1952) have been important in local shore alterations but it is not known if they have contributed significantly to world wide eustatism.

Similarly it is not known if Belousov's (1952) "permanent oscillations of the earth's crust" can be demonstrated in the sea level fluctuations of the Holocene. Certainly there does appear to be some periodicity in the sea level fluctuations as has already been noticed by others in the past, e.g., Florin's (1944) eustatic cycles of 1760 years' duration could very neatly apply to the Firth of Thames sea-level/time curve between M13 and M11, and between M11 and M4; and (b), Bakker's (1954) and Bennema's (1954) 525 yearly oscillations also roughly apply. However, such cycles may be caused by periodic changes of climate. Smaller cycles of sunspot-activities have been demonstrated by Willett (1951) and it may be possible that larger scale climatic cycles have also operated.

ACKNOWLEDGMENTS

Aid in levelling across the Miranda and Whakatiwai traverses was given by my wife and Mr B. C. Waterhouse of the Geological Survey, Auckland, and I am indebted to them for the giving up of their spare time for this purpose.

I am also indebted to Mr A. C. Bettany, Engineer of the Franklin County, for information concerning erosion of the coast line.

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