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A 7000-year Record of Great Earthquakes at Turakirae Head, Wellington, New Zealand

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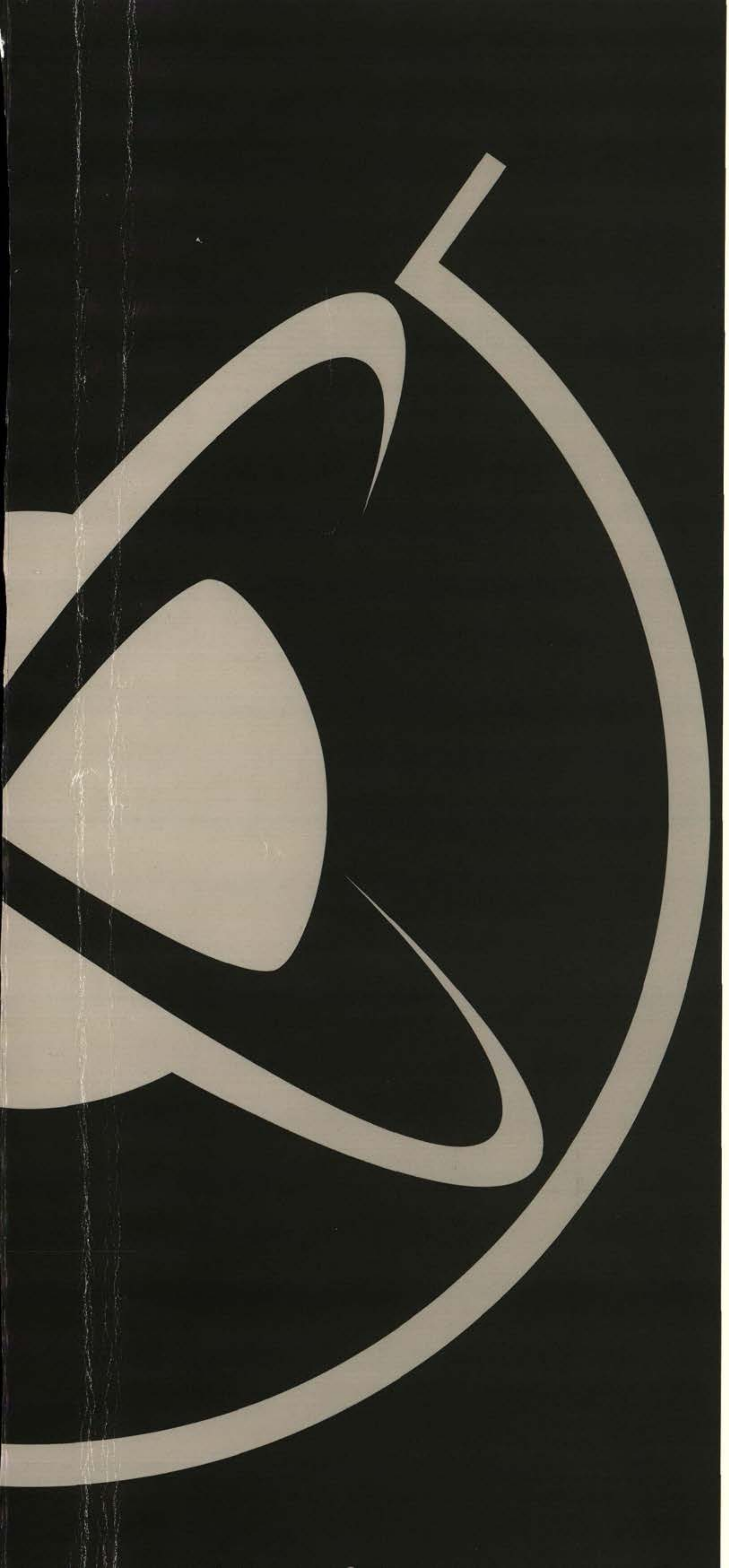

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A 7000-year Record of Great Earthquakes at Turakirae Head, Wellington, New Zealand

by

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Prepared for

EARTHQUAKE COMMISSION

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SUMMARY

Turakirae Head at the south coast of the North Island of New Zealand preserves a spectacular flight of four Holocene marine terraces, the lowest of which is marked by a storm beach ridge (BR2) raised in New Zealand's largest historical earthquake, the great Wairarapa earthquake of January 1855 (est. M8.2). Analysis of 23 surveyed beach-normal profiles across the terraces indicates that maximum uplift in the 1855 earthquake was 6.4 m, not 2.7 m as previously thought. The previous uplift event (BR3), formerly thought to date from 1460 AD, occurred *ca*. 200–382 BC, and had maximum uplift of 9.1 m. Two storm-beach ridges above these well-dated ridges indicate earlier uplift events of 5.5 and 3.0 m. The oldest preserved ridge (BR5) was raised by 3 m *ca*. 5100–5400 BC. The 4 events are the complete record of uplift through great earthquakes at this locality since sea level stabilised at about its present level about 7000 years ago.

All four coseismically uplifted, storm-beach ridges are tilted relative to sea level, with westward tilt being progressively greater with increasing age and uplift. The ridge BR2 first tilted in 1855, varies systematically in height from 1.5-6.4 m above the modern storm beach, reaching its maximum at the crest of the Rimutaka anticline.

Dated uplift events at Turakirae Head are slip-predictable. An uplift vs time plot provides the best estimate of the time of uplift (*ca* 3370±70 BC) of the only raised beach not otherwise dated (BR4). The coastal uplift rate at the crest of the anticline has been 2.91±0.04 m/ka over the last 7200 years.

A strong relationship between uplift magnitude and elapsed time since previous uplift suggests that probability of uplift of a given amount is proportional to accumulated elastic strain energy. Such a model suggests that the distribution of uplift magnitudes should be log normal. The data provide an acceptable fit to a log normal distribution (F = 46.8, 2.1% probability that model should be rejected). In such a model, the mean uplift per event is 5.90±1.26 m, but the most frequently occurring (modal) uplift is 4.92±1.05 m, and the relationship between uplift and elapsed time since previous uplift indicates a mean recurrence interval between uplift of 2030±430 years, but the modal interval is significantly shorter at 1690±360 years.

The 1855 uplift was not significantly larger than either the mean or the mode, suggesting that most of the uplift events at Turakirae Head are the record of great earthquakes of similar magnitude to that of 1855.

Introduction

The sequence of exceptionally well-preserved, raised Holocene marine beaches along the southern North Island coast at Turakirae Head (Figure 1) near Wellington City has long been recognised as a record of coseismic uplift. (Lyell 1856, 1868; Crawford 1867, Aston 1912; Wellman 1967, 1969; Stevens 1969, 1975; Moore 1987). Recognition that this beach-ridge sequence records past earthquakes resulted from uplift of the youngest ridge during the great earthquake of January 23, 1855, M >8.1 (Eiby 1989), New Zealand's largest historical earthquake. The earthquake was accompanied at least 75 km of surface rupture showing 9–13.5 m of dextral strike-slip along the Wairarapa fault, and uplift and tilting over an area of at least 12 000 km^2. Coastal uplift of 2.7 m was recorded by Edward Roberts (reported in Lyell 1856, 1868) 10 km to the northeast of Turakirae Head immediately after the earthquake.

Wellman (1967) recognised that the uplift of 1855 was clearly a model for the formation and uplift of the older beach ridges in the sequence. He recognised six gravel beach ridges, the youngest representing accumulation of beach gravel since the uplift of 1855. He surveyed the elevations of each beach ridge, and used the elevation change along ridges to calculate the amount of westward tilt and differences in elevation between beach ridges to determine the amount of uplift occurring in successive coseismic uplifts. By assuming Holocene sea-level changes to be the same in New Zealand as in other parts of the world, he calculated the age of the oldest ridge to be about 6,500 years old. In the absence of any radiocarbon dates, he calculated the time of each large earthquake by assuming constant average uplift rates, with the inter-event time recorded by the volume of material in each beach ridge - the larger the cross-sectional area of the ridge, the longer the time between earthquakes.

The first independent dates for the beach ridges were C^{14} dates presented by Moore (1987), from shell, wood and peat samples collected from behind and within beach ridges. He confirmed Wellman's estimate for the age of the highest beach ridge by dating two samples of wood immediately overlying beach gravels at the landward edge of the ridge. He reported dates from 21 other samples taken from other parts of the beach ridge sequence.

The studies of Wellman and Moore were based upon recognition of the present storm beach, and then counting the number of discrete beach ridges preserved between high tide and the foot of the Rimutaka Range. A critical step in interpreting the number and time of uplift of individual beach ridges is the recognition of the modern storm beach and the storm beach uplifted during the 1855 earthquake. Wellman and Moore argued that the modern ridge was a small gravel ridge closest to the present coast, and that a larger storm beach ridge at 2.5-3.3 m.a.s.l. was that uplifted in 1855. The larger ridge at about 9 m.a.s.l. at Cape Turakirae was estimated to have been uplifted about 500 years ago.

Our present study was motivated by the need to resolve better the recurrence of great earthquakes within 25 km of New Zealand's second largest city, containing its centre of government and about 400,000 people. We recognised several questions and possible errors from previous studies that, if addressed with new data, could significantly change the recurrence time of great earthquakes similar to that experienced by the fledgling colonial settlement of Wellington in 1855. Our study was developed to address the following problems:

(1) Our observations indicated that much of the beach ridge that previous workers had identified as uplifted in 1855 was still receiving material from post-1855 storms, such as small gravel, bricks, plastics, preservative-treated pinus and decaying organic matter. To account for this ongoing deposition on the supposed 1855 beach ridge, both Cotton (1921) and Moore (1987) independently hypothesised that the modern storm beach was in places over-riding the 1855 raised beach. However, neither recognised that if 1855 uplift was 2–2.5 m, their hypotheses implied either very substantial but unrecognised post-seismic subsidence, or post-1855 storm waves enormously higher than the highest

pre-1855. Our hypothesis was that the beach ridge identified by previous workers as uplifted in 1855 was the modern storm beach, and that uplift occurring from four, not five, great earthquakes is preserved along the Turakirae Coast.

(2) Few existing dates could be related directly to the time of uplift of each storm beach ridge. Most dated samples were from organic material reworked during storms or deposited once beach ridges had developed and been uplifted. Our preliminary studies showed that a large amount of previously unrecognised *in-situ* shell material was preserved between the inferred ca. 500 year old beach ridge and the 1885 uplifted beach ridge recognised by previous workers. Existing interpretations of Wellman (1967) and Moore (1987) indicate that this shell material must be about 500 years old, while our hypothesis indicated it was uplifted in 1855. This proposed age difference can be resolved with radiocarbon dating. Samples of *in-situ* shell material preserved beneath uplifted sea stacks offered the potential to date directly uplifts prior to 1855.

(3) Field observations of sample sites behind the highest beach ridge reported by Moore (1987) indicated that a further storm beach ridge is preserved above the one that he sampled. At least one beach ridge is probably older than 6,500 years.

(4) Existing interpretations suggested that single-event uplift amounts ranged from 2.5–9 m at Turakirae Head, with inter-event times ranging from 500 years to 2,500 years. If this large variation in uplift and periodicity could be confirmed, then it could provide valuable insight into processes producing great earthquakes at the subduction margin along much of the southeastern coast of North Island of New Zealand.

This paper reports the results of surveying, comparative photography (1911–1995) and radiocarbon-dating studies along the Turakirae Coast. New elevation and age data are used to re-evaluate the age and distribution of storm beach ridges preserved along the Turakirae Coast. New age data are used to determine the magnitude and recurrence of great earthquakes along the southern part of the Wairarapa fault and test existing models for the mechanism of the 1855 earthquake.

Survey and Sampling Procedures

Ridge nomenclature

In the earliest study of the raised beaches at Turakirae Head, Aston (1912) referred to the beaches by number, with 1 the youngest and 5, the oldest. Wellman (1967) recognised 6 ridges and labelled them A through F from lowest to highest. Stevens (1974) referred to them by their inferred ages (0, 114, 509, 3100, 4900, and 6500 years ago). Moore (1987) relabelled the six ridges identified by Wellman (1967) as BR0 to BR5. In this study, we retain Moore's nomenclature. We no longer recognise Wellman's ridge A as part of the population of storm beaches because it is ephemeral: similar ones formed and disappeared during the course of our study. We label storm beach ridges from BR1 (lowest)–BR5 (highest) from the coast to the foot of the Rimutaka Ranges (Figure 1).

Previous surveying work

There is some doubt as to how the earliest estimates of uplift in the 1855 earthquake were determined because Lyell (1857) did not record the survey method used. There is little doubt, however, that they were determined by a skilled observer using appropriate methods. Edward Roberts, who provided some of the estimates, was an engineer, seconded to the Wellington provincial government from the Royal Engineers to develop harbour facilities at Wellington. Lyell reports Roberts as accurately measuring the amount of uplift of rocks at Mukamuka Point (our profile 17 north of Mukamuka Stream, Figure 2), where he identified an uplifted white band of marine organisms which formerly had been just below low-tide level. Lyell reports the white band as being 9 feet (2.74 m) higher than before the earthquake. This value has been accepted by subsequent workers as the maximum uplift for not only Mukamuka Rocks, but also for all of the coast southwest to Turakirae Head. We, however, accept it only as a close minimum value at the point of observation, because we are not aware of a reason Roberts could have had to establish an accurate datum of mean sea level at the site, either before or after the uplift. It is unlikely that he would have determined the depth below low tide of the appropriate band of organisms before the event, and he could not have done so subsequently because he left the Wairarapa valley on 24 January to return to Wellington. He left for England within a few months.

Aston (1912) reported ridge heights of 9 ft, 40 ft, 60 ft, 80 ft and 95 ft, determined by aneroid barometer. These elevations are similar to the maximum values reported by Wellman, and found in our survey. Aston, who had a major botanical as well as geological interest in the ridges, fortuitously recorded heights from the location of maximum elevation of ridges, because this is where vegetation differences between ridges is best developed. Aston noted that the levels of the beaches were practically constant along their length based on his surveys, implying that he did not recognise the ridge sequence between Wainuiomata and Orongorongo Rivers as equivalent to that at Turakirae Head.

Beck (1958) surveyed two profiles with theodolite and stadia across the ridges: one about 400 m south east of Orongorongo River, and another at Turakirae Head about 1 km further southeast. He found little difference in heights of equivalent beaches between the two sites and generalised them as occurring at 8 ft, 22 ft, 36 ft and 45 ft. These sites appear to lie in an area where we found a kilometre of coastline with little difference in beach-ridge elevation. He was unable to resolve the large discrepancy between his survey data and those of Aston.

Using a local datum of approximate mean high water mark, Wellman (1967) surveyed the ridges by levelling between points about 100 m apart along the crest of each ridge with an automatic level. The effect of natural irregularities of about ±0.3 m were smoothed by averaging levels over distances of 500 m. This revealed progressive tilt of the ridges rising from west to east, and with increasing age of ridge. Extrapolations of averaged levels on ridges C through F converge near Pencarrow Head, while those for A and B converge on the outer western Wellington coast.

Surveying Methods for this Study

We surveyed 23 profiles normal to the shoreline at localities where the beach ridges were well developed between Pencarrow Head and Mukamuka Stream (Figure 2). We established elevations for each profile with respect to the Wellington Datum by levelling between existing horizontal survey traverse marks and all profiles. Most profiles were taken close to these traverse marks. In the northeastern part of the Turakirae Coast, existing survey marks are absent, but vertical elevation control was established by GPS survey (J. Beavan, personal communication 1995). We estimate the natural local variation in ridge height in the vicinity of our profiles to be about ±0.3 m, about twice the minimum surveying precision of ±0.15 m.

Profiles across the ridges (Figure 3) were annotated with ridge identification as profiling progressed, and these were then linked to provide longitudinal profiles along the ridges (Figure 4). Ridge identification primarily was based on position in the sequence, except insofaras BR1 and BR2 are traceable laterally from Pencarrow Head to Mukamuka Stream with no significant breaks that would create possibilities of misidentification. The older ridges (BR3, BR4 and BR5) each have a variety of identifying characteristics, the most obvious of which is their relative vertical separation within the sequence which is preserved in all profiles east of Baring Head. All ridges differ in morphological preservation, development of vegetation cover, relative weathering of surface clasts and soil development. Although it might appear that BR5 has been misidentified as BR4 at one point along the coast (Fig. 5, about 5 km from profile 22), the two are sufficiently distinct for this hypothesis to be eliminated. BR5 is missing from this site. Between Pencarrow and Baring Heads, identification of higher beaches is solely on position in the sequence and only BR1 and BR2 are identified with certainty.

At several sites, ridge surfaces are augmented by dunes, particularly in profile 24 where sand dunes of unknown thickness, possibly as much as 2–4 m, lie atop BR2 and BR3.

Within the limits of surveying errors, survey results presented here are statistically identical with those of Wellman, and differ only insofar as our profiles extend from Pencarrow Head to Mukamuka Stream. Wellman's profiles were confined to the centre of our survey, where the beach ridges are essentially continuous.

Sampling for Radiocarbon Dating

In his study of the ages of the beach ridges at Turakirae Head, Moore (1987) presents 23 radiocarbon dates from materials associated with the ridges, mainly from BR2 and BR5 (Table 1). The majority of these samples are transported shell material that provide only minimum estimates of the initial formation time of the storm ridge and maximum ages for its uplift. Samples from near the higher and older beach ridges are predominantly wood and peat that provide minimum estimates for the age of storm beach ridge uplift. Moore accepted the heights of ridges determined by Wellman (1967), and recorded the location of his dated samples with respect to the nearest storm beach ridge.

For this study, we selected shell material for radiocarbon dating predominantly from the marine-cut platform between the modern storm beach and that uplifted in 1855 in the vicinity of profile 7 (Figure 2). A range of shell species were collected at different parts of the platform ranging from just below the base of the BR2 (former high-tide level) to immediately behind BR1 (former low to subtidal level). Only samples judged to be preserved in growth position were collected, and their elevation with respect to modern sea level determined by survey methods described above. Species identification by A. G. Beu (personal communication 1994, 1995) was used to reconstruct the position with respect to sea level prior to emergence.

In addition to samples from the former tidal zone associated with BR2, the equivalent tidal zone associated with BR3 was searched for similar *in-situ* fauna. Despite extensive leaching and loss of most of the carbonate from this area, several sites were found where thick carbonate crusts of polychaete worm tubes (*Salmacina australis*,) had survived leaching, and preserved shells associated with them. Shells overgrown by the polychaete crust (NZA 4746), and shells nestling in and on the crust (NZA 4747: Table 1) were dated.

Prior to radiocarbon dating, all samples were scrubbed in water, dried, crushed and treated with dilute hydrochloric acid. Evolved carbon dioxide was collected, purified and counted in carbon-dioxide proportional gas counters to determine the conventional radiocarbon age (Table 1). All 12 samples dated were of short-lived species (<10 years), and in the case of larger species, the outer shell rims were dated.

Beach Ridges Along The Turakirae Coast

The shore at Turakirae Head presents a rocky coastal plain 300–600 m wide between the sea and the steep slopes of the Rimutaka Range (Figure 1). Along this boulder-strewn, sloping marine-cut platform are a series of five irregular ridges of coarse gravel, from 0–3 m high, crudely subparallel to the present shoreline and the flanks of the Rimutaka Range. The lowest in the sequence is the modern storm beach (Figure 6). This ridge marks the landward extent of the transport of gravel by storm waves. The four gravel ridges above the modern one are former storm beaches marking the limits of the transport of gravel by storm waves prior to the 1855 earthquake and previous uplift events. The rock platforms in front of each ridge are the corresponding wave-cut platforms, presently or formerly home to the sub-tidal, inter-tidal and supra-tidal flora and fauna of present and past shorelines.

The Modern Storm Beach (BR1)

The modern beach along the Turakirae Coast consists of a swash zone worked by waves during normal conditions and tides. Clasts on the beach are pushed up the beach in the direction of travel of the impacting wave, and carried directly down the local slope of the beach as the water drains back. In this way, clasts are moved along the beach (long-shore drift) when waves impact at an oblique angle to the shore. When fresh gravel becomes available, it is spread within the swash zone, adding to the seaward face of the beach, and if supply is plentiful, a small ridge may be built at the line of the local modal wave fetch. Thus, in normal sea conditions, longitudinal ridges may be built on the seaward beach face, particularly in the vicinity of the Orongorongo River mouth where supply is from the river. When storms fetch significantly higher waves, gravel on the beach face is moved higher on the beach, and ridges on the beach face are smoothed, or shifted higher up the beach. At the modal storm wave fetch on higher tides and storm surges, the minor ridges tend to accumulate as one, and a major storm beach ridge develops. A locally well-defined driftwood line landward of the crest of the modern storm beach attests to waves occasionally surging over the storm beach, but these exceptional waves are infrequent and rarely scour the crest to move it slightly inland.

Sediment sources for the modern beach currently are dominated by supplies from the major streams draining to the sea. Orongorongo River is the largest supply. At various points along the coast, particularly at the rapidly-forming young alluvial fan northeast of Barney's Hut and the coastal sea cliffs northeast of Mukamuka Stream, an abundant gravel supply is permitting the build up of a large modern storm beach ridge. Indeed, at many points along the coastline, the cross-sectional area of the modern beach ridge is similar to that uplifted in 1855 (see many of the profiles in Figure 3).

Direct erosion of the seabed within the shore and nearshore zones, out to the depth of storm wave base, perhaps as great as 25 m below mean sea level (Pillans & Huber 1995) are lesser sediment sources than the major streams. Where ancient alluvial fans and valleys with alluvial valley fills projected seaward to lower sea level positions of early Holocene and late Pleistocene times, or where ancient landslides from the slopes of the Rimutuka Range have carried rubble into the sea, the quantity of sediment available from direct erosion of the sea bed is locally large. This may be the dominant sediment source away from Orongorongo River and Mukamuka Stream. A small amount of sediment comes from direct erosion of the hard greywacke sandstone and mudstone bedrock, but where this is the only supply, the modern beach is very poorly developed without a defined ridge crest.

At a number of localities the seaward drainage of freshwater has been impeded by the growth of a large modern storm beach ridge. Ephemeral ponds behind the beach ridge permit the growth of peat and organic-rich soils. Near Barney's Hut, we recorded over 0.5 m of fibrous peat accumulating behind the modern beach ridge.

Identification of Modern Storm Beach Ridge

Critical to the interpretation of the tectonic history preserved along the Turakirae Coast is identification of the modern storm beach. Earlier studies have shown confusion as to its location, principally because the first major storm beach ridge ranges from 2–6 m.a.s.l., which is similar to the value of coseismic uplift in 1855. The earliest scientific reference to the beaches at Turakirae Head is Aston (1912). Aston (1912, pg. 209) knew from earlier records (Crawford, 1867) that the nearby coast to the north east (at Mukamuka Rocks) had been raised 2.74 m (9 ft) and "carefully searched the boulder-strewn shore a little above high-water mark, and was rewarded by finding traces of a shingle beach about that altitude (9 ft) above high-water mark. That the sea is now breaking on boulders and monoliths somewhat discounts the thought that beach No. 1 may be a mere storm beach." Aston photographed his Beach No.1 (Aston 1912, Fig. 4, reproduced here as Figure 8) and asserted that it was elevated by the 1855 earthquake.

The exact site from which Aston's Fig. 4 was photographed is a 2 m high boulder that is readily revisited (Figure 7). When rephotographed in 1995 (Figure 9), the ridge was found to have changed significantly over the intervening 84 years or so (compare Figs 8 and 9). The changes result from storm waves continuing to spill over the ridge, moving the crest a few metres inland of its position of *ca.* 1911. In August 1995, the seaward face of this ridge was well covered to the ridge crest with fresh drift wood and modern jetsam (Figure 6). Seaward of the coarse gravel ridge of BR1 was only a bouldery supra- and inter-tidal zone, swept clean of almost every movable clast. We believe that there is no possibility that Aston's Beach No. 1 was elevated 2.74 m in 1855: it is the modern storm beach that can be walked from the inner shores of Palliser Bay to Port Nicholson.

As a further test of our interpretation that earlier workers have misidentified the modern and 1855 storm beach ridges, we dated in-situ shell samples preserved between our modern (BR1) and the 1855 uplifted (BR2) storm beach ridges. Dates from 10 shell samples taken from three locations along the shore platform between BR1 and BR2 (Table 1) reveal a weighted mean conventional radiocarbon age of 488±13 yr BP and calibrated ages with a total range of 271-0 cal BP. The conventional radiocarbon age for 1850 is 498±10 yr BP, suggesting that most of these shells died close to 1855, assuming that the carbonate came from within shells that did not live longer than 10±5 years. While these age data do not have the dating resolution to establish directly an A.D.1855 age, they are sufficiently close to this time to accept that they date from the 1855 uplift. More importantly, they are not 500 years old as predicted by Wellman (1967) and Moore (1987). We believe that our observation of continued accretion of the beach ridge identified by Aston (1912) and our dates from between BR1 and BR2 unequivocally show that BR1 is indeed the modern storm beach, and BR2 is the storm beach that had accumulated prior to coseismic uplift on 23 January 1855.

Height Variation along the Modern Beach (BR1)

The modern storm beach varies in height along the coast (Figure 4). This is a function of size of clasts available, beach aspect to prevailing storm waves, gradient of the nearshore platform and wave energy dissipation on irregularities on the nearshore and foreshore platforms. It is at its highest (6.5 m.a.s.l.) near Pencarrow Head where it is built of much sand and fine gravel on a steeply sloping shelf. It ranges from 5–6 m.a.s.l. from Baring Head to Orongorongo River (Figure 2) where gravel and sand are in abundant supply, again on a steeply sloping shelf. Eastward to Turakirae Head, supply diminishes, particle size coarsens, shelf gradient decreases, and ridge height diminishes to about 3 m. In one small area of rocky coastline on the outermost western Palliser Bay coast, the supply is so limited that there is no crested ridge as elsewhere, and the maximum height of coarse cobbly gravel is anomalously low at 2.1 m (Profile 13, Figure 4). Here, where the bouldery coastal platform is at its broadest, much wave energy is dissipated against the rocks in a very low gradient runup to the storm beach. In this area, however, the landward limit of modern driftwood reaches to 3.3 m above sea level datum.

Because the modern storm beach is not a constant height above true sea level, and does not strictly present a synchronous surface, it provides an imperfect and imprecise reference datum to establish accurate values of coseismic uplift. Nevertheless, it is the most significant and persistent datum from which to determine local uplift in the 1855 earthquake. At a few very limited localities, zonations of living marine organisms relative to equivalent uplifted *in situ* fossils, as used by Roberts in 1855, are still an option for use in 1995. For determining uplift in earlier events, however, heights differences between storm-beach ridge crests is the only useable measure of uplift, however imprecise ridge height might be. The events recorded all are of such magnitude, that amounts of uplift are well determined, notwithstanding that reference data are imprecise.

Our surveys of beach ridge heights show substantial variation in heights of individual ridges (Figure 4). For the modern storm beach, the greatest height (6.4 m) was measured at Lake Kohangapiripiri near Pencarrow Head, and the lowest (2.1 m) a few hundred metres southwest of Barney's Hut. The trend in height variation for the storm beach raised in 1855 was very different, with the lowest point (5.2 m) at the southern end of Fitzroy Bay. and the highest (9.7 m) near Barney's Hut. Older ridges repeat this trend, but with increasing range in elevation from lowest to highest.

At profiles 2, 23 and 24 (Figures 3 and 4), the measured height of the modern storm beach includes small, but unknown thicknesses of dune sand above the beach gravel. Dune sand also buries BR 2 and 3 at profile 23 in Fitzroy Bay, but the unknown thicknesses are insufficient to explain the differences in equivalent ridge heights between profiles 23, 24 and 25. We presume that differences relate to real differences in storm-wave runup between the sites.

Height of 1855 Storm Beach (BR2)

Correct identification of the modern storm beach (BR1) and that uplifted in 1855 (BR2) permits definition of the pattern of uplift in 1855, independent of the single reliable observation taken along the Turakirae Coast by Roberts in 1855. BR2 can be followed from east of Pencarrow Head to a modern alluvial fan east of Barney's Hut, and then after a break of several kilometres, along several kilometres of coastline between Fisherman's Rocks and the rocky point east of Mukamuka Stream. Continuity and state of preservation of BR1 and BR2 prevents miscorrelation along about 20 km of coastline. Continuity of BR2 into Port Nicholson is limited by post-1855 urbanisation and particularly by construction of a coastal road to Pencarrow Head.

Figure 5 shows the distribution of the heights of all storm beach ridges relative to the height of the modern storm ridge. The maximum elevation of BR2 of 6.4 m above its modern equivalent occurs at Profile 14, close to Barney's Hut, 4 km northeast of Turakirae Head, and decreases to about 2–3 m to the east and west The distribution of heights of BR2 above BR1 (Figure 5) represents approximately the net uplift along this section of coast that resulted from the Wairarapa earthquake in 1855.

Heights of Older Beach Ridges (BR3, BR4, BR5)

Figure 5 also shows the cumulative uplift of BR3, BR4 and BR5 with respect to BR1. All show a similar height distribution to that occurring during the 1855 earthquake - a strong westward tilt. Only BR2 is preserved to the east of the zone of maximum uplift. Figure 10 gives the distribution of inferred, net single event uplifts for each of the four storm beach ridges preserved along the Turakirae Coast.

Wellman (1967) found the maximum uplift of beach ridges to be in the vicinity of Barney's Hut at what he determined to be the coastal intersection of the crest of the Rimutuka Anticline. Although the data (Figures 5 and 10) appear to define an anticline crest near this locality, surveying imprecision and real variation in beach-ridge heights along the profiles do not permit the axial trace of the anticline to be defined with much useful precision. Indeed, the data only define one limb, and it is only the absence of a surface fault trace through the landscape north of Barney's Hut which implies the existence of another fold limb between Barney's Hut and Fisherman's Rock. There is little significant gradient on the short lengths of raised beaches northeast of Barney's Hut. We assume, therefore, that this portion lies at the crest of the Rimutaka Anticline.

Development and Ages of Beach Ridges

Correct identifications of the modern and 1855 beach ridges, and observations of the development of the modern storm beach ridge permit an understanding of the relationship between sediment supply, storm-beach formation, growth and eventual abandonment in response to coseismic uplift.

Rate of Beach Development

Wellman (1967) assumed a constant rate of accumulation of gravel at any one part of the coast, and used ridge cross-sectional area to estimate times of uplift of some of the beach ridges. The assumption, however, is valid only in proximity to gravel sources which have continued to supply gravel to the beach. For example, the Orongorongo River and other significant streams such as Mukamuka Stream have always delivered gravel to the sea. However, at a number of localities, screes, landslides and small alluvial fans were sources of local supply only while they were within the reach of wave attack, but uplift has removed them from the coastal sediment budget. In these areas, beach ridge size is a function of both time and a very time-variant sediment supply. It is not clear for which locations Wellman determined ridge cross-sectional areas, hence it is not clear whether his estimates are likely to have been seriously affected by time-varying sediment supply.

Our rephotographing of Aston's Figure 4, and the new dates for *in-situ* marine fauna preserved on the 1855-uplifted platform indicate that storm-beach ridges form rapidly following sudden emergence of the coastal platform during great earthquakes. In just 140 years, a major modern storm beach ridge has developed that is almost equivalent in volume to the one accumulated along the same part of the coast for more than 2,000 years (Table 1). Indeed, a substantial ridge had developed by 1911 (Figure 8). Because storm beach ridges appear to grow rapidly along the newly-exposed coast, organic material begins to accumulate behind the ridge within about 100 years of its initial formation. Thus the age of the oldest organic material preserved behind a major storm beach ridge is close to the time of initial ridge formation, which is simultaneously the time of uplift and cessation of growth of the beach ridge above.

Model for Beach Ridge Formation and Uplift

Wellman (1967) argued that sudden uplift, as in 1855, was the emergence mechanism for all the other storm ridges, and that the complete sequence of beach ridges records all the earthquakes that have occurred along the Wairarapa fault over about the last 7000 years. He postulated that storm beach ridges represented periods of no uplift and constant relative sea level. The rock platform between ridges contained no beach ridges and represented an intertidal and subtidal wave cut-platform that became emergent as a result of coseismic uplift.

Our study confirms Wellman's observation that there are no beach ridges preserved between the large ridges of BR1-BR5. Our interpretation also shows that formation of storm beach ridges is practically instantaneous, so that the beach ridges preserved along the Turakirae Coast record all permanent, metre-scale uplifts that have affected it.

Our model for the formation and uplift of beach ridges along the Turakirae Coast has a beach ridge continuously forming during periods of stable relative sea level. The ridge is built quickly, then continually modified until it is suddenly uplifted several metres during a great earthquake. The uplift terminates further growth of the uplifted beach ridge and results in the emergence above sea level and subaerial exposure of the former intertidal and upper subtidal zones in front of the now emergent ridge. The flora and fauna that lived within this zone are killed, and all but the shell carbonate quickly decays in the moist, temperature conditions in this part of New Zealand. A new beach ridge forms rapidly near the maximum fetch of storm waves, up to several hundred metres seaward of the newly uplifted ridge. Peat accumulation commences behind the new ridge, and continues unabated behind the newly elevated one. With repeated uplifts, more ridges are stranded along the emergent coast. For any single beach ridge, the time of its initiation is recorded by the age of the intertidal and subtidal fauna landward of the ridge. A minimum estimate for the time of formation of the ridge is recorded by the oldest peat preserved immediately behind it. Thus the time of coseismic uplift of the ridge is recorded by the age of the *in-situ* fauna seaward of it, while the initiation of peat growth immediately behind the next seaward ridge provides a minimum age for the date of its uplift.

Dates of Individual Ridges and Time of Past Earthquakes

Our model for ridge formation and emergence along the Turakirae Coast can be used to reconstruct the paleoseismicity of the Wairarapa fault. If we can date the age of formation of each beach ridge by the flora and fauna preserved in association with the ridge and on adjoining shore platforms, then we can estimate the age of each earthquake and calculate the intervals between them. Thus, data from Table 1 can be used in conjunction with the coastal geomorphology and stratigraphy to estimate the dates of earthquakes preserved along the Turakirae Coast.

BR1 and BR2

BR 1 and BR 2 have ages determined from historical records of modern and 1855 AD respectively. Moore (1987) reported dates from 13 samples collected from within BR2. He used dates from intertidal *Halotis iris* that were transported up the beach profile to their collection position within the storm beach gravels to support a ca. 500 year age for the uplift of BR2. However, because all these samples are transported to an active storm beach ridge, their ages provide only a maximum age for the uplift of BR2.

BR3

The age of BR3 can be estimated from two samples collected beneath a former sea stack boulder on the shore platform seaward of BR3. In sites sheltered from the effects of wind and rain, large sheets of tubes of small polychaete worms (30 mm x 20 mm) are intertwined to form a dense calcareous crust up to 70 mm thick. The tubes are created by *Salamacina australis* which forms crusts in the shallow, subtidal zone (Morton & Millar 1968). A single sample from one of these crusts seaward of BR3 has an age of 1258-1106 cal BP (NZ 8212; Table 1).

The worm crusts were found in two localities to have overgrown barnacles (*Epopella* and *Tetraclitella*) and a limpet *Gadinalea conica*, indicating the same shallow subtidal environment as the worm crusts (A. G. Beu, pers com. 1995). However, within many of the tubes, large numbers of the intertidal bivalve *Lasaea rubra* and high-tide mussel *Xenostrobus pulex* are preserved. Dates from *Gadinalea conica* (NZA 4747) and *Xenostrobus pulex* (NZA 4746) are essentially the same at 2050–2565 cal BP. The date from *Xenostrobus pulex* is considered to be closest to the time of uplift because they have grown within the worm tubes that overgrow the *Gadinalea conica* sample. Thus the time of uplift of BR3 and initiation of formation of BR2 is between 2050–2450 cal BP.

A date of 1106–1258 cal BP (NZ 8212) from *Salmancina australis* is anomalously young when compared to the samples 100–1200 years older located immediately above and below it. That there is some contamination of this sample by modern carbon is shown by the high positive delta^{13}C value when compared to other marine samples that typically range from -2 to 2‰ (Jansen 1984). By contrast, a sample of *Salmancina australis* dated from the 1855 uplift is anomalously old, and has a delta^{13}C value more typical of marine samples. The causes of these incompatible ages are unknown, but based on the two samples dated in this study, *Salmancina australis* does not produce radiocarbon dates that accurately reflect the time of shore platform uplift.

BR5

The age of uplift of BR5, and initiation of BR4, is recorded by the oldest driftwood and peat accumulated behind BR4. The oldest samples from behind BR4 is NZ 4420 (7379–7021 cal BP). Thus, Beach Ridge No. 5 first rose above the fetch of waves *ca.* 5100–5400 BC, If the uplift rate has been uniform over time, BR5 probably began to form *ca.* 6300 BC (Figure 11), but this estimate does not consider global eustatic changes in sea level around that time.

BR4

Only the time of initiation of BR4 has been determined in this study by radiocarbon dating: it began to form *ca.* 5100–5400 BC (as determined from NZ 4420 above). An uplift vs time plot (Figure 11) provides the best estimate of the time of uplift of BR4. Based on a uniform rate of uplift model, and a eustatically stable global sea level, BR4 probably first rose above the fetch of waves *ca.* 3370±70 BC when it was raised by 5.5 m near Barney's Hut.

Average Return Period of Uplift

Beach ridge uplift and beach ridge age are very highly correlated (Figure 11), with cumulative uplift explaining 99.98% of the variance in age. The slope of the line connecting all four earthquake events indicates and average uplift rate of 2.9±0.04 m/ka for the last 7200 years at the crest of the Rimutaka anticline. The strong relationship between accumulated uplift at Turakirae Head and elapsed time suggests that probability of uplift of a given amount is proportional to accumulated elastic strain energy. Such a model implies that the probability density distribution of uplift magnitudes (Figure 12) should be log normal. The data provide an acceptable fit to a log normal distribution (F = 46.8, 2.1% probability that model should be rejected). In such a model, the mean uplift per event is 5.90±1.26 m, but the most frequently occurring (modal) uplift is 4.92±1.05 m. The relationship between uplift and elapsed time indicates a mean recurrence interval between uplift of 2030±430 years, but the modal interval is significantly shorter at 1690±360 years (Figure 13).

The 1855 event at 5.975 m uplift (average of three measurements near anticline crest) was not significantly larger than either the mean or the mode, suggesting that most of the uplift events at Turakirae Head are the record of great earthquakes of similar magnitude to that of 1855.

Limitations of the evidence

What is missing from the interpreted record, is evidence for possible subsidence. The coastal plain at Turakirae Head was not cut in its entirety in the late Holocene, but its entire surface was trimmed in that time, and all evidence of uplift events prior to cessation of rapid post-glacial sea-level rise apparently was obliterated in the marine transgression and subsequent regression across the plain. With this model of the effect of relative subsidence of the land, it is apparent that the direct evidence available for interpretation from this coastline could not detect episodic subsidence. Thus, the possibility of infrequent subsidence events cannot be dismissed on available direct evidence. The calculated uplift rate for the last 8000 years, however, shows evidence of having been remarkably uniform. If there had been subsidence in the area, it certainly did not occur in the last 140 years, yet must have occurred in such a pattern as to have preserved a remarkably tight-fitting linear relationship between time and net uplift. Such a hypothesis is too incredible to sustain, and so we conclude on indirect evidence that there has been no subsidence in the last 8000 years. Episodic subsidence with a longer recurrence interval than 8000 years remains a possibility, because long-term uplift rates, calculated from uplift of supposed Interglacial marine platforms in the area, are substantially less that corresponding rates for the last 8000 years. There also is adjacent evidence of subsidence in the presence of sedimentary basins in Palliser Bay, Port Nicholson and Cook Strait.

Implication to Tectonic Models of the Wellington Area

Prior to this study, a number of tectonic models were developed in attempts to explain the pattern of uplift accepted prior to this study (Darby & Beanland, 1992). The best-fit model was considered to be a listric Wairarapa fault model involving rupture on 0–50 km width of the deeper part of the subduction interface. An alternative flexed Wairarapa fault model involving an 8-km left-stepping offset of the Wairarapa fault between Lake Wairarapa and Palliser Bay (where thrust faults, Bloom [1951], and anticlinal folding, Grapes and Wellman [1988], are identified) was considered, but rejected as not producing a satisfactory fit to the available data. In particular, localised uplift west of the fault in this model was considered to be excessive at >4 m, and was too far north to produce the expected 2.7 m at Turakirae Head. This model did not include slip on the subduction interface.

We now recognise a particularly localised pattern of high uplift (>5m) very closely conforming to the flexed Wairarapa fault prediction, but the centre of local uplift is significantly further south, near Turakirae Head. The implication is that there was indeed a significant left step in the 1855 Wairarapa faulting, but the step was not between Lake Wairarapa and Palliser Bay, but further south, possibly at the Mukamuka Stream shear zone of Begg and Mazengarb (1996). Begg and Mazengarb (1996) recognise southward extensions of recent traces on the Wairarapa fault into the Rimutaka Range, with little offset. These can not be traced south of their intersection with the head of Mukamuka Stream, and hence there must be some fault offset in this vicinity.

The known pattern of surface faulting and ground deformation in 1855 at the southern end of the Wairarapa fault is more complicated than that modelled by the flexed Wairarapa fault model of Darby and Beanland (1992), but it is not greatly so. The qualitative distribution is sufficiently well modelled by it to suggest that the actual event was qualitatively very similar to the model, but differed mostly in the position of the offset. A model positioning the offset 10 km southwest of the Darby and Beanland flexed-fault model, would likely fit the revised uplift pattern exceptionally well. A significant implication of this model is that the 1855 earthquake did not involve slip on the subduction interface.

Conclusions

The hypothesis first put forward in Aston (1912), that Beach Ridge No. 1 along the coast at Turakirae Head was raised 2.7 m by the 1855 earthquake is unequivocally refuted by evidence that:

1 Beach Ridge No. 1 contains modern artefacts: plastics; sawn and preservative-treated pinus lumber; and partly decayed seal carcases;

2 Beach Ridge No. 1 has continued to evolve under the influence of storm waves since photographed by Aston *ca.* 1911;

3 Beach Ridge No. 1 continued to evolve under the influence of storm waves during the course of this study (1992-95);

4 Beach Ridge No. 1 is subparallel to the Wellington mean sea-level datum and shows none of the pattern of deformation which grows progressively with height in the sequence of other beach ridges around Turakirae Head;

5 Beach Ridge No. 2 and its associated former tidal pools contain fossils which date from the early to mid 19th century, positively identifying it as the beach ridge first raised by the 1855 earthquake;

6 Uplift at Turakirae Head in 1855 varied along the coast from 1.8 m near the mouth of Wainuiomata River to 6.4 m near Barneys Stream (average from 3 profiles in the vicinity of maximum uplift, 5.975 m). 1855 uplift was >4 m along more than 3.5 km of coastline based on height differences between Beach Ridges Nos. 1 and 2.

Beach Ridge No. 1 will continue to evolve at about its present range of heights until the next uplift event. It began to form after the coseismic uplift of 23 January 1855. Beach Ridge No. 2 first rose above the fetch of waves at 9.30 PM 23 January 1855 when it was raised a maximum of 6.4 m near Barney's Hut, and began to form *ca.* 200-382 BC. Beach Ridge No. 3 first rose above the fetch of waves *ca.* 200-382 BC (NZ 4746, 2603±86 BP; NZ 4747, 2563±78 BP) when it was raised a maximum of 10.0 m near Barney's Hut, and probably began to form *ca.* 3500 BC. Beach Ridge No. 4 is undated by radiocarbon dating, but based on a uniform rate of uplift model, and a eustatically stable global sea level, it probably first rose above the fetch of waves *ca.* 3370±70 BC when it was raised by 5.5 m near Barney's Hut, and began to form *ca.* 5100–5400 BC. Beach Ridge No. 5 first rose above the fetch of waves *ca.* 5100–5400 BC, and probably began to form *ca.* 6300 BC, but the latter estimate does not consider effects of global eustatic changes in sea level.

Beach ridge uplift, and hence age, fit log-normal probability density distributions. The mean uplift per event is 5.90±1.26 m (error at 1 standard error of the mean of 4 events), but the most frequently occurring (modal) uplift is 4.92±1.05 m. The 1855 event was not significantly different from either the mean or the mode, suggesting that most of the uplift events recorded at Turakirae Head are evidence of great earthquakes of similar magnitude to that of 1855.

Beach ridge uplift and beach ridge age are very highly correlated, with cumulative uplift explaining 99.98% of the variance in age. From the relationship between uplift and elapsed time since previous uplift, it follows that the mean recurrence interval between uplift events is 2030±430 years, but the modal interval is significantly shorter at 1690±360 years.

The pattern of uplift established for the 1855 earthquake in this study closely follows that predicted by the flexed-Wairarapa fault model of Darby and Beanland (1992) but the significant (8 km) left step was not at the thrust between Lake Wairarapa and Palliser Bay, but some 10 km southwest, possibly at the Mukamuka Stream Shear zone of Begg and Mazengarb (1996). The excellent qualitative fit to this model implies that the 1855 earthquake probably did not involve significant (if any) slip on the subduction interface.

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Table 1

List of radiocarbon dates relating to beach ridges at Turakirae Head.

NZ Fossil Record Number[1]	NZMS 270 Sheet R28 Grid Reference[2]	Sample Type[3]	$\delta^{13}C$ (‰)	Conventional ^{14}C age[4] (years B.P.)	Calibrated age (95%)[5] (cal B.P.)	NZ Laboratory Number[6]	Beach Ridge	Elevation (masl)*
N164/117		*Haliotis iris*	2.3	766±33	484–336	NZ 4229[7]	BR2	ns
R28/f1	69607390	*Haliotis iris*	1.4	809±33	509–413	NZ 4278[7]	BR2	ns
R28/f2	69607390	*Haliotis iris*	1.2	870±33	543–460	NZ 4279[7]	BR2	ns
R28/f10	72127395	*Haliotis iris*	1.7	601±32	313–152	NZ 4530[7]	BR2	ns
R28/f22	69407410	*Haliotis iris*	1.7	565±32	284–129	NZ 5101[7]	BR2	ns
R28/f23	69507400	*Haliotis iris*	2.0	613±55	408–125	NZ 5102[7]	BR2	ns
R28/f24	69607380	*Haliotis iris*	2.6	681±32	416–281	NZ 5103[7]	BR2	ns
R28/f25	70107265	*Haliotis iris*	2.1	596±28	304–156	NZ 5104[7]	BR2	ns
R28/f26	70307260	*Haliotis iris*	2.3	564±32	283–128	NZ 5105[7]	BR2	ns
R28/f27	70907300	*Haliotis iris*	2.2	571±32	287–134	NZ 5106[7]	BR2	ns
R28/f28	71407345	*Haliotis iris*	2.3	747±41	475–311	NZ 5107[7]	BR2	ns
R28/f29	71407345	*Haliotis iris*	2.3	830±28	514–439	NZ 5108[7]	BR2	ns
R28/f30	71707365	*Haliotis iris*	2.1	789±40	507–351	NZ 5109[7]	BR2	ns
R28/f59a	70427269	*Haliotis iris*	1.6	473±47	230–0	NZ 8140a	BR2	2.8
R28/f59b	70427269	*Haliotis iris*	2.3	466±41	221–0	NZ 8140b	BR2	2.8
R28/f62	70417266	*Serpulorbus zealandicus*	1.1	518±43	268–52	NZ 8213	BR2	2.8
R28/f63	70417266	*Haustrum haustorium*	3.1	489±35	214–77	NZ 8214	BR2	2.8
R28/f61a	70437270	*Diloma nigerrima*	2.0	490±36	243–0	NZ 8215a	BR2	4.5
R28/f61b	70437270	*Diloma nigerrima*	0.3	474±48	231–0	NZ 8215b	BR2	4.5
R28/f62a	70417266	*Melagraphia aethiops*	1.4	519±44	271–53	NZ 8270	BR2	2.8
R28/f62b	70417266	*Turbo smaragdus*	2.5	509±29	255–71	NZ 8271	BR2	2.8
R28/f62c	70417266	*Cellana denticulata*	0.3	452±45	198–0	NZ 8272a	BR2	2.8
R28/f62c	70417266	*Cellana denticulata*	0.3	454±50	198–0	NZ 8272b	BR2	2.8
R28/f65	70427269	*Salmacina australis*	2.4	977±36	637–523	NZ 8211	BR2	ns
R28/f64a	70427288	*Xenostrobus pulex*	1.3	2603±86	2565–2073	NZA 4746	BR3	9.9
R28/f64b	70427288	*Gadinalea conica*	1.3	2566±78	2450–2050	NZA 4747	BR3	9.9
R28/f64c	70427288	*Salmancina australis*	7.0	1604±32	1258–1106	NZ 8212	BR3	9.9
R28/f6	71577380	peat	-27.7	1450±50	1402–1243	NZ 4417[7]	BR3	ns
R28/f13	71907407	peat	-26.9	270±60	330–0	NZ 4548[7]	BR3	ns
R28/f3	71557400	peat	-29.4	4100±80	4826–4316	NZ 4414[7]	BR4	ns
R28/f4	71557400	freshwater shells	-5.3	10050±100	11942–10996	NZ 4415[7]	BR4	ns
R28/f5	71557400	wood fragments	-25.3	5840±90	6791–6410	NZ 4416[7]	BR4	ns
R28/f7	71557400	peat	-27.7	-47±45	modern	NZ 4418[7]	BR4	ns
R28/f8	71557400	peat	-28.3	2980±70	3263–2878	NZ 4419[7]	BR4	ns
R28/f9	71557400	wood fragments	-26.1	6360±80	7379–7021	NZ 4420[7]	BR4	ns
R28/f11	71557400	wood fragment	-22.6	6060±100	7161–6661	NZ 4550[7]	BR4	ns
R28/f12	71557400	wood	-23.9	5960±90	6980–6497	NZ 4549[7]	BR4	ns

Notes:

(1) Numbers are the New Zealand fossil record file, except N164/117 which is a NZ Archeological Association site number.

(2) Locations are 4-digit eastings and northings estimated from 1:25,000 scale maps by Moore (1987) and surveyed for this study.

(3) Shell species identified by Dr A. G. Beu, Institute of Geological and Nuclear Sciences, Lower Hutt

(4) Coventional radiocarbon age as defined by Stuiver and Pollach (1977).

(5) Calibration from Bard et al (1993) and Stuiver and Braziunas (1993) with geogrpahic offset (Delta-R) of -30±13 (McFadgen & Manning 1990) for shell samples. -40 years for terrestrial samples

(6) All samples dated by the Institute of Geological and Nuclear Sciences gas counters, except those with NZA that are dated by accelerator mass spectrometry.

(7) After Moore (1987)

Figure 1

Evidence for uplift of parts of the Wellington region during powerful earthquakes is preserved at the southern end of the Rimutaka Range. At Turakirae Head left-of-centre foreground) a broad coastal platform is ringed by stranded beach ridges. Thin Holocene beach and peat deposits mantle parts of the platform. The grey gravel strip immediately above high-tide level at an elevation of about 3 m is the current storm beach ridge (BR1). The first prominent beach ridge above it (BR2) was raised during the 1855 Wairarapa earthquake. A higher beach was raised during an earthquake dated at c. 200–382 BC (BR3). The highest beach ridge visible on this photograph of the coastal platform (BR4) started forming c. 5100–5400 BC and was raised about 3500 BC. A higher beach still (BR5) is not discernible in this photograph.

Between Baring Head (extreme left of photo) and Orongorongo River (centre), flattened ridge-crest surfaces at increasing elevation are uplifted remnants of ancient coastal platforms much like the present one. They are believed to have been cut during Interglacial periods when sea levels were similar to those of the present day. Wellington City and Port Nicholson form the background (Photo by Lloyd Homer).

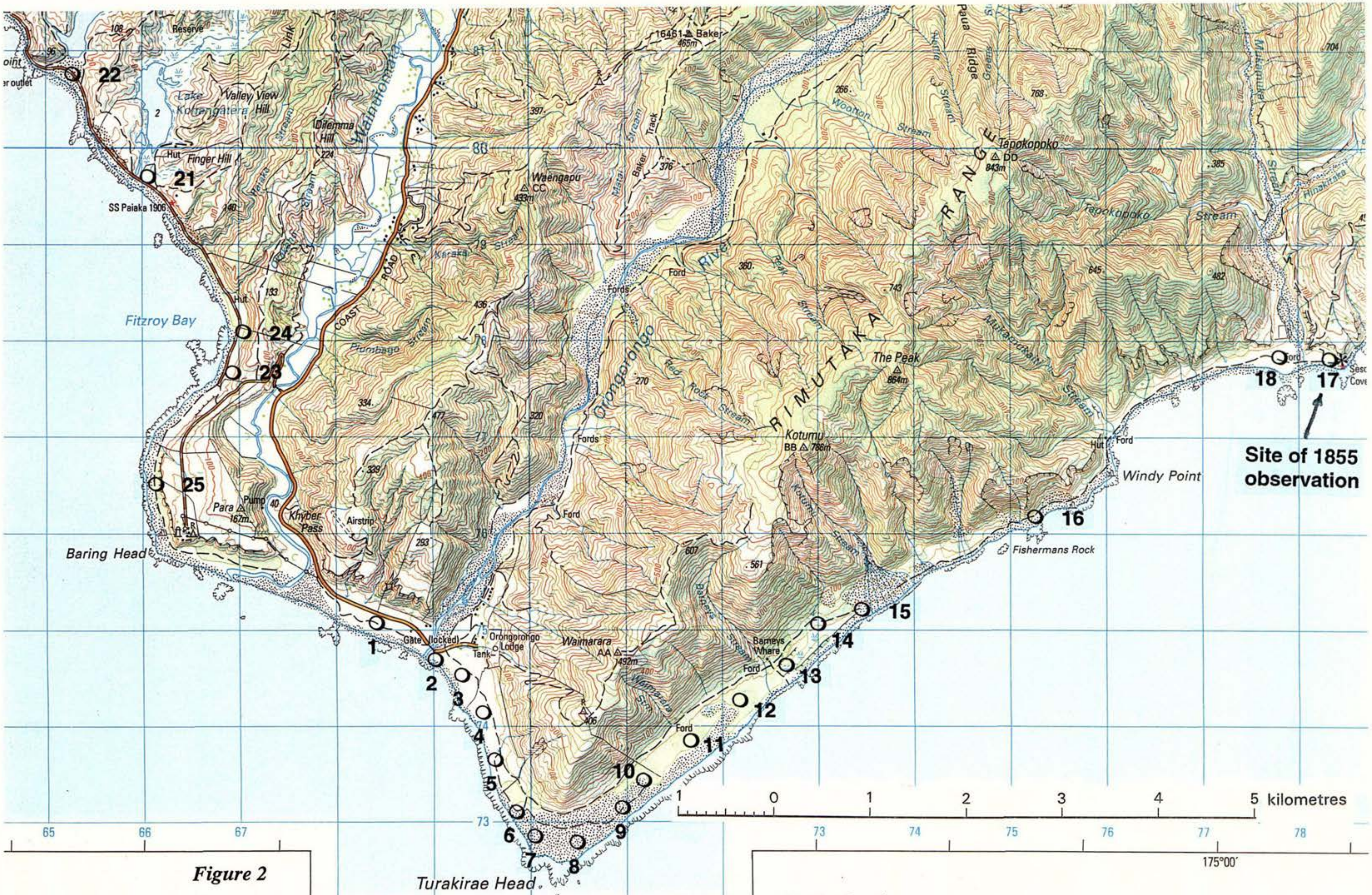

Figure 2

Map of the southern Wellington coast in the vicinity of Turakirae Head, showing approximate locations of measured beach profiles, including measurement made by Edward Roberts in 1855. (Part of Infomap R27-28 reproduced under license).

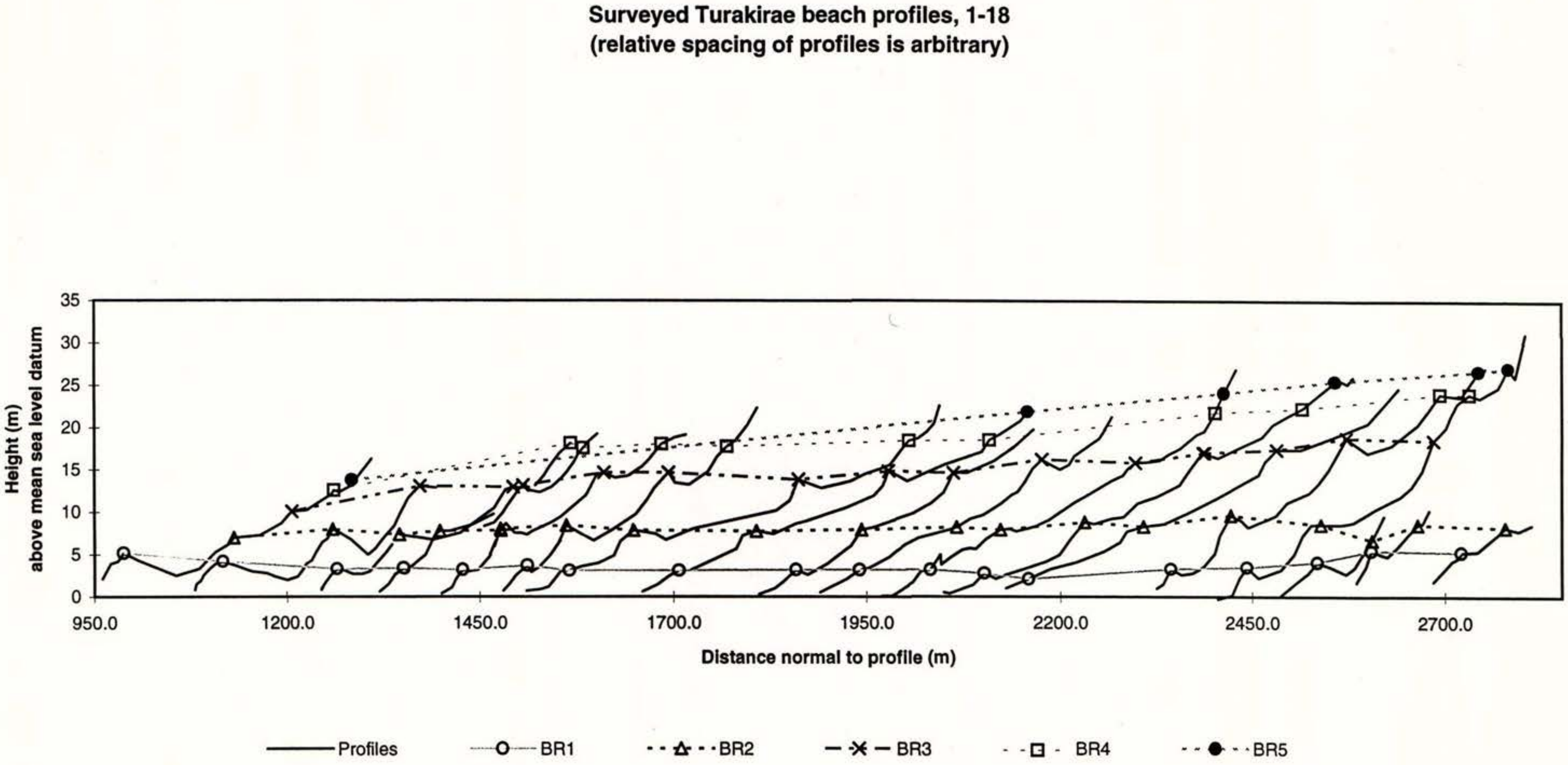

Figure 3

Representative shore-normal profiles across the coastal platform at Turakirae Head, showing correlation of beach ridges and relative beach-ridge sizes. Profiles 1–18 are shown. Lateral positions of profiles relative to one another are arbitrary (see Figures 2 and 4 for relative positioning of profiles).

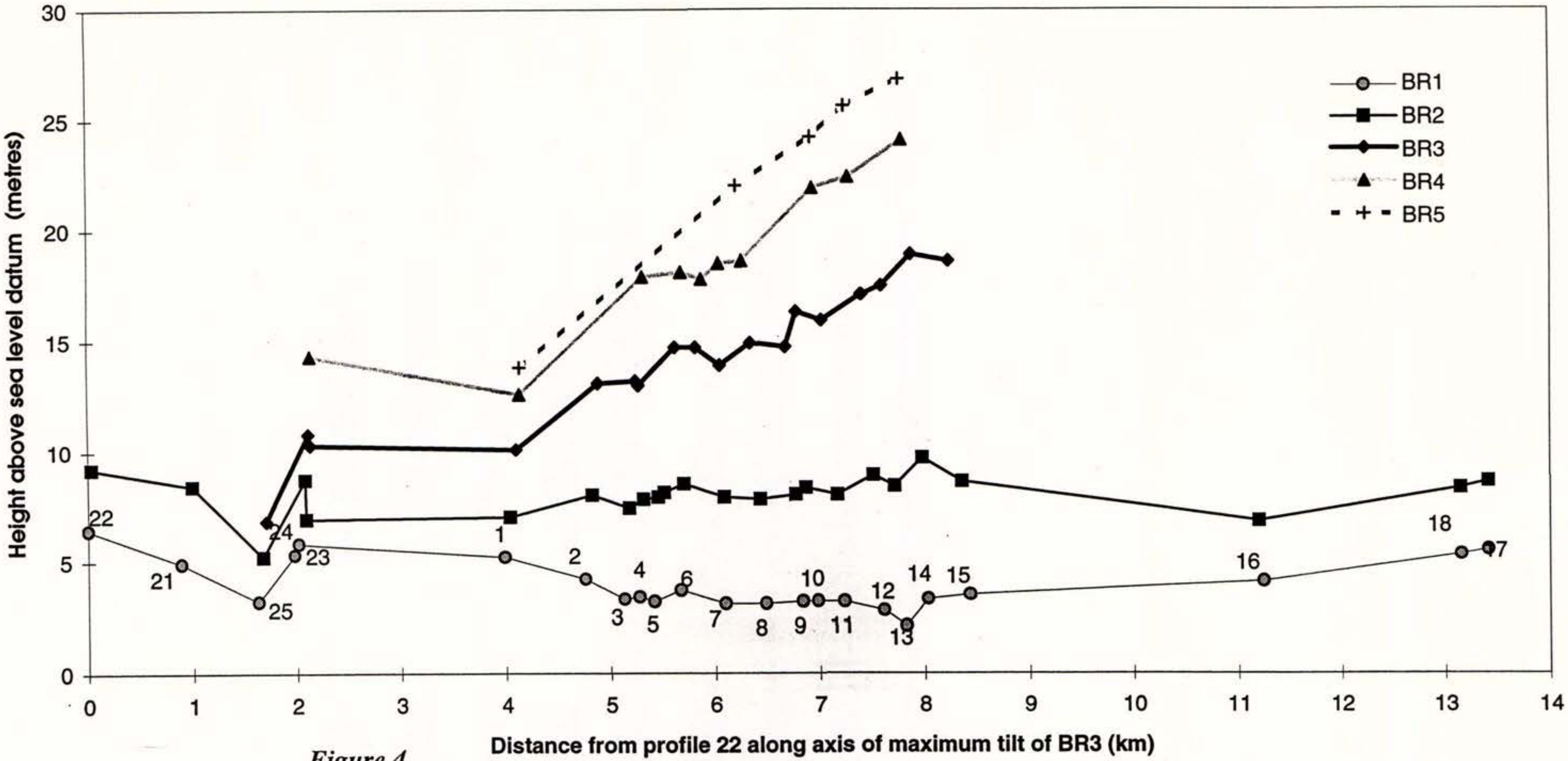

Figure 4

Longitudinal profiles of beach ridges along the south Wellington coast between Pencarrow Head and Mukamuka Rocks. Profiles have been projected perpendicular to the axis of maximum tilt of BR3. The axis of tilting of the beach ridges was determined by the same method as used by Wellman (1967). Surveyed heights for each beach ridge were projected onto a vertical plain, approximately east-west. This plain was rotated about a vertical axis until the gradient of the line formed by the projected heights was at a minimum, which corresponded to the vertical plane being normal to the axis of maximum tilt. No significant difference in axial direction for any of the raised beaches was noted, so all longitudinal beach profiles were projected onto the normal to the plane of maximum tilt of BR3. The data for BR3 combined both abundance and well defined tilt, and so the direction of its axis of tilting was the best defined.

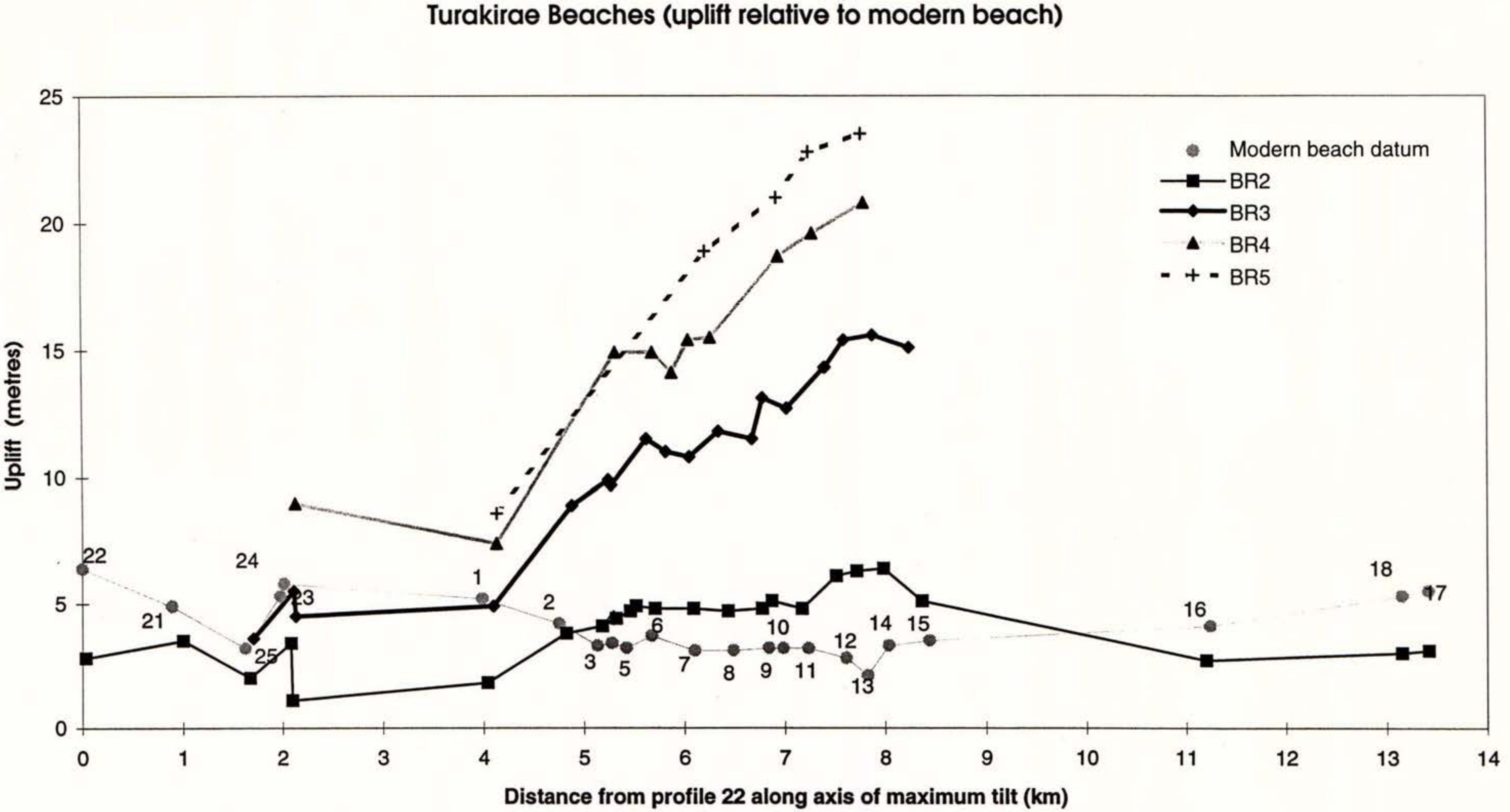

Figure 5

Elevation of beach ridges relative to the height of the modern storm beach ridge (BR1) perpendicular to the axis of maximum tilt of BR3 as determined above. Elevation of the modern storm beach (BR1) also is plotted.

Figure 6

The modern storm beach near Barney's Hut, littered with modern drift wood and seaweed. This beach was erroneously identified by Aston (1912) as the beach raised 2.74 m in 1855 (see Aston 1912, Figure 4 reproduced as Figure 8 below).

Figure 7

Boulder which appears to mark the site from which Aston photographed the modern beach c. 1911 which appears as Figure 4 in Aston (1912), erroneously identified as the beach raised in 1855. Barney's Hut (Figure 2) is in the background. Prominent ridge in middle ground is beach identified in this study as being the one raised in 1855, here nearly 6 m higher than the modern storm beach.

Figure 8

The modern storm beach near Barney's Hut as photographed c. 1911 by Aston and figured in Aston (1912, Figure 4) as the beach raised in 1855. Compare with Figure 9 below

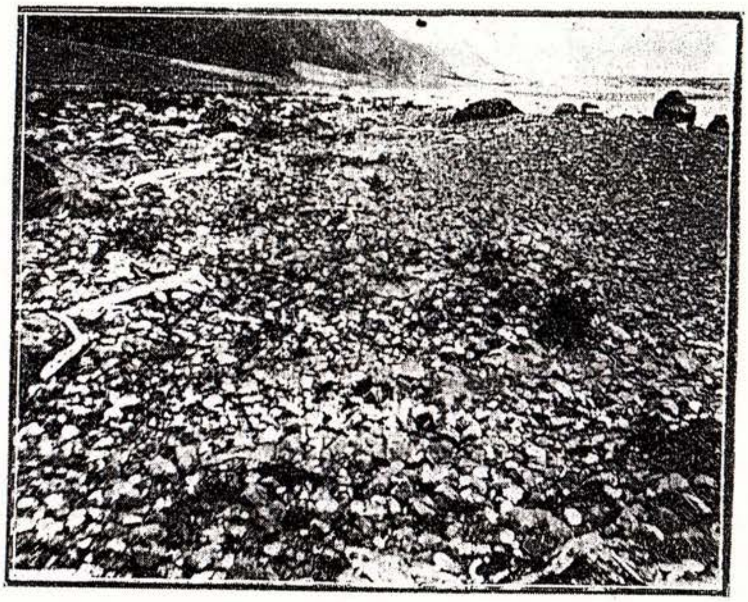

Fig. 4.

Figure 9

The modern storm beach near Barney's Hut as photographed in 1995 to replicate the photograph of Figure 4 of Aston (1912). Compare with Figure 8 above. Note large rocks in the middle ground which occur also in Figure 6. These also are identifiable in Figure 8. Comparison of Figures 8 and 9 show some additional accretion of gravel and slight shifting of the position of the crest of the beach, but clearly it is the same beach, and was substantially formed by 1911.

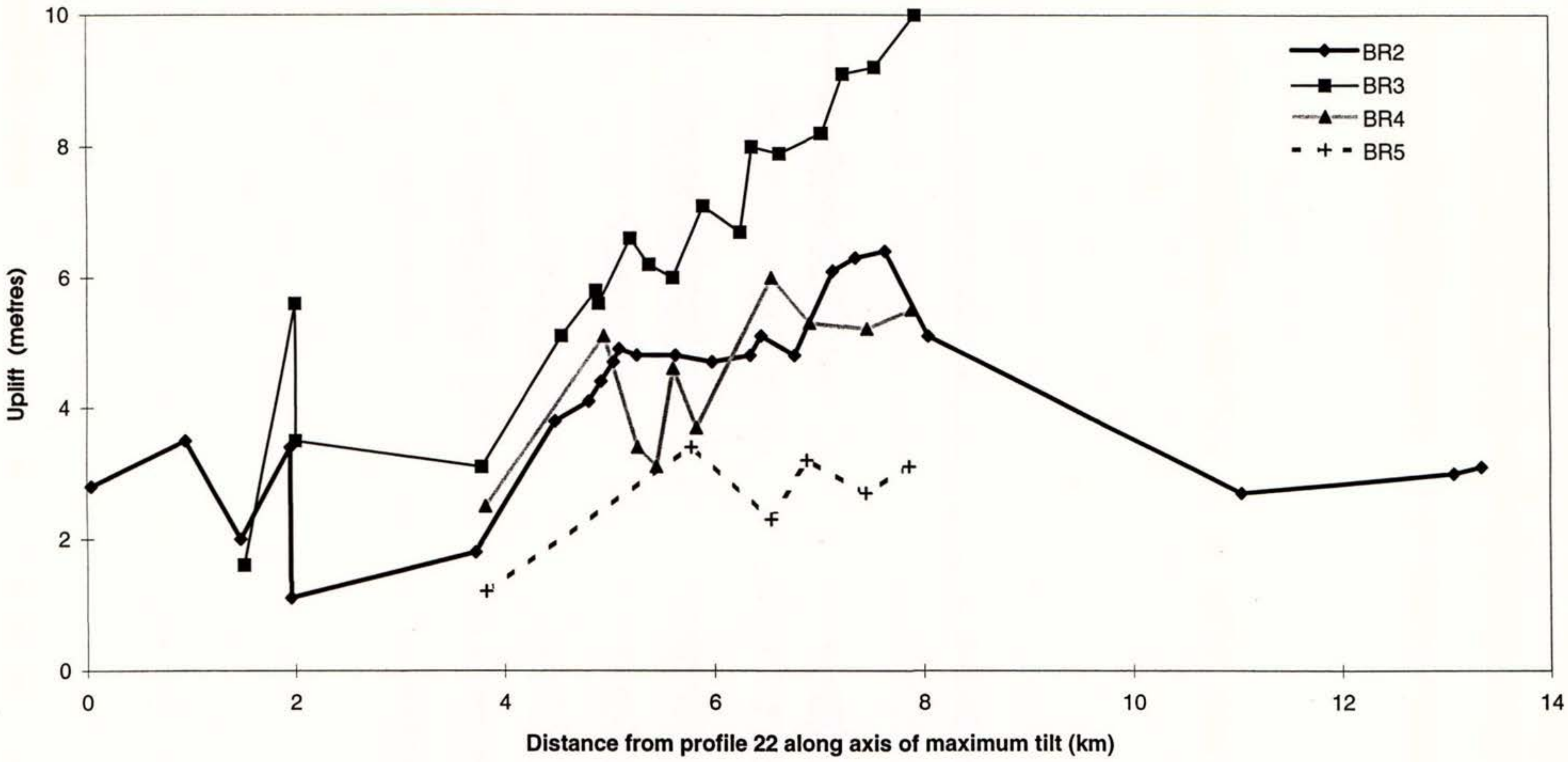

Figure 10

Single event uplifts for four storm beach ridges along the Turakirae Coast. The height differences between beaches has been determined from averaging beach heights from the four profiles in the vicinity of the maximum uplift near Barney's Hut as a way to overcome problems of surveying uncertainty and beach-profile irregularity. Maximum uplift between BR1 and BR2, and between BR2 and BR3 has been determined as the differences between averages of four height measurements. For BR4 and BR5, only two measurements of each are available for averaging.

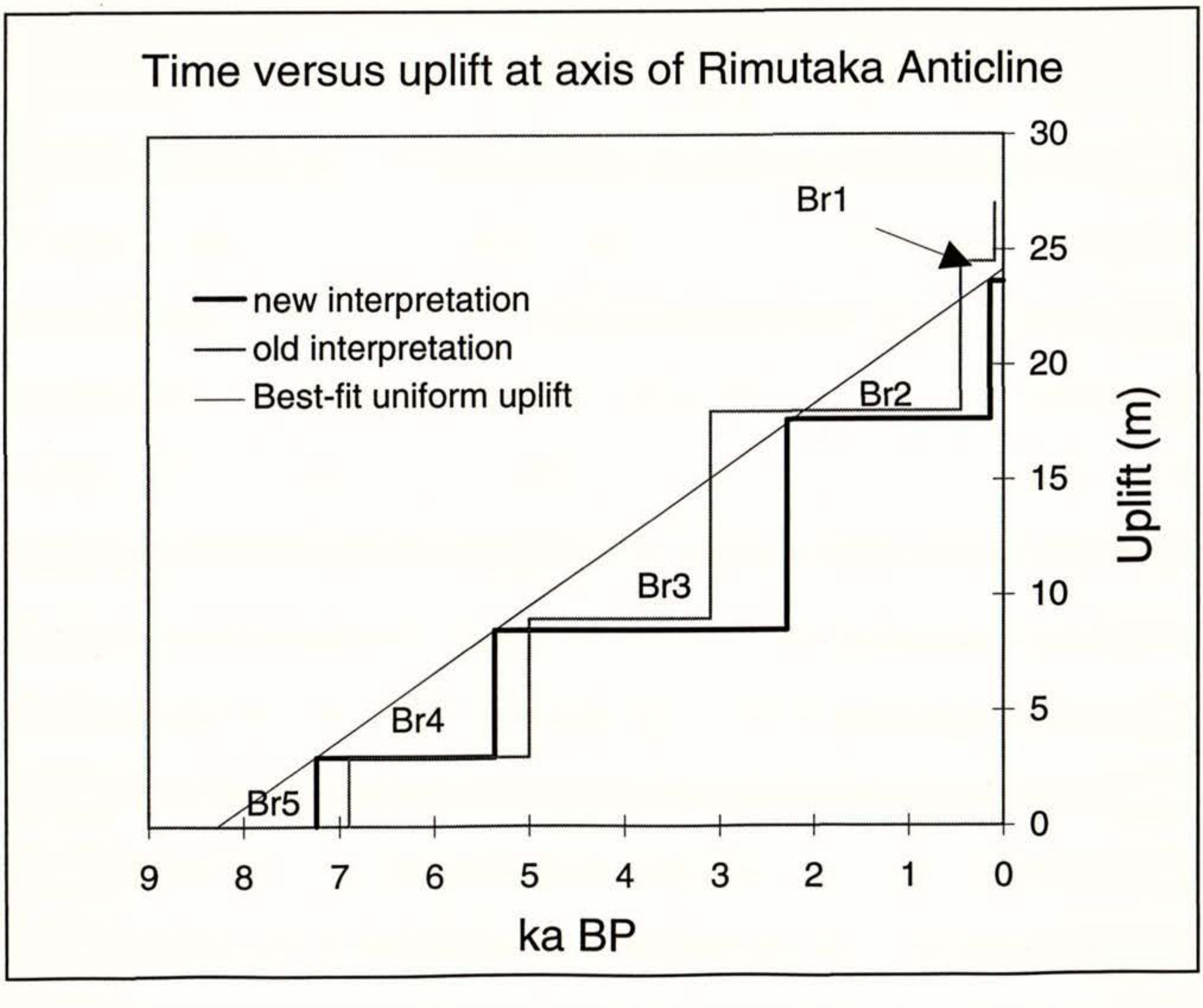

Figure 11

Time versus uplift at the axis of the Rimutaka anticline. The old interpretation essentially is that of Wellman (1967) updated by inclusion of radiocarbon dating by Moore (1987). Line of best fit to uniform uplift is fitted to dates of uplift of BR2, BR3 and BR5 to provide best estimate of time of uplift of BR4 which remains undated by radiocarbon dating.

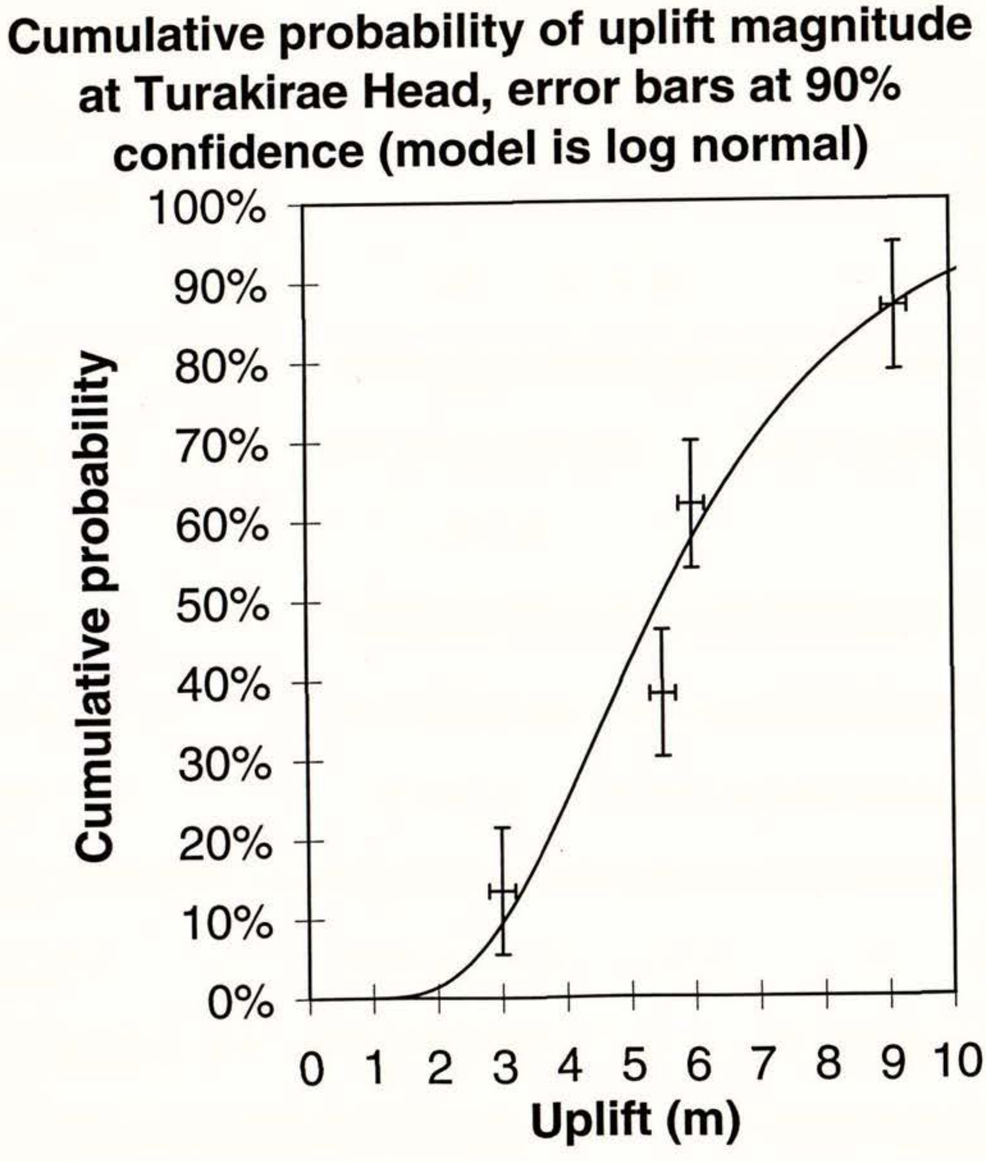

Figure 12

Cumulative probability density distribution of uplift magnitude near the crest of the Rimutaka anticline at its intersection with the coast. Line is best-fit log-normal distribution fitted to the 4 uplifts. Each uplift is average of measured values near the anticline crest (see Figure 10). Error bars on probability are at 90% confidence level.

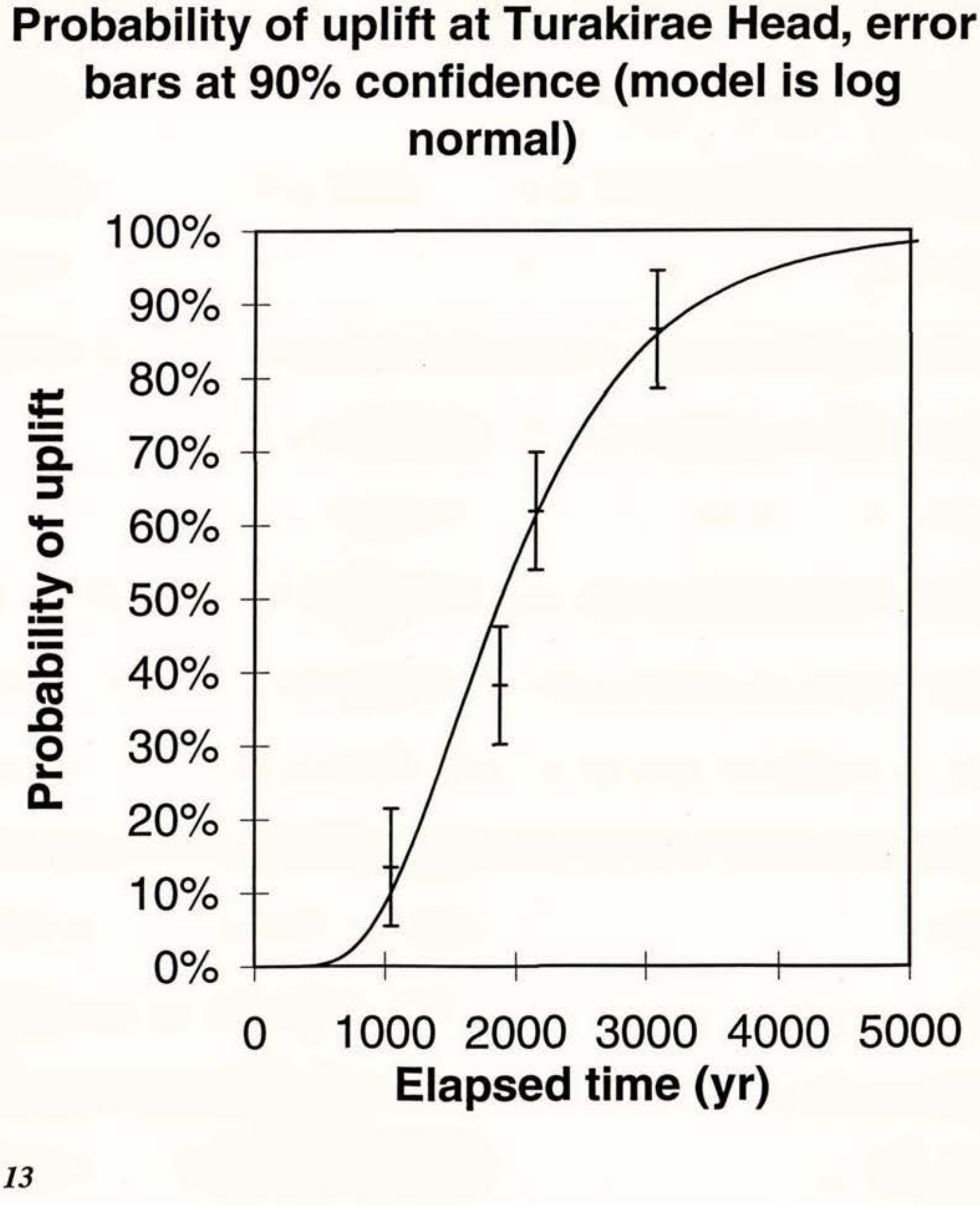

Figure 13

Estimated probability of uplift at Turakirae Head after a given elapsed time. Line is best-fit log-normal distribution fitted to the estimated timing of the 4 events. Error bars on probability are at 90% confidence level.

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