REGRESSION TREND LINES OF RIDGES AND SWALES ON THE EMERGENT BEACH AT GISBORNE, NEW ZEALAND

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Abstract

The emergent sand-beach system at Gisborne consists of six recognisable groups of ridges and swales. It is about three miles wide and four miles long and rises gradually from 15ft above sea level at the coast to 40ft inland. From time to time the emergent beach has been mantled with air-borne volcanic ash including ash beds of the Waimihia Lapilli, Taupo Sub-group Members 9 - 13, Taupo Pumice, and Kaharoa Ash Formations. As the dates of these eruptions are known, the times of formation of the groups of beach ridges and swales have been determined as follows:

Group 1: c. 9000 B.C. – c. 1400 B.C.
Group 2: c. 1400 B.C. – (?) 850 B.C.
Group 3: (?) 850 B.C. – c. A.D.   131
Group 4: c. A.D.   131 – c. A.D. 1020
Group 5: c. A.D. 1020 – c. A.D. 1650
Group 6: c. A.D. 1650 –   A.D. 1956

Evidence of recent earth movements has been noted in ridges and swales of Group 1, and of possible movements in those of Group 3. Changes in sea level could not be established and were taken from Wellman and Schofield. No attempt was made to distinguish directly wind-blown sand from wave-deposited sand; instead, a shell layer (assumed to be associated with the intertidal strand) was used as a marker bed to indicate the approximate sea level at the time when the shells were deposited.

Elevations of ridges and swales in each group were measured on a 15,000ft transect across the beach system. Then, overall linear and quadratic regressions as well as linear regressions for each group separately were computed. For both of the overall linear and quadratic regressions the trend lines show a fall seaward, but the separate trend lines for each group are as follows:

Group 1:   Highly significant seaward decline.
Groups 2 and 3 combined: Very highly significant seaward decline.
Group 4:   Highly significant seaward incline.
Groups 5 and 6 combined: No significant change.

The departure of the regression trend lines within Groups 1 to 6 from the overall linear and quadratic trend lines suggests that the trends of elevation across the emergent beach at Gisborne should be regarded more as a series of discontinuous trends rather than as one overall continuous trend of seaward decline. Though the overall trend of declining elevation is seaward, the corresponding fall in sea level is likely to be more apparent than real because of compounding of fall in sea level with earth movements.

The trends of ridge elevations are statistically stronger than those of swales. Elevations about the trend lines, however, do not appear to be random, and when tested by the D-statistic suggest a non-periodic oscillation about the trend lines. This oscillation appears to have been induced by the amount of wind-blown sand. Consequently, because of wind-blown sand, the surface form may not be a reliable guide to sea-level changes.

Regressions have been computed for the Seven Mile Beach, Tasmania, and here also there is a suggestion of an oscillation about a trend. The Tasmanian beach system had already been examined by the method of least squares and the product-moment correlation coefficient. The validity of the latter is briefly discussed.

INTRODUCTION

According to Davies (1961), coastal sand ridges consist of a berm of wave-deposited sand and a mantle of wind-blown sand. The wind-blown sand, derived from the beach, appears to be variable in amount and is largely responsible for the erratic elevations of ridges. To arrive at a trend line for sea-level changes in a coastal sand ridge system the ideal would be to measure the elevation of the wave-deposited sand, ridge by ridge, but to remove the wind-blown sand to do this is impracticable. Accordingly, a measure of the surface form of the coastal sand ridge system has to be adopted. To compensate for variations in sand supply by wind, and by this means to smooth out irregularities in ridge elevations, Davies (1958, 1961) has subjected profiles of Tasmanian sand ridge systems to statistical analysis by the method of least squares. This method enabled him to obtain lines of best fit for the surface of ridges and swales and he considered that the trends of these lines would give an approximation to sea-level trends over the entire period of ridge formation. His trend lines showed a fall seaward. He concluded that ridge elevations may be more significant than swale elevations as indicators of sea-level change and that ridges slope seaward more steeply than swales (Davies, 1958).

In 1956, a transect 15,000ft long was surveyed across the emergent beach system at Gisborne and the surface form of the system revealed by the survey suggested an apparent fall in sea level. No attempt was made to distinguish wind-blown sand from wave-deposited sand; instead, attention was directed to a buried shell layer (about 12 to 24in. thick) which was assumed to have been associated with the intertidal strand and subsequently covered with both wave-deposited and wind-blown sand. The depth of the shell layer from the surface was measured and plotted graphically, and the resulting curve also showed a fall towards the sea (like that of the surface form); but this curve could not be reconciled with a sea-level curve obtained by Schofield (1960) for eustatic sea-level changes in the Firth of Thames. It was at this time that evidence of earth movements was discovered at Gisborne where these movements may have influenced the apparent trend of changes in sea level.

As sand ridge systems are seldom examined statistically in New Zealand, and as Davies is pioneering this new field, it was decided to subject the sand ridge system at Gisborne to statistical analysis by linear and quadratic regressions to see what conclusions could be arrived at from calculated trend lines.

THE EMERGENT BEACH AT GISBORNE

The emergent beach at Gisborne has been described by Henderson and Ongley (1920) and by Pullar (1962) and has been further examined in great detail by Pullar (in prep. [a]). Briefly, it comprises a belt of nearly 100 low, continuous, closely spaced, parallel sand ridges. The belt is about three miles wide and four miles long and rises from about 15ft above sea level at the coast of Poverty Bay to 40ft inland (Figure 1). The ridges are oriented approximately east to west and fall gently towards the west where they become buried by alluvium. The beach ridges have not been disturbed after their formation so that there are no sand plains and "blow-out" dunes.

Air-borne Volcanic Ash

From time to time the emergent beach has been showered with air-borne volcanic ash, and ash beds of the following formations have been noted: Waimihia Lapilli (erupted 3400 ±70 years B.P.*, N.Z. 14C 2 [c. 1400 B.C.]), Taupo Sub-group Members 9-13 (Healy, 1964), Taupo Pumice 1819 ±17 years B.P. (Healy, 1964, p. 34) (c. A.D. 131), and Kaharoa Ash (930 ±70 years B.P., N.Z. 14C 10 [c. A.D. 1020]). The oldest ridges on the beach have all of these ash-beds present at the surface while the youngest have no ash mantle at all; thus the minimum age of a ridge of the emergent beach can be determined by identifying the ash bed lying imediately on the beach sand.
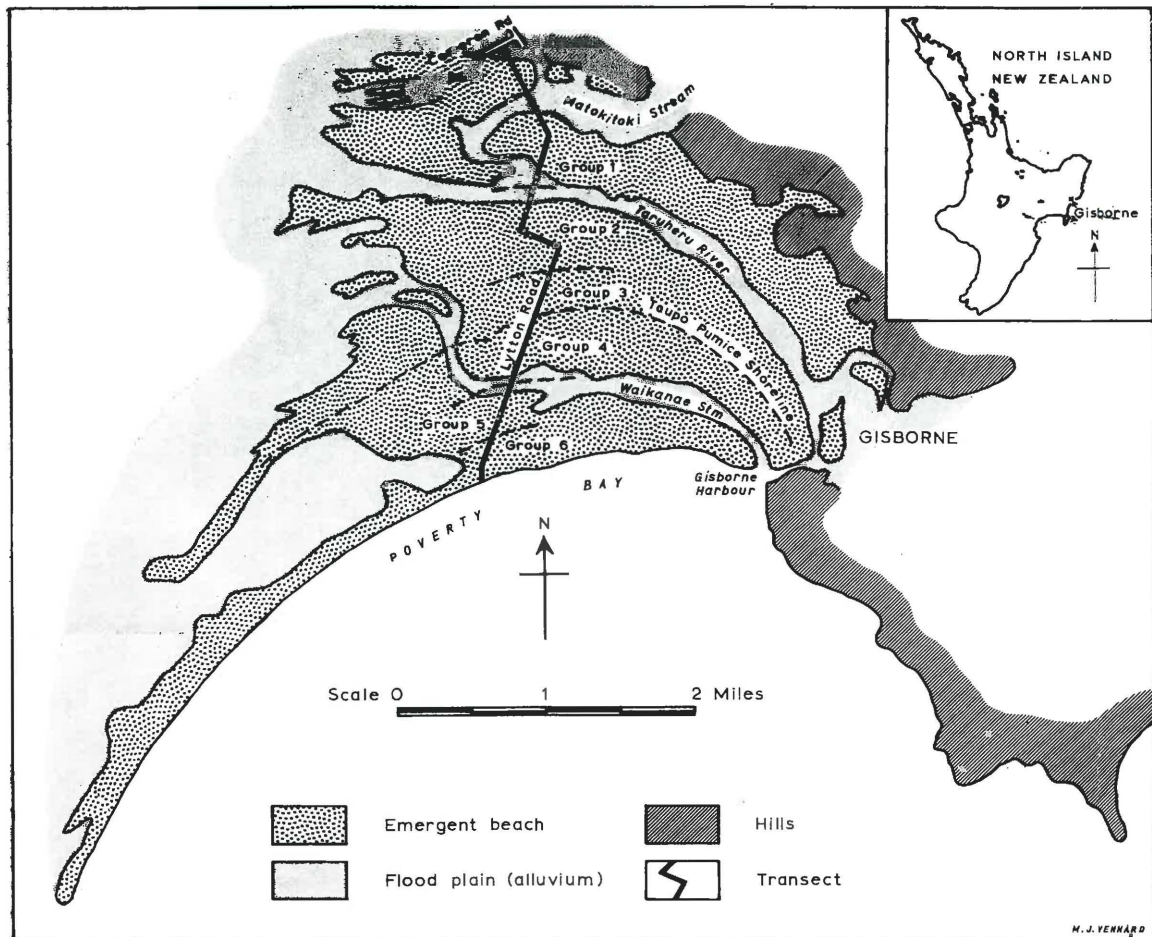
* All ages B.P., i.e. before 1950.

Figure 1. Emergent beach at Gisborne showing transect and Groups 1 to 6 of ridges and swales. (Urban area not shown; locality map inset.)

The Shell Layer

In a section on the surveyed transect (Pullar, in prep. [b]), the beach sand (wave-deposited plus wind-blown) is about 20 to 30ft thick and rests on estuarine mud. Within the sand are two separate shell layers and a gravel layer as well as occasional logs lying horizontally and parallel to the shoreline. The shells, gravel, and logs were evidently cast up by the sea. The upper shell layer (called the "shell layer" in this paper — see Figure 2C) consists of tightly packed shells and is about 12 to 24in. thick. Its original position on the intertidal strand is not known definitely. However, by considering the present shoreline the following facts can be applied to solve this problem. High water mark for ordinary tides is $+ 2.4$ft (above mean sea level) and for the highest registered tide $+ 3.7$ft, though during the storm of 20 - 22 February 1953, wave level reached $+ 9.8$ft. The lower limit of driftwood and the upper limit of shells along the present shoreline is $+ 6.1$ft but observations suggest that most shells are concentrated within the intertidal strand. For the moment, therefore, the shell layer is assumed to have formed at a high-water mark of $+ 2.4$ft.

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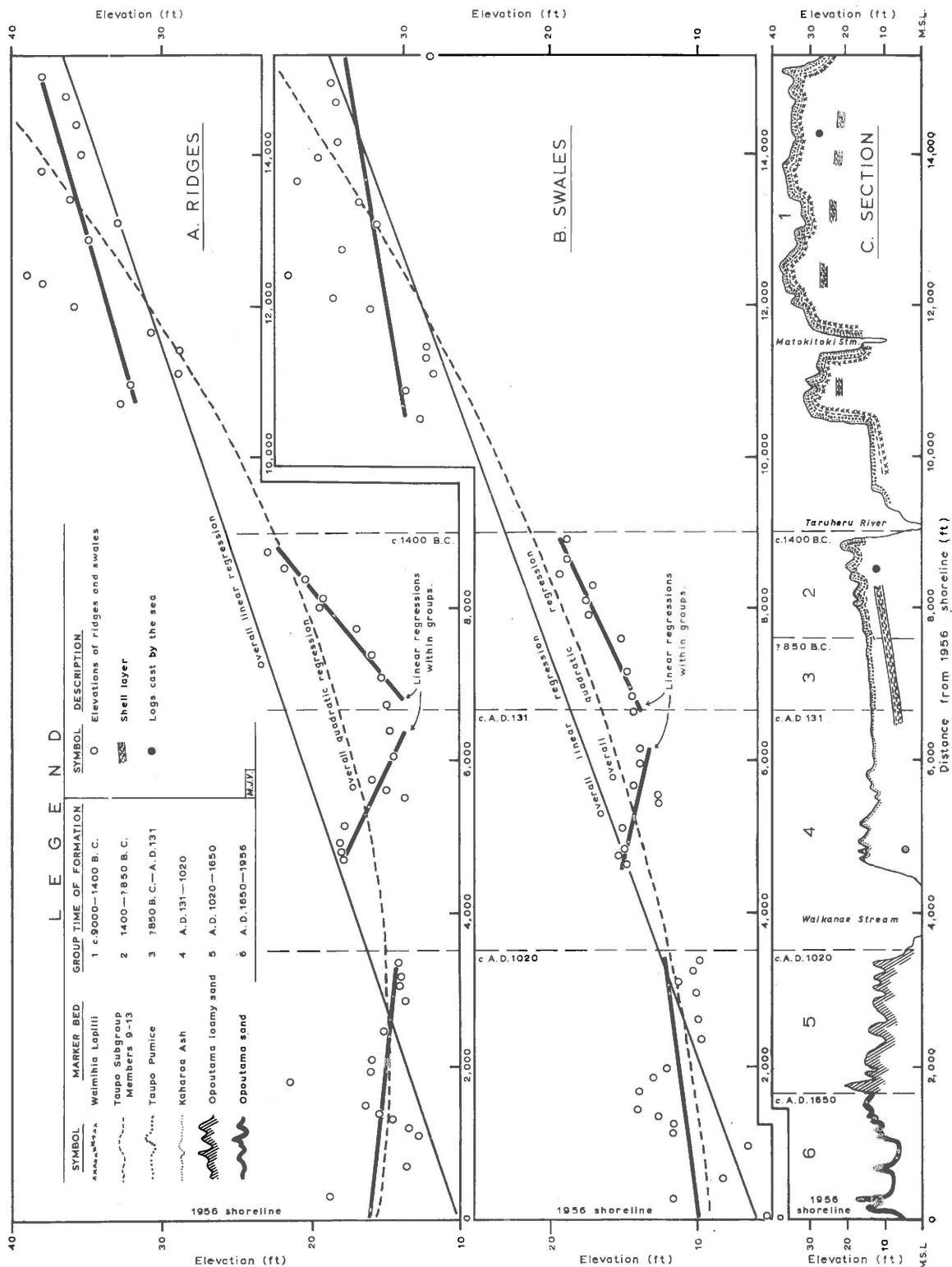
Figure 2. Emergent beach system at Gisborne. A. Elevations of emergent beach
ridges with overall linear regression, overall quadratic regression, and "within-group"
linear regressions; B. Elevations of emergent beach swales, with regressions as for
Figure 2A; C. Section across emergent beach system from 1956 shoreline to a point
some 15,000ft inland.

Figure 3. Overall linear regressions, Seven Mile Beach, Tasmania, for A. Elevations of ridges; B. Elevations of swales. (From a point inland to *c*. 1956 shoreline, 4500ft distant [from data supplied by Dr J. L. Davies: figure from Figure 1, Davies, 1958].)

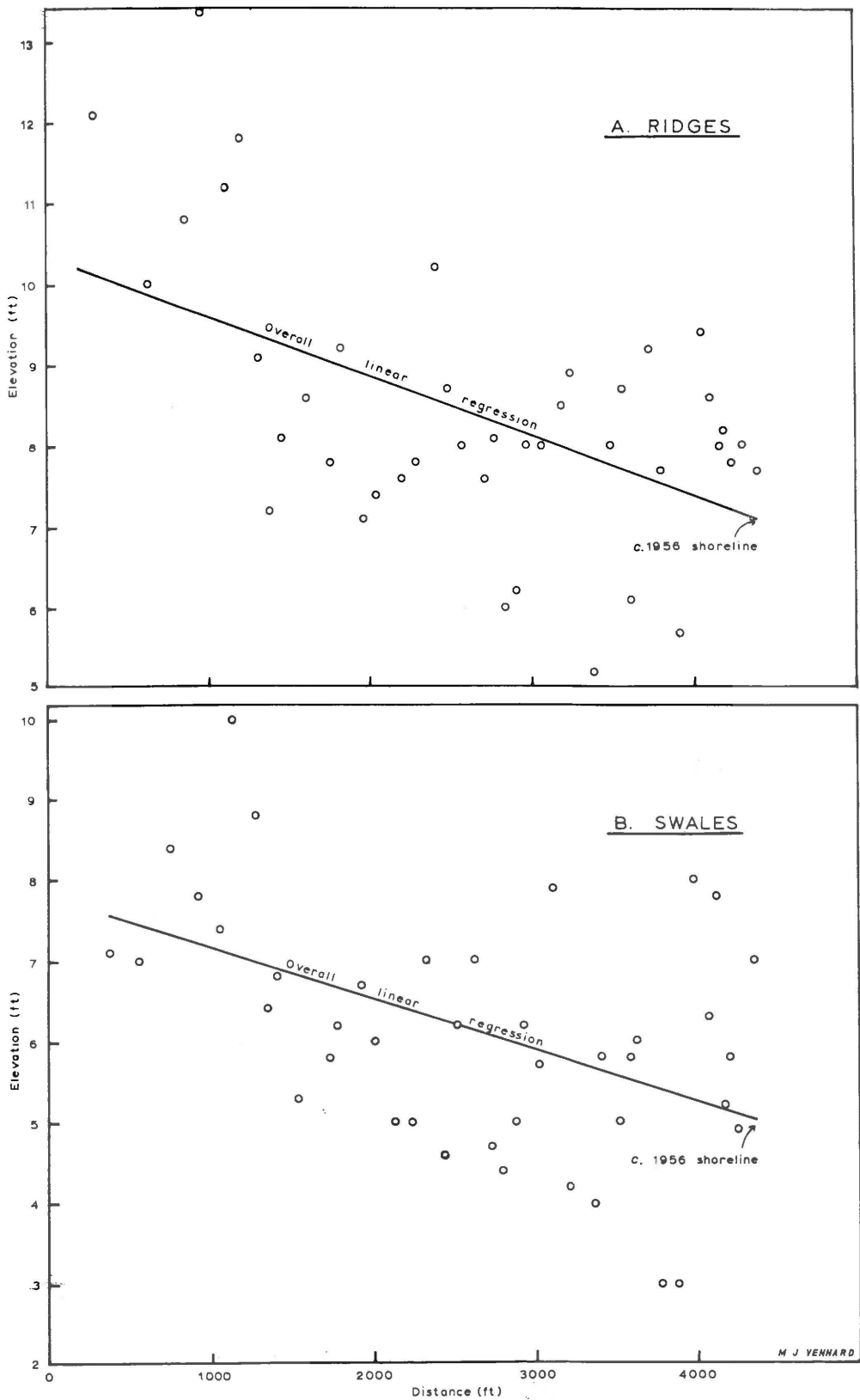The crest of the wave-deposited sand berm is assumed to be about + 6ft, as determined by the present-day upper limit of shells. Therefore, the thickness of wind-blown sand can be estimated by subtracting 4ft (estimated thickness of wave-deposited sand berm above the shell layer) from the ridge elevations. Driftwood may be unreliable as a measure of the upper limit of wave-deposited sand: for example during the storm of 10 April 1968, drift logs of two to three feet diameter were cast as high as +11ft on the shore near Whakatane.

Sea-Level Changes

Wellman (1962) considered the sea level at the time of the Taupo Pumice eruptions (1819 ±17 years B.P.) to have been about three feet below the present level and at the time of the Waimihia Lapilli eruption (3400 ±70 years B.P.) to have been nearly 10ft higher. Schofield (1960, 1964) also considered the sea level to have been higher 3000 years ago, but Schofield (1968) and Pullar (1968) suggested that the sea level at the time of the Taupo Pumice eruptions could have been 10ft lower than that of today.

As sea-level changes could not be established on the emergent beach at Gisborne, those of Wellman and Schofield were accepted for the time being.

Earth Movements

Gisborne is well known to be in a tectonically mobile area. Evidence for recent warping includes the following:

1. The oldest part of the emergent beach rests on a wave-cut platform now uplifted about 30ft above present sea level.

2. This uplift is related to tilted beds observed in a sewer trench at Gisborne. These beds consist of ash beds of the Waimihia Lapilli and Taupo Sub-group Members 9 - 13 Formations, intercalated with beds of organic mud, and are tilted towards the coast at about three degrees. Warping is thought to have occurred c. 200 B.C. (Pullar, 1968).

3. Sea-rafted Taupo Pumice boulders at + 15ft (above present mean sea level) were seen in a swale seaward of the last ridge mantled with air-borne Taupo Pumice. Because driftwood from present-day storms is cast no higher than + 11ft, the line of pumice boulders at + 15ft suggests that warping took place after the Taupo Pumice eruptions of c. A.D. 131.

4. Sections of the emergent beach show that the shell layer rises consistently from the present shoreline inland. Its position has been assumed to correspond to changes in sea level. The shell layer in inland sand ridges (ridges formed before the Waimihia eruption of 3400 ± 70 years B.P.) occurs 25ft above present sea level. In the Firth of Thames, Schofield (1960) indicated that sea level was 7ft higher 4000 years ago. Consequently, the greater elevation of the shell layer at Gisborne can be assumed to be more the result of earth movements than of sea-level changes.

SECTION ACROSS EMERGENT BEACH

The transect was surveyed along Lytton Road from the present shoreline to Cameron Road, but the section had to be offset a little at several points to avoid houses and trees (Figure 1). From 6000ft to 8000ft from the present shoreline the surface is almost flat with a series of ridge "ripples" and in this part of the line not every ridge was surveyed.

Groups of Ridges and Swales

The section was divided into six groups of ridges and swales according to the volcanic-ash beds that mantled them and according to their soil profiles which were established from a detailed soil survey of the Gisborne Plains (Pullar, 1962). On the ground, some groups are not contiguous because they are separated by flood plains of both the Waikanae Stream and the Taruheru River; but for statistical purposes, each group is assumed to be connected.

The boundary between each group is assumed to be a shoreline (as indicated by a swale) and is the commencing point for measuring cumulative distances of ridges and swales for each group. For most groups the actual position of the terminal shorelines cannot be found directly because of cutting and filling by the sea; the position where a new ash bed appears does not necessarily indicate the position of the shoreline at the time of the eruption of the ash. Instead, the positions of new ash beds indicate the time spans of formation of the groups of ridges and swales.

Elevations of ridges and swales were measured from the mean sea level established by the Poverty Bay Catchment Board in 1950.

Group 1 (c. 9000 B.C. – *c.* 1400 B.C.). The inland terminal boundary of Group 1 is obscure and masked by alluvium and its date has been assumed to be somewhat later than that of the Waiohau eruption (11,250 ±200 years B.P., N.Z. 14C 568), the ash from which has been identified at the base of the sand and provides a maximum age. Ridges and swales are pronounced and they are mantled by Waimihia Lapilli, Taupo Subgroup Members 9 - 13, Taupo Pumice, and Kaharoa Ash. A surface elevation for the ridges had to be estimated across the deeply entrenched Matokitoki Stream. In the ridges, the thickness of the wind-blown sand component is estimated to be four to eight feet.

Group 2 (c. 1400 B.C. – (?) 850 B.C.). The inland terminal boundary of Group 2 is assumed to be on the shoreline that existed at the time of the Waimihia Lapilli eruption (3400 ±70 years B.P.) but has since been obscured by erosion by the Taruheru River. The flood plain along the left bank of the river, however, has Waimihia Lapilli within three feet of the present surface, and, at the time of the eruption, this area could have been an estuary with the shoreline a further 20 chains or so seaward. The surface is mantled with Taupo Subgroup Members 9 - 13, Taupo Pumice, and Kaharoa Ash. The wind-blown sand component in the ridges is estimated to be about three feet thick.

Group 3 ([?] 850 B.C. – *c.* A.D. 131). The inland terminal boundary of Group 3 is assumed to be on the shoreline that existed at the time of the eruption of Taupo Subgroup Members 9 - 13. These ash members can be recognised separately on terraces near Taupo but are represented by a single ash bed on the beach ridges and in alluvium at Gisborne; this bed may represent Members 11 and 12 erupted *c.* 850 B.C. (Healy, 1964; p. 38). The ridges and swales are mantled with Taupo Pumice and Kaharoa Ash. They are very subdued and, as they are like ripples on the surface, the elevation of each ridge and swale was not measured separately in this part of the section. The shell layer is within five feet of the surface and consequently little wind-blown sand is considered to be present.

Group 4 (c. A.D. 131 – *c.* A.D. 1020). The inland terminal boundary of Group 4 is the shoreline that existed at the time of the Taupo Pumice eruptions of *c.* A.D. 131 and it is well marked on the ground by sea-rafted pumice boulders. The ridges and swales are mantled only by Kaharoa Ash. Near the inland terminal boundary the wind-blown sand is estimated to be one to three feet thick; at the seaward boundary, a buried log was used instead of the shell layer to measure thickness of wind-blown sand which was estimated to be up to seven feet thick.

Group 5 (c. A.D. 1020 – *c.* A.D. 1650). The inland terminal age of Group 5 is fixed by the Kaharoa eruption, the ash from which was identified on a ridge bordering the left bank of the Waikanae Stream near Lytton Road. The inland terminal boundary, however, has been obscured by the flood plain of the Waikanae Stream and so it is assumed to be a few chains seaward of the ash-covered ridge (Figure 2C). The soil on this group of ridges and swales is classed as *Opoutama loamy sand* which has an A horizon of black (5Y 2/2) loamy sand on a (B) horizon of olive yellow (2.5Y 6/6) sand. This profile is quite distinct from that of *Opoutama sand* which is formed on the younger ridges and swales of Group 6 (q. v.). No observations were made on the depth of the shell layer from the surface, but by extrapolation from a neighbouring transect, the wind-blown sand in the ridges is estimated to be five feet thick, and in some of the higher ridges, to be eight to 15 feet.

Group 6 (c. A.D. 1650 – A.D. 1956). The inland terminal boundary is the soil type boundary between *Opoutama loamy sand* and *Opoutama sand*. The latter soil is characterised by an A horizon of dark greyish brown (2.5Y 4/2) sand on a C horizon of pale yellowish brown (2.5Y 6/4) sand. Wind-blown sand in the ridges is estimated to be eight to 10 feet thick, except in a foredune where it is about 13 feet. The seaward boundary is the present shoreline at mean sea level.

STATISTICAL METHOD

Overall Regression

First the data are treated as a whole and consideration is given to linear regressions (as obtained by least squares) of ridge elevations and swale elevations, h_r and h_s, on the distance, d, measured (in 10ft units) from the present shoreline i.e. from the first identified swale. The estimated lines (Figure 2) are:

$$\text{Ridges:} \quad h_r = 10.03 + 0.0174d$$
$$\text{Swales:} \quad h_s = 6.03 + 0.0191d$$

These account for 79.4% and 86.8% of the variation in ridge elevations and swale elevations respectively. They are highly significant in the conventional statistical sense, and both exhibit a seaward fall.

It is clear from Figure 2A, 2B, however, that these regressions are not entirely satisfactory. The points are clearly not randomly distributed about the lines, there being a marked tendency for the points near the ends of the range of distance to lie above the line while points in the middle lie below it. Accordingly any improvement that can be made by the addition of a second-degree term to the regression needs investigation. The estimated curves are then:

$$\text{Ridges:} \quad h_r = 15.68 - 0.007176d + 0.00001645d^2$$
$$\text{Swales:} \quad h_s = 9.27 + 0.005086d + 0.000009368d^2$$

As shown in Appendix 1 the quadratic terms are highly significant and the quadratic regressions now account for 89.9% and 90.0% of the variation in ridge and swale elevations respectively.

It is not intended that these statistical results should be taken to imply that there exists an underlying curvilinear relationship between ridge or swale elevations and distances from the present shoreline. The quadratic used is merely a convenient and simple means of tracking the points smoothly, and in spite of its apparent adequacy (coefficients of determination being 90%) there remains some doubt about its suitability (see below). The fundamental relationship, if any, may involve time and, although a greater distance inland from the present shoreline corresponds to a point further back in history, the relationship between distance and time certainly is not linear. The conversion to a time scale, were it possible, may well remove the curvilinearity, or may even reverse it. Also, since the authors

have merely tracked the points that were measured, there is no justification in making inferences outside the range of the data and, in particular, in attempting prediction of future ridge and swale heights.

Tests of Randomness

As Kendall and Stuart (1966) have pointed out, there is no limit to the number of tests that can be set up for the purpose of testing whether, given an ordered series of observations u_1 u_2, . . . u_n, they can have arisen by chance in that order by sampling independently on n occasions from a population of unknown characteristics.

In the present situation certain assumptions have been made: specifically, the usual assumptions made in fitting regressions of the type considered above are:
$$y_i = a + bx_i + cx_i^2 + e_i, \qquad i = 1, 2, \ldots . . n \qquad (1)$$
where x_i are known constants and e_i are random variables independently distributed with zero mean and common variance. It is, of course, not necessary to assume normality of the distribution of the residuals, e_i, in order to obtain best linear unbiased estimates of the parameters, a, b, c; however, this assumption is here included.

The problem of testing for serial correlation in least squares regression has been considered by Durbin and Watson (1950, 1951) and the test proposed by them is well known. In the present situation, however, a quicker test is considered which is clearly an approximation but nevertheless adequate for this purpose. The properties or merits of the quicker test are not discussed in this paper, but its use and interpretation are described briefly. This test appears to have reasonable power against the class of alternatives of potential interest to the authors, namely oscillation, not necessarily periodic, about a trend. From the observed departures of the points from the regression line we may define a quantity D thus:
$$D = \sum_{i=1}^{n-1} \left| Z_i - Z_{i+1} \right| \qquad (2)$$
For a quadratic regression Z_i is given by:
$$Z_i = y_i - \bar{a} - \bar{b}x_i - \bar{c}x_i^2 \qquad (3)$$
where $\bar{a}$, $\bar{b}$, and $\bar{c}$ are the least squares estimates of a, b, c. If a linear regression is used, then
$$Z_i = y_i - \bar{a} - \bar{b}x_i \qquad (3a)$$
Thus to assess to what extent the observed departures from the regression line are non-random, the value of D obtained from (2) is compared with that expected if departures are random, i.e. the expectation $E(D)$ from (4). When the departures from the regression line (residuals), are independently and normally distributed with zero mean and common variance σ^2, it has been demonstrated (Kamat, 1953) that $E(D)$, the expected value of D, is given by
$$E(D) = 2(n-1) \, \sigma \, / \, \sqrt{\pi} = 1.128379 \, (n-1) \, \sigma \qquad (4)$$
Kamat (op. cit.) also demonstrated that the variance is given by
$$\text{Var}(D) = (1.052264 \, [n-1] - 0.325504) \, \sigma^2 \qquad (5)$$
Observe that the quantity just expressed is not Var(D) in the sense the present authors use since the estimation of a, b and c is not allowed for. However, it should be adequate as a first approximation. Note also that σ^2 is unknown so that in the above formula (5), the residual mean square after the fit (s^2) would be used, and this is a further approximation.

The limitations brought about by these approximations can be removed. Kamat, in the same paper, presents results concerning the quantity $W = (D/[n-1])/s$, in particular, its expectation $E(W)$, variance and several upper and lower percentage points of its distribution. The s in the above formula is, however, not quite the

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same quantity that the present authors have denoted by s. Since the present paper is not intended as a contribution to theoretical statistics no attempt has been made to determine the analogous statistic which is strictly appropriate to the situation. For sufficiently large values of n the difference is inconsequential and accordingly values of W computed with s, in the sense used here, may be compared with Tables 4 and 5 of Kamat's paper. The conclusions which are drawn will be unaffected.

Let the test now be applied to the quadratic fit of the ridge and swale data, comparing the values of D and W derived from the data with their expectations, $E(D)$ and $E(W)$ respectively (Table 1). Where oscillation occurs, D (or W) will be less than its expectation $E(D)$ (or $E(W)$).

Table 1. Application of test to ridge and swale data.

	Ridges	Swales
D	79.20	87.00
$E(D)$	162.60	181.00
$S.D.(D)$	21.00	22.70
W	0.55	0.54
$E(W)$	1.15	1.15

The figures are such that, even allowing for the approximations involved, the hypothesis of independence cannot be accepted, i.e. departures from the regression line are not random. The overall quadratic is thus not a good representation of the data.

Regressions within Groups

As has been described above, the section can be divided into six groups of ridges and swales which can be distinguished by ash beds and by soil profiles. Reference to Figure 2 suggests that the departure from randomness may, in part, be ascribed to the existence of these groups. It may, perhaps, be argued that an overall fit is meaningless and that only the trends within these independently defined groups need be examined. The data are now examined by linear regression and the results are summarised in Table 2 (see also Appendix II).

Table 2. Linear regressions within groups of ridges and swales.

Group		Regression	D	$E(D)$	$S.D.(D)$	W	$E(W)$
1	Ridges:	$h_r = 31.4 + 0.01475d$	29.9	43.8	10.2	0.77	1.18
	Swales:	$h_s = 30.2 + 0.0100d$	34.1	54.7	12.3	0.70	1.18
2 & 3	Ridges:	$h_r = 13.5 + 0.04115d$	5.3	7.4	2.3	0.80	1.23
	Swales:	$h_s = 14.1 + 0.0237d$	7.3	6.6	2.0	1.23	1.22
4	Ridges:	$h_r = 18.1 - 0.02405d$	8.8	9.6	3.0	1.03	1.23
	Swales:	$h_s = 14.9 - 0.0062d$	6.4	7.7	2.4	0.93	1.23
5 & 6	Ridges:	$h_r = 16.1 - 0.0047d$	25.9	37.5	8.7	0.78	1.18
	Swales:	$h_s = 10.0 + 0.0048d$	26.5	43.8	9.9	0.68	1.18

In Group 1 there is a highly significant seaward decline in the ridge elevations. A seaward decline in the swale elevations, however, is not significant (in the sense of statistical testing) at conventional probability levels (5% or better). It should be noted, however, that the innermost swale is much lower than one would expect and this one point has had a disproportionate effect on the result. The D-statistic (and the W-statistic) suggests non-randomness of the individuals about the trend and, indeed, inspection of Figure 2 suggests oscillation as an alternative to randomness.

Groups 2 and 3 have been combined as their common boundary is contiguous and ill-defined; there is little, if anything, about the plotted points to suggest a

change in either trend or elevation. The ridges and swales both exhibit a very highly significant seaward decline. The D-statistic (or W-statistic) gives a suggestion of non-randomness, possibly oscillation, for the ridges but not for the swales.

A highly significant seaward *incline* is demonstrated by the ridges of Group 4. An incline, not significant at the 5% level, also appears with the swales. Group 4 is contiguous with Group 3 but has a well-defined inland terminal — the shoreline of *c.* A.D. 131, where the Taupo Pumice boulders are seen — and the trend clearly changes from those of Groups 2 and 3. For both ridges and swales the D-statistic is less than expectation although it could not be judged significantly so; the same applies to the W-statistic.

Groups 5 and 6 have also been combined. They are contiguous and, although their boundary is well defined, there is little, if anything, that would suggest a change either in trend or elevation. Indeed, the regressions for both ridges and swales are not significant; the D-statistics (and W-statistics), however, are again substantially less than their expectation, and oscillation rather than randomness is suggested.

SEVEN MILE BEACH, TASMANIA

Davies' data for the Seven Mile Beach, Tasmania, has been examined by the method applied here to the emergent beach at Gisborne and the following statistics have been obtained:

$$
\begin{aligned}
\text{Ridges:} \quad h_r &= 7.1 + 0.007407d \\
D &= 55.4,\ E(D) = 66.6,\ S.D.(D) = 9.4 \\
W &= 0.94,\ E(W) = 1.15
\end{aligned}
$$

$$
\begin{aligned}
\text{Swales:} \quad h_s &= 5.0 + 0.006319d \\
D &= 51.5,\ E(D) = 63.1,\ S.D.(D) = 9.0 \\
W &= 0.92,\ E(W) = 1.15
\end{aligned}
$$

Field measurements as supplied by Davies have their starting point inland, whereas at Gisborne, the starting point was the present shoreline. Overall linear regression trend lines of ridges and swales for the Seven Mile Beach, Tasmania, are shown in Figure 3 (see also Appendix III) and are included for comparison with trend lines calculated for the emergent beach at Gisborne (shown in Figure 2).

The D-statistics (and the W-statistics) obtained here scarcely provide, in themselves, justification for rejecting the assumption of randomness, but it is interesting to observe that these statistics are again less than their expectations and by more than the estimated standard deviation, so that Davies' data tend to reinforce, and certainly would not contradict, a conjecture of oscillation about a trend.

On the basis of the recalculation there appear to be some errors in Davies' (1958) reported results; however, the differences are relatively small and would not alter his interpretation.

In the present paper the presentation of correlation coefficients has been avoided. The correlation coefficient is a measure of the degree of association between two variables, and valid estimation along conventional lines depends on random sampling of a bivariate normal universe. These conditions clearly do not pertain here and, although the square of the correlation coefficient — the so-called coefficient of determination — provides a measure of how well the fitted line tracks the data, it is felt that this is better expressed by the usual testing of the regression coefficient (there is, of course, a correspondence between the F-statistic and the coefficient of determination) since misleading interpretation of the product-moment correlation is less likely.

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DISCUSSION

1. Rather than representing a continuous trend of falling sea level and elevations, the emergent beach should be regarded as representing a discontinuous trend; the natural divisions of the emergent beach, that is, the groups of ridges and swales that have been separated, should be regarded as representing segments of this discontinuous trend and can be correlated with geological phenomena with the aid of marker beds. Within groups, however, there is, in general, evidence that departures from the trend line (of seaward incline or decline) are of an oscillatory rather than a random nature. In the field, trend lines within the groups of ridges and swales are not always evident because the elevations are partly dependent on the thickness of wind-blown sand.

2. Although the regression trend lines, for the most part, show a fall towards the sea the overall trend does not necessarily imply a corresponding fall in sea level. Because of tilting of Groups 1 and 3 towards the sea by earth movements, these groups have a component trend due to earth movement but similar to that caused by a fall in sea level. If the hypothesis of a general sea-level fall is accepted, then (owing to the earth movement) the overall regression lines (Figure 2) tend to exaggerate the fall.

3. The very highly significant seaward decline in both ridges and swales of Groups 2 and 3 is consistent with the subdued form of the ridges and swales, and with the closeness of the shell layer to the surface, suggests that they were built fairly rapidly in association with falling sea level. Perhaps at this time there was a real fall in sea level, but the amount of fall has been obscured by subsequent earth movements after the Taupo Pumice eruptions.

4. The highly significant seaward incline shown in ridges of Group 4, following the very significant decline in Group 3, is suggestive directly of earth movements or of increased amounts of wind-blown sand. The presence of pumice boulders on the Taupo Pumice shoreline at an elevation of +15ft, however, lends support to the suggestion of earth movements.

5. The regression lines for ridges in Groups 5 and 6, which were formed during the last 1000 years, show no significant trend. The ridges are more variable in height than those of the older groups and (according to the estimates presented) have a greater proportion of wind-blown sand which tends to mask any change in elevation due to change in sea level.

6. From an inspection of Figure 2, the amplitude of oscillation is evidently greatest in Groups 1, 5, and 6 which are the groups with the highest components of wind-blown sand. Consequently it appears that the oscillation is primarily related to the amount of wind-blown sand.

7. Because a continuous series of observations on the elevations of the shell layer could not be obtained in the section at Gisborne, it is not possible to make a comparison of trends of the surface form of the ridges and swales with those of the surface form of the wave-deposited sediments. If the latter is assumed to be a measure of sea-level change, then from the limited observations of the shell layer, it seems that the surface form of the ridges and swales may not be a reliable guide to sea-level change; departure of this surface form from that of the wave-deposited sediments is caused by wind-blown sand.

CONCLUSIONS

1. Although the overall regression trend lines show a continuous fall seaward, the trend does not necessarily imply a corresponding fall in sea level. On the part of the emergent beach older than 1000 years, the trend appears to have been accentuated by earth movements.
2. Trends in elevations of ridges appear to be statistically stronger than those of swales, and this conclusion confirms that of Davies in connection with Seven Mile Beach, Tasmania.
3. The product-moment correlation coefficient is not the most appropriate method for statistical analysis of ridges; beach systems may be better studied by the fitting of trend lines followed by some form of analysis of the residuals.
4. Ridge and swale elevations appear to be oscillatory about the chosen regression trend lines although the period of oscillation is not necessarily fixed. Since this is true of both the emergent beach at Gisborne and the Seven Mile Beach in Tasmania, it would be of interest to examine other beach systems from this standpoint. For the present it is suggested that the oscillation is primarily related to the different amounts of wind-blown sand that have been incorporated in the ridges and swales and have caused differences in their elevations.
5. Because of the influence of wind-blown sand on elevation, the surface form of ridges and swales is not necessarily a reliable guide to sea-level changes.

ACKNOWLEDGEMENTS

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APPENDIX I

Analysis of variance tables for overall regression on emergent beach, Gisborne.

Source	D.F.	S.S.	M.S.	F
Ridges: Total	50	28,878.71		
Mean	1	24,842.20		
	49	4,036.51		
Linear regression	1	3,205.36		
Quadratic regression	2	3,630.25		
Quadratic term	1	424.89	424.89	48.0‡
Residual	47	406.26	8.64	
Swales: Total	53	24,989.90		
Mean	1	20,211.79		
	52	4,778.11		
Linear regression	1	4,149.13		
Quadratic regression	2	4,302.56		
Quadratic term	1	153.43	153.43	16.1‡
Residual	50	475.55	9.51	

‡ Indicates significant at 0.1% level of probability.

APPENDIX II

Analysis of variance tables for linear regression within groups on emergent beach, Gisborne.

Scource	D.F.	S.S.	M.S.	F
Group 1				
Ridges: Total	16	19,478.70		
Mean	1	19,321.00		
	15	157.70		
Regression	1	63.98	63.98	9.56†
Residual	14	93.72	6.69	
Swales: Total	17	18,149.18		
Mean	1	17,975.76		
	16	173.42		
Regression	1	35.77	35.77	3.90
Residual	15	137.65	9.18	
Groups 2 and 3				
Ridges: Total	9	3,184.39		
Mean	1	3,117.36		
	8	67.03		
Regression	1	63.32	63.32	94.5‡
Residual	7	3.71	0.67	
Swales: Total	10	2,906.65		
Mean	1	2,873.02		
	9	33.63		
Regression	1	30.21	30.21	70.3‡
Residual	8	3.42	0.43	
Group 4				
Ridges: Total	9	2,386.02		
Mean	1	2,361.96		
	8	24.06		
Regression	1	16.09	16.09	14.1†
Residual	7	7.97	1.14	
Swales: Total	9	1,854.19		
Mean	1	1,846.13		
	8	8.06		
Regression	1	2.90	2.90	3.92
Residual	7	5.16	0.74	

Groups 5 and 6

Source								D.F.	S.S.	M.S.	F
Ridges:	Total	...	...	...	..	...	...	...	16	3,829.60		
	Mean	...	...	...	...	...	...		1	3,757.67		
									15	71.93		
	Regression	...	...	...	...	...	...		1	3.34	3.34	0.68
	Residual	...	...	...	...	...	...		14	68.59	4.90	
Swales:	Total	...	...	...	..	...	...	...	17	2,079.88		
	Mean	...	...	...	...	...	...		1	1,987.20		
									16	92.68		
	Regression	...	...	...	...	...	...		1	4.20	4.20	0.71
	Residual	...	...	...	...	...	...		15	88.48	5.90	

† Indicates significant at 1% level of probability.

‡ Indicates significant at 0.1% level of probability.

APPENDIX III

Analysis of variance table for linear regression on Seven Mile Beach, Tasmania.

Source								*D.F.*	*S.S.*	*M.S.*	*F*
Ridges:	Total	...	...	...	...	...	...	...	42	3,105.50		
	Mean	...	...	...	...	...	...	...	1	2,990.46		
									41	115.04		
	Regression	...	...	...	...	...	...		1	32.31	32.31	15.6†
	Residual	...	...	...	...	...	...		40	82.73	2.07	
Swales:	Total	...	...	...	..	...	...	...	41	1,649.20		
	Mean	...	...	...	...	...	...		1	1,551.34		
									40	97.86		
	Regression	...	...	...	...	...	...		1	21.57	21.57	11.0†
	Residual	...	...	...	...	...	...		39	76.29	1.96	

† Indicates significant at 1% level of probability.