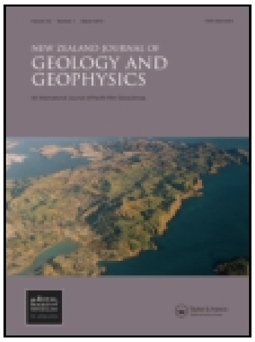

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Late Holocene uplift of beach ridges at Turakirae Head, south Wellington coast, New Zealand

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With an appendix:

Macrofauna of raised beaches at Turakirae Head

ALAN G. BEU

Abstract Holocene terraces at Turakirae Head on the south coast of the North Island, New Zealand, record four recent earthquakes from simultaneous rupture of the Wairarapa Fault and flexure of the Rimutaka Anticline. The lowest tread and riser is the modern marine platform and storm beach that began forming when the area was raised during the M_w 8.2 Wairarapa earthquake of AD 1855 January. The remaining chronology is established by radiocarbon dating, *in situ* ^{10}Be surface-exposure dating, and slip-predictable uplift estimation. Prior to AD 1855, uplifts occurred at 110–430 BC (max. 9.1 m), 2164–3468 BC (6.8 m), and 4660–4970 BC (7.3 m). Earlier uplift of unknown magnitude occurred at c. 7000 BC but went unrecorded because of rapidly rising sea level. Sea level was still rising when the two oldest surviving beach ridges were raised.

Uplift at Turakirae Head in AD 1855 varied from 1.5 m at the Wainuiomata River to 6.4 m at the crest of the Rimutaka Anticline. Older beaches also are tilted, with the amount of tilt increasing with age. Coastal uplift at the anticline crest has averaged 3.32 ± 0.17 mm/yr over the past 9000 yr, and has changed little over the past 0.5 m.y. Uplift fits a slip-predictable model of earthquake occurrence, and is log-normally distributed with a mean of 7.3 ± 0.7 m. The most frequently occurring uplift is 7.1 ± 0.9 m. Uplift in AD 1855 was not significantly smaller than mean or mode, suggesting that the Turakirae Head sequence records four great earthquakes of at least similar magnitude to that of AD 1855. The mean earthquake recurrence interval is 2194 ± 117 yr; the modal interval is 2122 ± 193 yr.

At the crest of the anticline, the coastal platform was cut entirely during the postglacial rise of sea level until shortly before 4660–4970 BC. Away from the crest, however, it may have been partially cut during low sea level of the penultimate glaciation. The open-ocean radiocarbon reservoir correction (δR) for 10 ^{14}C dates of coastal marine shells that died in AD 1855 at Turakirae Head is 3 ± 14 cal. yr BP (and not −31 ± 13 cal. yr BP, the currently accepted δR for central New Zealand coastal waters).

Keywords Wairarapa; Turakirae; Rimutaka Range; AD 1855 earthquake; paleoseismology; coastal uplift; radiocarbon dating; ^{10}Be surface exposure dating; Mollusca

INTRODUCTION

The region around Wellington was raised dramatically during a great earthquake on AD 1855 Jan 23^{d} 2130^{h}. This paper revises previous interpretations of the preserved record of that event along the southeast coast of Wellington. The coastal section at Turakirae Head (Fig. 1, 2) is a gazetted Site of Special Scientific Interest, preserving a very accessible flight of five Holocene marine terraces of international scientific interest and acclaim. Here we report ages for the complete sequence of five Holocene beach ridges at the head, BR1 through BR5 (following the beach-ridge nomenclature of Moore 1987). These consist of historical observation (BR1 and BR2), radiocarbon (^{14}C) ages (BR2, BR3 and BR5), ^{10}Be/^{9}Be surface-exposure ages (BR5), and a model age from slip-predictable uplift (BR4). The historical observation corrects inexplicable errors relating to the ages of BR1 and BR2 in earlier studies, and substantially increases the maximum uplift recorded from the 1855 earthquake. The correction removes a number of enigmas arising from earlier studies. We present new ^{14}C age determinations for the timing of the 1855 uplift and a revised estimate of the open-ocean reservoir correction for central New Zealand ocean water. Surface-exposure ages for BR5 were derived by measurement of *in situ*-produced cosmogenic ^{10}Be in quartz grains within sandstone boulders. BR4 and BR5 probably formed before sea level stabilised at its present level, and uplift of these ridges is adjusted to the lower sea levels of their epochs. The internal consistency of the data is discussed and the relationship between uplift and time is established. The new data and interpretation allow

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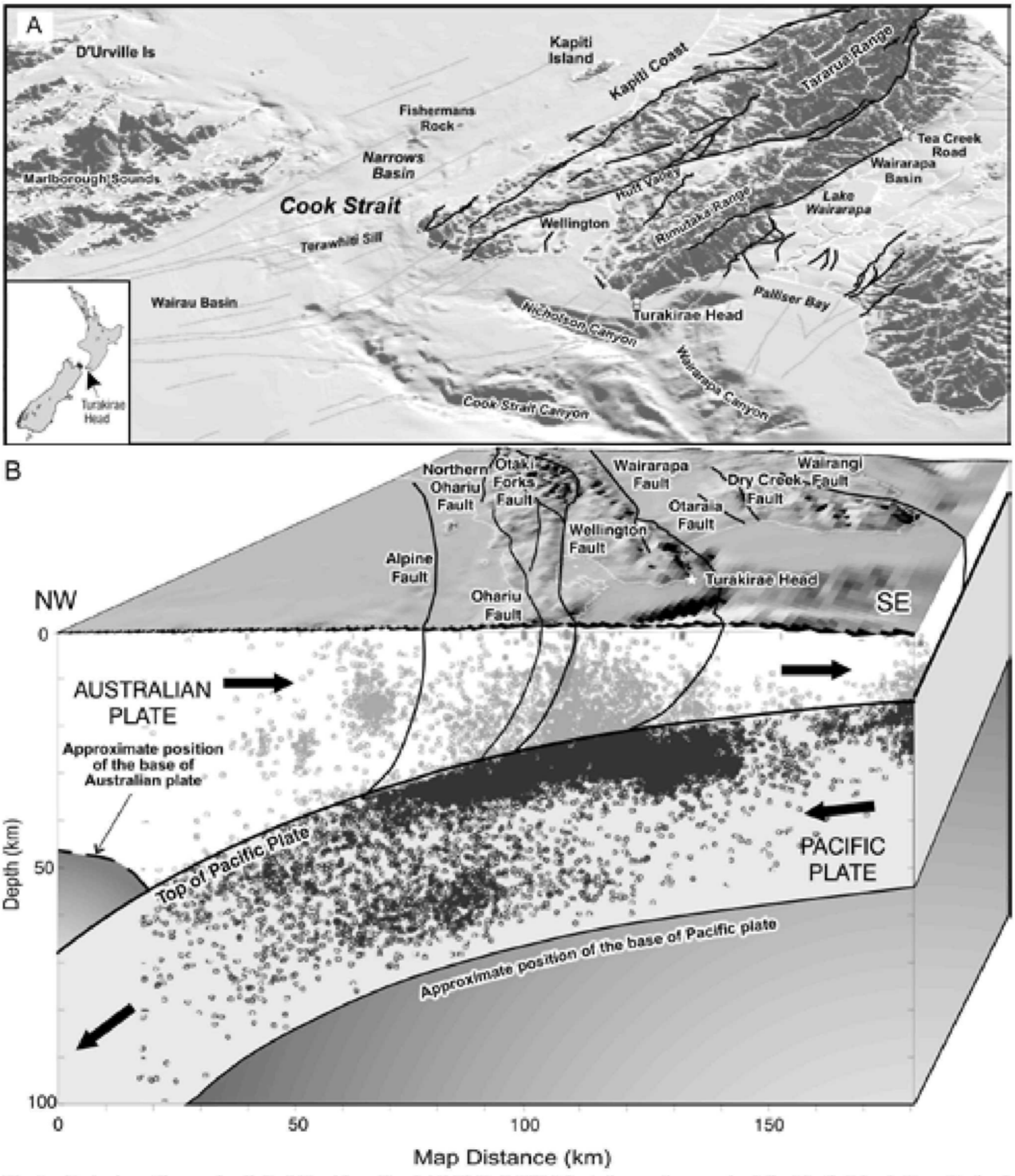

Fig. 1 Tectonic setting and relief of Turakirae Head (41°27′S 174°55′E) at the southern end of the North Island, New Zealand. **A**, Distribution of active faults on a shaded-relief perspective view of the Wellington area (viewed from the southeast). **B**, Seismicity ($M_L \leq 4.0$ earthquakes between 1987 and 1993 within 20 km of a northwest–southeast generalised section through Cook Strait) associated with the regional 3D structure of the Wellington region (after Begg & Johnston 2000; offshore faults and bathymetry from NIWA, active faults from the GNS Science Active Faults Database).

determination of a return period of great earthquakes on the south segment of the Wairarapa Fault that is longer than previously estimated. The Holocene beach ridges at Turakirae Head were deposited on a conspicuous marine-cut bedrock platform; the timing of cutting of this and higher platforms is also discussed.

This paper discusses a variety of different time-scales: the historical AD-BC calendar; conventional ^{14}C years; calibrated (siderial) years before the present (cal. yr BP); and corrected (but uncalibrated) ^{10}Be/^{9}Be surface-exposure years. The historical observation of the event of AD 1855 has no uncertainty, and the 50 years since the AD 1950 standard of reference for

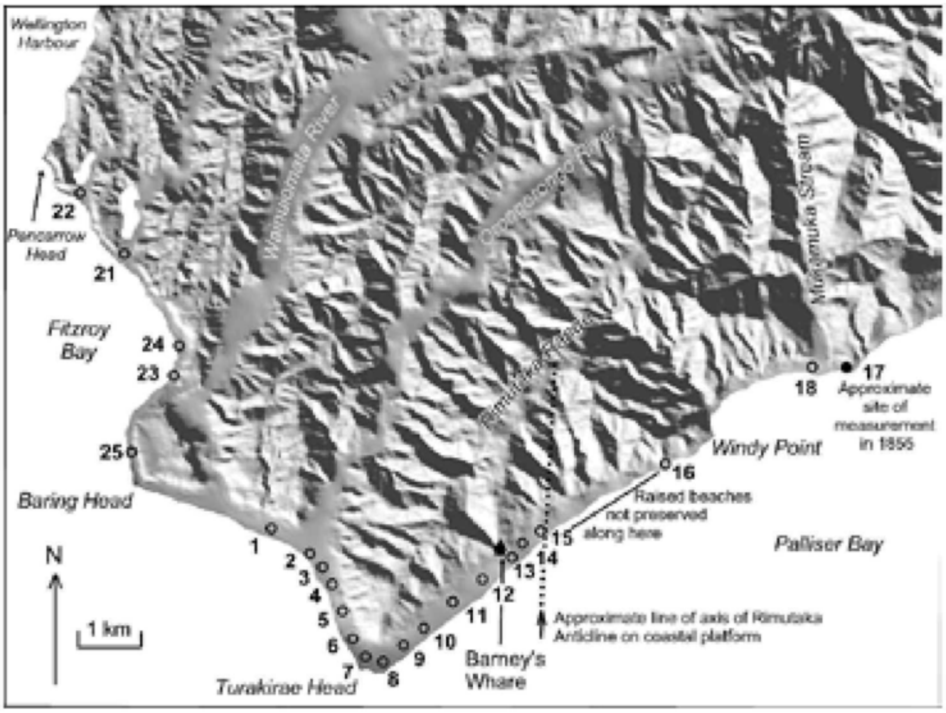

Fig. 2 Locations of measured beach profiles, including the probable measurement site (profile 17) of Edward Roberts in AD 1855 where there has been no detectable relative sea-level change in over 150 yr. There are no profiles 19 and 20. Turakirae Head is at 41°27′S 174°55′E. New dates reported here come from the vicinity of profile 7 (^{14}C) and Barney's Whare (profiles 12 and 14, ^{10}Be). Axis of the Rimutaka Anticline (dotted line) is estimated by maximising the slope of the projection of BR3 in Fig. 4. Topography is illuminated from the southwest.

BP is a significant proportion of its 95 yr BP age. For these reasons we have referenced all of the beach-ridge ages to the historical calendar except where this is inconvenient in the graphical use of the data.

PREVIOUS WORK ON BEACH-RIDGE AGE AND LOCAL GEOLOGY

Aston (1912) recognised five beach ridges in the vicinity of Barney's Whare (Fig. 2), and identified the ridge that we now know as BR1 as the beach ridge raised in AD 1855. He deduced this because BR1 corresponded in height above sea level to that reported by Edward Roberts (in Lyell 1856) for the AD 1855 uplift a few kilometres north along the coast at Mukamuka Rocks (Fig. 2, locality 17). In the area of his study, we now know that he should have looked more than 6 m higher. So began confusion as to the identity of the modern beach ridge (BR1) and that which was raised in AD 1855 (BR2). The confusion is heightened by general use of the term "1855 beach" within the local Earth Science community, an unfortunate choice of nomenclature because historically AD 1855 is the one year that Wellington had two beaches. Cotton (1921) was the first to recognise a problem with the identification of BR1 as the beach raised in AD 1855, and correctly identified BR1 and BR2 in nearby Fitzroy Bay. Cotton (1921), however, accepted Aston's (1912) identification at Turakirae Head and noted how the modern storm beach was overwhelming BR1 there. He appears not to have realised the consequences of this hypothesis, which implied either a dramatic change in local wave climate, with storm waves now lapping more than 2 m higher than they had before AD 1855, or subsidence of the uplift in the intervening years. Either would have been an important finding had it occurred (the latter further implying major slip on the subduction interface in AD 1855). The simpler explanation, that Aston (1912) had misidentified BR1, was not entertained.

Wellman (1967, 1969) recognised six beach ridges and used historical observation and relative beach-ridge size to estimate times of uplift, and hence ages, for BR2 to BR5, based on the assumption that BR1 was raised in AD 1855. He too commented on the apparent overwhelming of BR1 by the modern storm beach (BR0) without recognising the implications. The equivalent of Wellman's additional beach ridge occasionally was seen in our study, but was mobile between many of our visits, and ephemeral. Wellman attempted to estimate times of uplift and duration of ridge formation by assuming a constant uplift rate and constant rate of beach accretion. With misidentification of the beach raised in AD 1855, his calibration was in error, and beach-accretion rate is highly dependent on local sediment supply and the stability of sea level at the time.

Moore (1987) accepted that BR1 had been raised in AD 1855, and presented 23 ^{14}C dates from materials associated with the beaches, mainly BR2 and BR5 (Table 1). The majority of Moore's (1987) samples were transported shells that date episodes of accretion of BR2 and hence provide only minimum estimates of the initiation of the beach and maximum ages for its uplift. Samples from near the older beaches were predominantly wood and peat that provide close minimum estimates for the time of uplift. Moore (1987) recorded the location of his dated samples with respect to the nearest storm beach. The stratigraphy of his samples is well described and not disputed here. Moore (1987) believed that he had direct dating for BR1, and ^{14}C dating for BR2 and BR5. He estimated the ages of BR3 and BR4 indirectly by assuming a constant average rate of uplift, while recognising that his interpretation of the data did not support a constant rate.

Stevens (1969, 1975), Ward (1971), and Ghani (1978) also have discussed the ages of Turakirae beach ridges. All perpetuate the error of Aston (1912). Stevens (1969) inferred uplift of BR2 to be at AD 1460, based on an interpretation of Māori oral tradition reported in Best (1918) of a Haowhenua

Table 1 ^{14}C and ^{10}Be dates relating to beach ridges at Turakirae Head.

NZ Fossil Record number[1]	NZMS 270 Sheet R28 grid reference[2]	Sample type	δ^{13}C (‰)	Conventional age (yr BP ± 1 σ)[3]	Calibrated age (95%) (cal. yr BP)[4]	NZ laboratory number[5]	Beach ridge	Elevation (m a.s.l.)[6]
^{14}C dates								
N164/117	71607365	*Haliotis iris*	2.3	766 ± 33	477–312	NZ4229[7]	BR2	No survey
R28/f1	69607390	*Haliotis iris*	1.4	809 ± 33	501–400	NZ4278[7]	BR2	No survey
R28/f2	69607390	*Haliotis iris*	1.2	870 ± 33	531–449	NZ4279[7]	BR2	No survey
R28/f10	72127395	*Haliotis iris*	1.7	601 ± 32	297–144	NZ4530[7]	BR2	No survey
R28/f22	69407410	*Haliotis iris*	1.7	565 ± 32	279–115	NZ5101[7]	BR2	No survey
R28/f23	69507400	*Haliotis iris*	2.0	613 ± 55	378–121	NZ5102[7]	BR2	No survey
R28/f24	69607380	*Haliotis iris*	2.6	681 ± 32	413–268	NZ5103[7]	BR2	No survey
R28/f25	70107265	*Haliotis iris*	2.1	596 ± 28	290–146	NZ5104[7]	BR2	No survey
R28/f26	70307260	*Haliotis iris*	2.3	564 ± 32	279–113	NZ5105[7]	BR2	No survey
R28/f27	70907300	*Haliotis iris*	2.2	571± 32	282–122	NZ5106[7]	BR2	No survey
R28/f28	71407345	*Haliotis iris*	2.3	747 ± 41	475–291	NZ5107[7]	BR2	No survey
R28/f29	71407345	*Haliotis iris*	2.3	830 ± 28	507–425	NZ5108[7]	BR2	No survey
R28/f30	71407345	*Haliotis iris*	2.1	789 ± 40	497–320	NZ5109[7]	BR2	No survey
R28/f59a	70427269	*Haliotis iris*	1.6	473 ± 47	247–10	NZ8140a	BR2	2.8
R28/f59b	70427269	*Haliotis iris*	2.3	466± 41	235–10	NZ8140b	BR2	2.8
R28/f62	70417266	*Serpulorbus zealandicus*	1.1	518 ± 43	267–10	NZ8213	BR2	2.8
R28/f63	70417266	*Haustrum haustorium*	3.1	489 ± 35	243–10	NZ8214	BR2	2.8.
R28/f61a	70437270	*Diloma nigerrima*	2.0	490 ± 36	245–10	NZ8215a	BR2	4.5
R28/f61b	70437270	*Diloma nigerrima*	0.3	474 ± 48	249–10	NZ8215b	BR2	4.5
R28/f62a	70417266	*Melagraphia aethiops*	1.4	519 ± 44	268–10	NZ8270	BR2	2.8
R28/f62b	70417266	*Turbo smaragdus*	2.5	509 ± 29	249–10	NZ8271	BR2	2.8
R28/f62c	70417266	*Cellana denticulata*	0.3	452 ± 45	229–10	NZ8272a	BR2	2.8
R28/f62c	70417266	*Cellana denticulata*	0.3	454 ± 50	239–10	NZ8272b	BR2	2.8
R28/f65	70427269	*Salmacina australis*	2.4	977 ± 36	632–508	NZ8211	BR2	No survey
R28/f64a	70427288	*Xenostrobus pulex*	1.3	2603 ± 86	2481–2059	NZA4746	BR3	9.9
R28/f64b	70427288	*Gadinea conica*	1.3	2566 ± 78	2380–2031	NZA4747	BR3	9.9
R28/f64c	70427288	*Salmacina australis*	7.0	1604 ± 32	1243–1072	NZ8212	BR3	9.9
R28/f6	71577380	peat	–27.7	1450 ± 50	1417–1280	NZ4417[7]	BR3	No survey
R28/f13	71907407	peat	–26.9	270 ± 60	476–269, 212–143, 17–5	NZ4548[7]	BR3	No survey
R28/f3	71557400	peat	–29.4	4100 ± 80	4838–4410	NZ4414[7]	BR5	No survey
R28/f4	71557400	freshwater shells	–5.3	10050 ± 100	12271–12219, 12127–11216	NZ4415[7]	BR5	No survey
R28/f5	71557400	wood fragments	–25.3	5840 ± 90	6860–6413	NZ4416[7]	BR5	No survey
R28/f7	71557400	peat	–27.7	–47 ± 45	Modern	NZ4418[7]	BR5	No survey
R28/f8	71557400	peat	–28.3	2980 ± 70	3355–2842	NZ4419[7]	BR5	No survey
R28/f9	71557400	wood fragments	–26.1	6360 ± 80	7427–7156, 7118–7091, 7058–7032	NZ4420[7]	BR5	No survey
R28/f11	71557400	wood fragments	–22.6	6060 ± 100	7212–6668	NZ4550[7]	BR5	No survey
R28/f12	71557400	wood	–23.9	5960 ± 90	7003–6560	NZ4549[7]	BR5	No survey
^{10}Be dates								
T1-1	72207455	*In situ* core	–	8200 ± 1600	5400–10900	Be547	BR5	25.6
T1-2	72207455	boulder	–	5200 ± 1200	3300–7100	Be549	BR5	25.6
T2-1	72557470	boulder	–	6500 ± 900	5000–7900	Be550	BR5	26
T2-2	72557470	boulder	–	7900 ± 1100	6000–9800	Be551	BR5	26

[1] N164/117 is a NZ Archaeological Association site number; T1 and T2 are site numbers.

[2] 4-digit eastings and northings.

[3] Conventional radiocarbon (^{14}C) age or corrected ^{10}Be surface-exposure age.

[4] Calibrated ^{14}C ages using the methods of Stuiver et al. (1998) with geographic offset (δ-R) of 0 ± 13 yr BP for both shell samples (this paper) and terrestrial samples (following current New Zealand ^{14}C dating best practice; Roger Sparks pers. comm. 2001).

[5] NZ- samples dated by Institute of Geological & Nuclear Sciences (now GNS Science) gas counters. NZA- and Be- samples dated by accelerator mass spectrometry Rafter Laboratory, GNS Science).

[6] By survey to the Wellington datum.

[7] Recalibrated after Moore (1987).

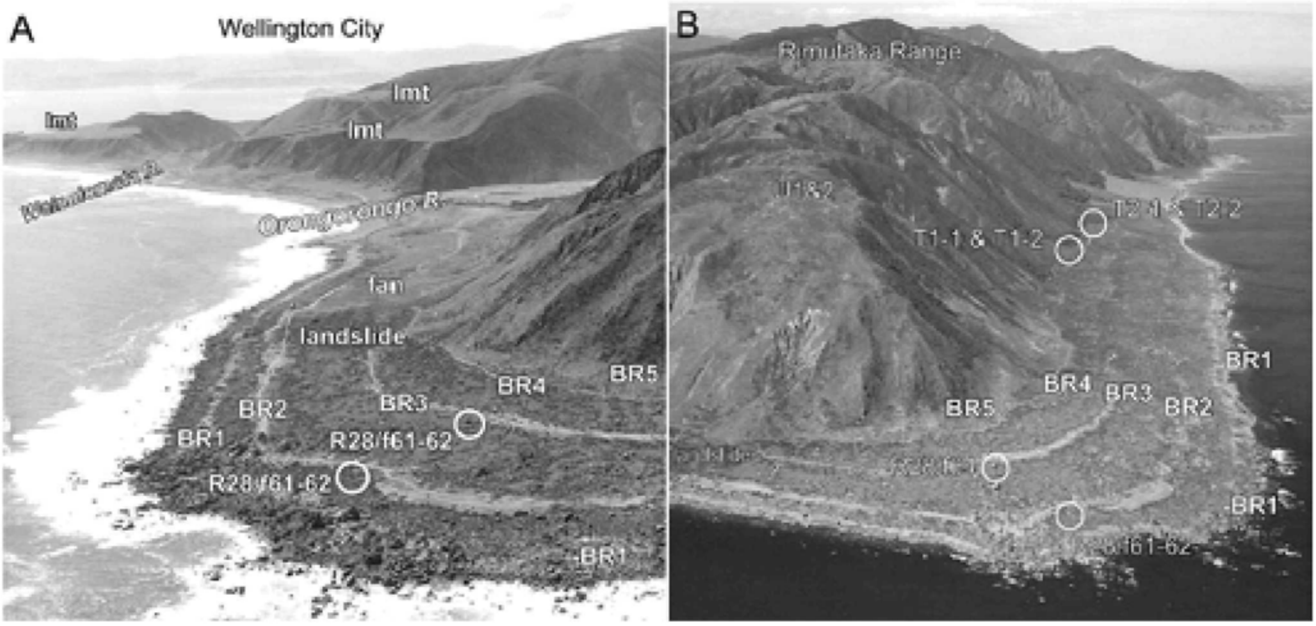

Fig. 3 Aerial views of Turakirae Head showing gravel beach ridges (BR1–BR5) ringing a broad coastal platform. Sites of new radiocarbon dates are circled and labelled with the site fossil-record numbers. The modern storm beach ridge is absent at -BR1 because there is no local supply of gravel to form it. Sites marked "fan" and "landslide" are gravel deposits truncated by BR2, which provide the local sources of gravel to form BR2. BR0 of Wellman (1967, 1969) appears ephemerally in the vicinity of the mouth of Orongorongo River during minor storms, and is mobile until its gravel adds to the face of BR1 there in major storms. *(Photos: Lloyd Homer.)* **A**, View to northwest towards Wellington City, with raised interglacial marine terraces (lmt) in background. **B**, View to northeast along the axis of the Rimutaka Range. T1 and T2 are sample locations for ^{10}Be surface exposure dating of BR5. U1 and U2 are sites with remnant interglacial beach gravel (Ota et al. 1981).

earthquake said to have raised an island in Wellington Harbour to become Wellington's Miramar Peninsula.

Hull & McSaveney (1996) were the first to make a major revision of the interpretation of the beach ridges. We use their survey data here. Hull & McSaveney (1996) present details of the survey methodology which are not repeated here. The publicly available report, however, has limited circulation, and so some of their material is repeated here for a wider audience. We confirm much of their interpretation, but revise their interpretation of uplift of BR4 and BR5 to account for lower sea levels when they were forming. This revision changes their estimate of the age of BR4 and increases the recurrence interval of great earthquakes on the Wairarapa Fault.

Begg & Mazengarb (1996) followed the interpretation of Hull & McSaveney (1996) in their discussion of the Turakirae beaches. They also discussed ages of the adjacent higher marine terraces cut into the bedrock of the south end of the ranges (Fig. 2) using the data and interpretation of Ota et al. (1981).

The local bedrock is highly indurated Mesozoic greywacke (broken formation; Begg & Mazengarb 1996) with a metamorphic (uplift) age of 135–154 Ma (George & Graham 1991). It is exposed extensively in sporadic outcrops on the modern coastal platform and in former stacks among the raised beaches. Sediments on the platform are locally derived.

THE BEACH RIDGES AND UPLIFT

The beach ridges (Fig. 3, 4A) are the crests of storm beaches, and owe their origin to a very stormy coast and episodic tectonism. There are no natural sections fully exposing the stratigraphy across any beach ridge, and no trenching was carried out in our study. Several of the younger beach ridges had been locally mined for sand and gravel prior to our study, but only poor exposures of sections remained. Texturally, the ridges range from gravelly sand near major rivers, through sandy gravel, to isolated cobbles scattered on eroded bedrock where there is little sediment supply from long-shore drift. Modern and older ridges in Fitzroy Bay are locally capped by dune sand of variable unknown thicknesses. The height of the crest of the modern beach ridge varies widely (2.1–6.5 m) along the coast (Fig. 4A): its height appears to be determined mainly by the grain-size of available sediment, and the local wave climate. Beach-ridge heights surveyed by Wellman (in Wellman 1967) do not differ from the measurements of Hull & McSaveney (1996) (Fig. 4A). Comparison of BR1 with a photograph taken at the same spot near Barney's Whare by Aston in c. 1910 indicates that beach-ridge height there has been stable in the long term relative to protruding large boulders, and that the ridges grow broader as they accrete more sediment. The ridges accrete dominantly on the seaward face. In severe storms, some waves surge over the ridge crest, carrying sediment from the seaward face and depositing it on the landward face. Sometimes there is deposition on the crest, and sometimes there is erosion, with apparently no net increase in height. Although the crest of the modern storm beach is overtopped frequently each year, none of the authors has ever been present at such a time; neither apparently had any of the previous authors. There is a substantial drift of sediment along the shore, and so the modern beach may not be accreting everywhere.

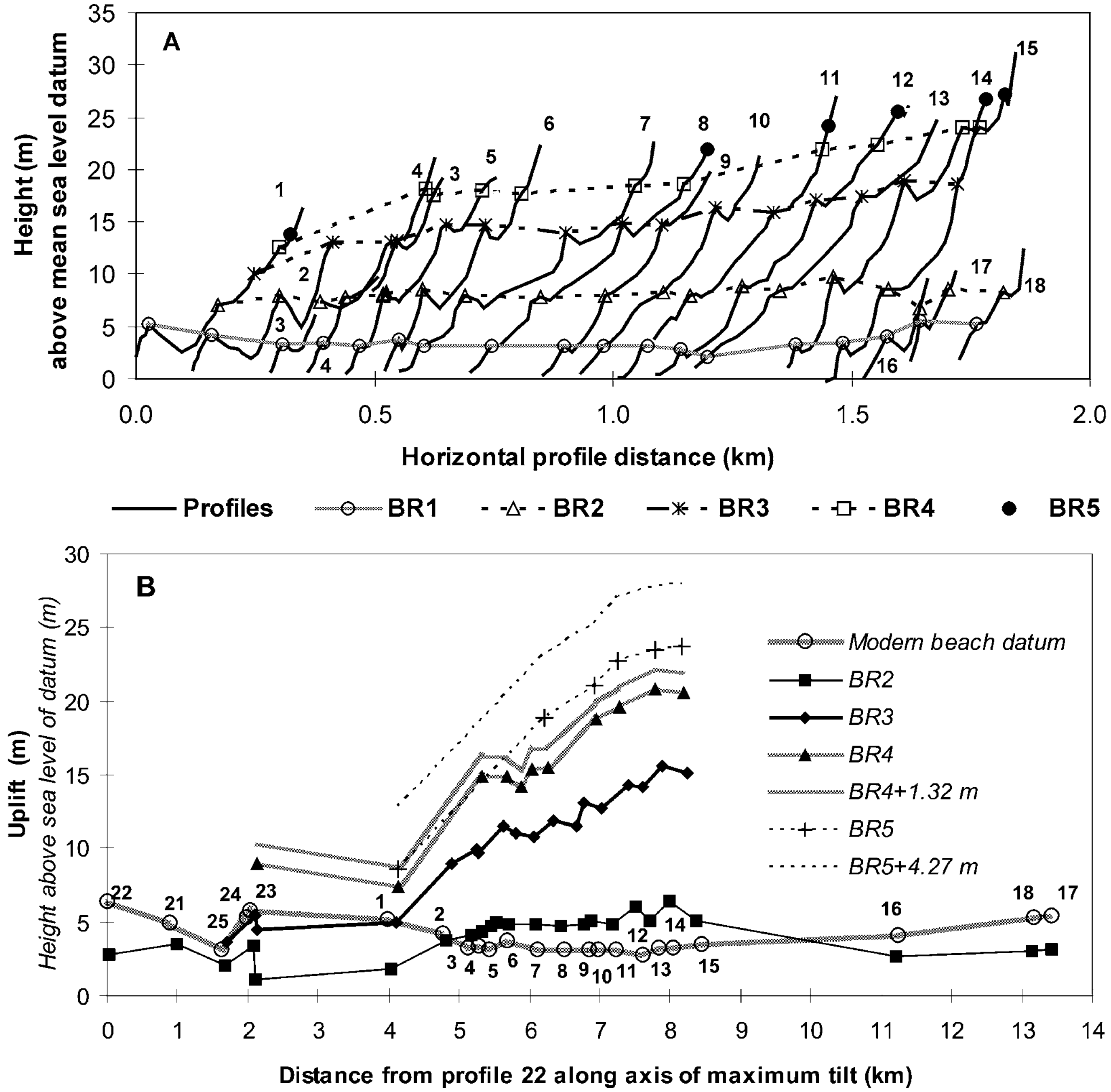

Fig. 4 Beach-ridge profiles and uplift in the vicinity of Turakirae Head. **A**, Surveyed beach profiles 1–18 of Fig. 2. Relative spacing of profiles and horizontal datum are arbitrary. Identification of beach-ridge crests is by field observation during surveying. Note closer vertical spacing of higher beach ridges, which is explained in this paper as resulting from uplift of BR5 and BR4 at lower sea levels (–4.27 and –1.32 m, respectively, as discussed in text). **B**, Profiles of cumulative beach uplift normal to the axis of the Rimutaka Anticline (see Rimutaka Range; Fig. 1A, 2). Apparent uplift of BR4 and BR5 also is shown without adjustment for lower sea level. Also presented is the modern beach crest (BR1) showing the variability in height along the coast assumed to hold for earlier crests and hence used as uplift datum. Numbers refer to profile measurement sites (Fig. 2). BR5 is found at few sites, and is absent from some sites where its preservation might be expected. There is no preservation of raised beaches between profiles 15 and 16. Orientation of the profile projection in B is 9° clockwise from east to west.

The most recent beach ridge BR1 was initiated following uplift of the coast in the AD 1855 Wairarapa earthquake (Grapes & Downes 1997). Next in the sequence is ridge BR2 formed before AD 1855, followed by ridges BR3, BR4, and BR5. All five are younger than the period of very rapid postglacial sea level rise (Gibb 1986; Peltier 2002) when the sea was last able to attack the head of the Holocene shore platform at the foot of the steeper slopes of the Rimutaka Range, but both BR4 and BR5 probably formed while sea level was still rising (see Discussion).

Hull & McSaveney (1996) used the elevation of the crest of BR1 along the coast as the stable reference datum for determining uplift (Fig. 4B), on the untested assumption that the wave climate around Turakirae Head has changed little over time, and with minor changes in offshore geometry accompanying uplift of the seafloor. We still utilise this assumption. Elevations of ridge crests were used for determining uplift because the historical record for BR1 near Barney's Whare (Fig. 2) showed that the ridges grow laterally but not vertically. The modern rock platform is not a stable datum because the sea is still cutting it. BR1 shows an anomalous dip at profile 13 (Fig. 4). While BR1–BR3 on nearby profiles 12 and 14 have pronounced crests with landward declivities, profile 13 has none (Fig. 4A). Notes taken during surveying indicate that the landward limit of modern driftwood on profile 13 was at 3.3 m elevation, similar in height to the beach-ridge crest on adjacent profiles and to their limits of driftwood, but the top of the profile 13 storm beach was 1.2 m lower. The interpreted uplift patterns of higher beach ridges are all more regular if the dip is used than if it is ignored. Hence, we reason that the anomaly is caused by locally fixed beach dynamics of some form that also affected earlier beaches there.

The four Holocene storm-beach ridges above the modern one are tilted relative to sea level (Fig. 4), with tilt increasing with age and uplift (Wellman 1967) due to a repeating pattern of tilting in each event. The region of maximum coastal uplift from the AD 1855 earthquake is c. 4 km northeast of Turakirae Head, where the measured uplift is 6.4 m (Hull & McSaveney 1996). BR3 has a maximum elevation of 15.5 m at the same locality; BR4, 21 m; and BR5, 24 m. The uplift maxima appear to define where the crest of the Rimutaka Anticline reaches the coast (as identified by Wellman 1967), but there is no preservation of raised beach ridges on the opposing flank of the anticline due to the presence of a succession of very large and active debris-flow fans that reach to the sea. Ota et al. (1981) studied the higher, pre-Holocene marine terraces of the area. These terraces also show tilt increasing with age and uplift, but there is too little preservation of terraces in the vicinity of the anticline crest to define its trend away from the immediate coastline.

RADIOCARBON DATING

Sampling and processing

Most of the 23 ^{14}C dates published by Moore (1987) come from transported shells deposited in the later stages of accretion of BR2 (Table 1), and provide only minimum estimates of the initiation of the ridge and maximum ages for its uplift. Moore (1987) also obtained samples of mostly wood from within a unit of calcareous silt behind BR5 (and overlying beach gravel). They date the beginning of accumulation behind BR5, and also the cessation of movement of BR5 gravel which underlies them. Hence, they provide estimates for the age of uplift of BR5.

For this study, we dated shells collected predominantly from the marine-cut platform between the modern storm beach and that raised in AD 1855 in the vicinity of profile 7 (Fig. 2–4). A number of species (Appendix 1) were found at different parts of the platform ranging from immediately seaward of the foot of the seaward face of BR2 (former high-tide level) to immediately landward of the landward face of BR1 (former low to sub-tidal level) (R28/f61–62, Fig. 3). Only shells seen to be in growth position (or inferred to have fallen from growth position at death) were taken, and their present elevations were surveyed by methods described in Hull & McSaveney (1996). Species identification and ecology (Appendix 1) were used to infer position with respect to sea level before emergence. The former tidal zone associated with BR3 also was searched for *in situ* fauna. Despite extensive leaching and consequent loss of most of the shells from this area, several sites were found where thick carbonate crusts of polychaete worm tubes (*Salmacina australis*) had survived leaching and had preserved embedded shells. Shells overgrown by polychaete crust (NZA4746) and shells nestling in and on the crust (NZA4747, Table 1) were dated (R28/f64, Fig. 3). The decline in preservation of shell material between BR2 and BR3 leaves little likelihood that equivalent materials survive in the former tidal zones associated with BR4 and BR5. None were found for this study.

Before dating, all larger shell samples were scrubbed in water, dried, crushed, and treated with dilute HCl. Evolved CO_2 was collected, purified, and counted in CO_2 proportional gas counters to determine conventional ^{14}C ages (Table 1). The 12 samples dated this way were of short-lived species (<10 yr); for larger species, the outer shell rims were dated.

Marine-reservoir correction for marine shells at Turakirae Head

Eleven ^{14}C samples were obtained from the fossil fauna of former tidal pools raised during the uplift of AD 1855. One of them (NZ8211) clearly belongs to a different population of ages, and was excluded from further analysis (see below). The other 10 have a weighted-mean conventional ^{14}C age of 488 ± 13 yr BP. The year AD 1855 corresponds to a marine model age of 485 ± 4 yr BP (Stuiver et al. 1998). Because the time of death is known, the difference between their weighted mean apparent ^{14}C age and the marine model age provides an estimate of the ^{14}C open-ocean reservoir correction (δR) for AD 1855 ocean water at Turakirae Head (3 ± 14 yr). If we consider that the shells might have been several years old when the organisms died, this clearly is not a significant correction. It is, however, significantly different from the currently accepted δR for central New Zealand coastal waters of –31 ± 13 based on 11 shells growing from AD 1923–57 (McFadgen & Manning 1990). Accordingly, the calibrated ages from marine shells used in this paper (Table 1) have an applied δR correction of zero.

^{10}BE DATING

Sampling and processing

Samples for ^{10}Be surface-exposure dating were taken from BR5 at 26 m above sea level (Fig. 3, localities T1 and T2). One sample (T1-1) was a 5 cm diameter, 15.5 cm deep drill core taken from either the substrate or (more probably) a very large, mostly buried boulder. The other three samples were large fragments of boulders. Because of the young expected age of BR5 (<10 ka; Hull & McSaveney 1996), very large samples of up to 10 kg were taken. This ensured that sufficient pure quartz could be obtained from the greywacke (sandstone) to yield precise dates. For surface-exposure dating, it is essential to extract ^{10}Be only from quartz which was separated, purified, and analysed for ^{10}Be by accelerator mass spectrometry (AMS) following the method detailed in Graham et al. (1998). This method essentially follows that used at Lawrence Livermore National Laboratory (California, USA), but incorporates aspects of the procedures used at PRIME lab (Purdue University, Indiana, USA) and the University of Pennsylvania (USA) former AMS facilities.

The sampled rock surfaces showed no signs of significant erosion, being covered with sparse, thin layers of lichens and moss up to a few millimetres thick. Given the size of the boulders and the expected young age, it is unlikely that significant overturning had occurred. The sample sites (Fig. 2B) are on the southeastern lee of a relatively steep cliff face, which partly shields the sites from cosmic rays (see discussion of production-rate corrections below).

Age calculation

The ^{10}Be surface-exposure dating method assumes a known production rate of ^{10}Be atoms within the quartz due to nuclear interactions as cosmic rays hit oxygen nuclei in the silica lattice. The "standard" production rate for ^{10}Be (i.e., at >60° geomagnetic latitude and sea level) is taken to be 5.1 ± 0.3 atoms g^{-1} yr^{-1}, (Stone 2000). Corrections to the ^{10}Be production rate for geomagnetic latitude (–7%) and altitude (+2%) follow the model of Stone (2000) after Lal (1991), while those for geometry (i.e., shielding from surrounding hills) are after Nishiizumi et al. (1989). The shielding corrections are not significant for the Turakirae Head sample sites, ranging from 2 to 3%, but since they are known and systematic, they have been applied (Table 2). The production rate for *in situ* cosmogenic isotopes within the top 5 cm of a rock surface is constant (Masarik & Reedy 1994), but decreases to 0.980 and 0.948 for 0–10 cm (samples T1-2, T2-1 and T2-2) and 0–15 cm cross-sections (sample T1-1), respectively (assuming a 2.65 g/ml density for greywacke).

CHRONOLOGY OF THE TERRACES

BR1 and BR2

Before the work of Hull & McSaveney (1996), it was believed that BR1 was raised in AD 1855 (Aston 1912; Cotton 1921; Wellman 1967; Stevens 1969; Ward 1971; Ghani 1978; Moore 1987). From the beginning of our study, we recognised BR1 as the modern storm beach, which could not have been there before the AD 1855 earthquake. Since this implied that BR2 was the active beach before AD 1855, we sought evidence to support this hypothesis. Indirect evidence included:

(1) BR1 contains many modern artefacts: plastics, sawn and preservative-treated *Pinus* lumber, and partly decayed seal carcasses;

(2) BR1 continued to change under the influence of storm waves since it was photographed by Aston c. 1911;

(3) BR1 continued to evolve during and subsequent to our studies (although we never saw it active during a storm);

(4) BR1 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) BR2 and its associated former tidal pools contain fossils in growth position which yield ^{14}C dates from the mid 19th century, positively identifying it as the beach ridge first raised by the AD 1855 earthquake.

The compelling evidence, however, that moves the identification from the realms of a well-tested hypothesis to fact, is the AD 1856 map made by people who were in Wellington at the time and who labelled the beach now known as BR2 as the beach raised in AD 1855 (Grapes & Downes 1997). Thus, BR1 and BR2 have ages directly determined from historical records as *modern* and AD 1855, respectively. That is, BR1 is the crest of the modern active storm beach and began to form in late January 1855 when BR2 was raised above the fetch of the sea and ceased to be active.

Beach ridges apparently form very rapidly on the south Wellington coast, a fact not appreciated by earlier workers. BR1 had assumed much its present form when Aston first became acquainted with it within 55 years of its birth. This is not surprising considering that a substantial BR0 can form and disappear in just a few storms.

BR3

The time when BR3 was raised and BR2 was initiated can be determined from samples collected beneath two former sea-stack boulders on the shore platform seaward of BR3 (R28/f64, Fig. 3). In these sheltered localities, large (30 × 20 mm) sheets of intertwined tubes of small polychaete worms form dense calcareous crusts up to 70 mm thick, which have survived leaching by runoff from rain and wind-blown sea spray. The tubes are created by *Salmacina australis* (Appendix 1), which forms crusts in the shallow, subtidal zone (Morton & Miller 1968). A sample from one of these crusts seaward of BR3 yielded a ^{14}C age of 1604 ± 32 yr BP, which corresponds to 1243–1072 cal. yr BP (NZ8212; Table 1).

The worm crusts had overgrown barnacles (*Epopella* and *Tetraclitella*) and a limpet *Gadinea conica*, indicating the same shallow subtidal environment as the worm crusts (Appendix 1). Large numbers of the intertidal micro-bivalve *Lasaea rubra* and high-tide mussel *Xenostrobus pulex* were preserved within many of the tubes. ^{14}C dates from *G. conica* (NZA4747, 2566 ± 78 yr BP) and *X. pulex* (NZA4746, 2603 ± 86 yr BP) are identical within error. The true age of *X. pulex* should be younger, however, because they grew within the worm tubes that overgrew the *G. conica* sample. The time of uplift of BR3 and initiation of formation of BR2 is estimated to have been very shortly after 2060–2380 cal. yr BP (110–430 BC).

The date of 1243–1072 cal. yr BP (NZ8212) from *Salmacina australis* is anomalously young when compared with

Table 2 ^{10}Be AMS analytical data and correction factors. Errors are 1 σ.

Field number	GNS sample number	^{10}Be/^{9}Be from AMS (10^{-14})	^{9}Be carrier added (mg)	Weight of quartz in sample (g)	^{10}Be concentration in quartz (10^3 atoms/g ± 1 σ)	Shielding correction (%)	Sampling depth (cm)	Attenuation due to depth (%)	Exposure age (ka ± 1 σ)*
T1-1	547	6.0 ± 1.2	2.04	223.16	36.7 ± 7.1	3.7	0– 5	4.0	8.2 ± 1.6
T1-2	549	7.4 ± 1.6	1.02	224.68	22.5 ± 4.9	3.7	0–10	7.8	5.2 ± 1.2
T2-1	550	10.2 ± 1.3	1.02	244.87	28.4 ± 3.7	2.2	0–10	7.8	6.5 ± 0.9
T2-2	551	11.0 ± 1.5	1.02	216.14	34.7 ± 4.6	2.2	0–10	7.8	7.9 ± 1.1
							Error-weighted mean		6.7 ± 0.7

*Using a production rate of 4.9 atoms g^{-1} yr^{-1} (i.e., 5.1 atoms g^{-1} yr^{-1}, scaled to the geomagnetic latitude and altitude of the site after Stone (2000).

the samples 1000 yr older located stratigraphically above and below it. This sample has a high positive $\delta^{13}C$ value (7.0‰), compared with modern marine samples, which typically range from –2 to 2‰ (Jansen 1984). Being enriched in ^{13}C, it is likely to contain excess ^{14}C, and hence give an anomalously young age. By contrast, a sample of *S. australis* from the AD 1855 raised tidal pools (NZ8211) is anomalously old, but has a δ ^{13}C value typical of marine samples. The causes of these incompatible ages are unknown, but based on the two samples dated in this study, *S. australis* does not produce ^{14}C dates that accurately reflect the times of shore-platform uplift. We suggest that the worm-tube calcium carbonate may be susceptible to diagenetic alteration, and so is unsuitable for accurate ^{14}C dating.

BR4

No suitable organic material has yet been found from which to date the time of uplift of BR4 and initiation of BR3 using ^{14}C dating; BR4 was considered to be too young to be reliably dated using *in situ* produced cosmogenic ^{10}Be. Its age previously has been inferred from its position in the uplift sequence (Wellman 1967, 1969; Moore 1987; Hull & McSaveney 1996), and this can be repeated using revised interpretations of the ages of other ridges (see Discussion).

BR5

We obtained no new ^{14}C dates for BR5. The apparently oldest materials behind BR5 are freshwater shells (R28/f4, Table 1), but NZ4415 (10 050 ± 100 yr BP recalibrated after Moore 1987) is another ^{14}C anomaly since it is more than 4000 yr older than any of the four dates of associated driftwood (NZ4416, NZ4549, NZ4550, NZ4420). Moore (1987) suggested that old carbon was incorporated in the shell structure. Thin beds of marble crop out along the modern coastal platform, so it is conceivable that the organisms lived in an environment rich in calcium carbonate leached from a source devoid of ^{14}C. The carbonate would have been in solution as bicarbonate, and so it is likely that at least half of the carbonate available for shell secretion would have come from an atmospheric, non-^{14}C-deficient source. If the freshwater shells had only half the atmospheric ^{14}C concentration at their time of death, they would appear to be about one ^{14}C half-life older (i.e., 5570 yr) than their true age. Comparison of the ages of the two closely associated samples R28/f4 and R28/f5 (10 050 ± 100 and 5840 ± 90 yr BP) show this to be approximately the case. Like Moore (1987), we choose to ignore this sample.

The time of uplift of BR5, and initiation of BR4, is better recorded by a number of ^{14}C dates of wood from behind BR5. Organic material could accumulate behind BR5 immediately there was a ridge with a landward declivity, but if the sea were rising continually (see Discussion), such accumulated material would be continually overwhelmed by beach gravel, until the ridge was first raised and the sea stopped overtopping it. NZ4420 (7427–7032 cal. yr BP, recalibrated after Moore 1987) is the oldest sample, but it is significantly older than three other samples (NZ4416, NZ4549, and NZ4550) more closely associated with the underlying beach gravel of BR5. These have an error-weighted mean ^{14}C age of 5946 ± 54 yr BP. Thus, BR5 first rose above the fetch of waves at c. 4660–4970 BC.

With uplift, the beach cobbles and boulders of BR5 ceased to be subject to disturbance by the fetch of storm waves, and so surface-exposure dates of these materials using *in situ*-produced cosmogenic ^{10}Be provide an independent means of directly dating the time that BR5 was first raised. Adjusted for topographic shielding, and attenuation of production rate with depth, $^{10}Be/^{9}Be$ ratios indicate a mean surface-exposure age of 6.7 ± 0.6 ka for BR5 (Table 2). This estimate is consistent with the age determined by ^{14}C dating discussed above.

DISCUSSION

Eustatic sea-level changes

Interpretation of uplift history at Turakirae Head is strongly dependent on knowledge of local eustatic sea level. If BR5 and BR4 formed at times when sea levels were lower than present, then their uplifts would be greater than is apparent from their heights above the modern beach (Fig. 4). Past interpretations (Wellman 1967, 1969; Moore 1987; Hull & McSaveney 1996) assume that the Turakirae record postdates all significant eustatic change, and so the relative heights of beach ridges of various ages directly represent the uplift in earthquakes. Analysis of dated New Zealand Holocene sea-level markers (Gibb 1986) supports this assumption, but our dating of BR5 indicates that BR5 was forming and mobile during a major 25 m rise (Gibb 1986; Peltier 2002), and rose above the fetch of waves in an interval when the New Zealand eustatic sea-level curve (Gibb 1986) is unconstrained by data. For this reason, we chose to use the global eustatic curve of Peltier (2002), which is better constrained by data around the times of interest. Interpolation of Fig. 1 of Peltier (2002) indicated a sea level c. 4.27 m lower than present when BR5 was raised. A sea level of –4.27 m at c. 6800 yr BP appears to lie within the error limits of data plotted in Fig. 4 of Gibb (1986). In addition, the Peltier (2002) eustatic curve compensates for modelled isostatic responses to sea-level loading of the coast, whereas the Gibb (1986) curve does not—this adjustment is significant. If we are to prefer the Peltier (2002) sea-level model for BR5, then we should also accept the same model for BR4, and adopt a sea level at the estimated time of formation of BR4 of –1.32 m. Sea level had stabilised at present-day values by the times of cessation of building of BR3 and BR2 (Gibb 1986; Peltier 2002).

Increasing the uplift of BR5 by 4.27 m has a significant influence (cf. BR5 and BR5 + 4.27 m in Fig. 4B; see also Tables 3 and 4, and Fig. 5 and 6 discussed later). Although it does not change the age of BR5, it markedly affects estimates of recurrence times, and hence the seismic hazard from earthquakes raising Turakirae Head. The slip-predictable uplift model of Hull & McSaveney (1996) is insensitive to the amount of uplift of BR5, but estimates of time since the previous uplift, and time until the next uplift (BR4), are dependent on it (see next section). Adjusting for eustatic sea level changes estimates of the lengths of the interseismic intervals pre-BR5, BR5–BR4, and BR4–BR3. The former two are lengthened considerably, while the latter is shortened (Table 3), resulting in an overall significant increase in the mean recurrence interval, and a marked decrease in the variance.

The effect of the reinterpretation was so profound that we sought independent confirmation that sea level might have been varying during the formation of BR4 and BR5. Support for a steadily slowing sea-level rise, as per the Peltier (2002) model, until after BR4 had ceased forming, comes from several lines of circumstantial evidence. Fragments of BR5 are found against the foot of the postglacial wave-cut cliff. In many places it is not likely to have been preserved because of subsequent mass-movement adjustments of the steep slope, but it also is missing from some sites that have yet to adjust. This is consistent with formation of BR5 under a highly erosional regime, with the sea directly attacking the bedrock in many places. Such a regime may be indicative of rapidly rising sea level. Also, as a matter of probability on a coastline rising on average by amounts of 7.3 m every 2000 yr (see next section), it is highly unlikely that the last event before cessation of rapidly rising sea level would not have lifted the active beach of the day above the fetch of future waves, to be preserved. Hence, we should expect that BR5 might represent the last uplift during rapidly rising sea level, and so eustatic sea-level change should not be ignored. Last, we can compare and contrast those beach ridges known to have formed at stable sea level (BR1–BR3) with those thought to have formed during rising sea levels (BR4–BR5). BR4 and BR5 consistently have little width in cross-profile (Fig. 4A), appearing as defined ridges with a landward declivity behind them only near Barney's Whare, where large alluvial fans ensure a major sediment supply for rapid accretion.

Table 3 Summary beach-ridge data used in analysis.

Beach ridge	Continuity and width	Elevation at anticline axis[1] (m a.s.l.)	Height above BR1 (m)	Date of completion (BP)	Apparent uplift (m)	Sea level at time of uplift[4] (m)	Uplift (m)	Height at profile 1[5] (m a.s.l.)	Interval since prior uplift (yr)
BR0	discontinuous, ephemeral	–	variously –ve	–	0.0	0.0	0.0	–	–
BR1	continuous broad	2.9	0	–	0.0	0.0	0.0	5.2	150
BR2	continuous broad	8.9	6.0	95	6.0	0.0	6.0	7.0	2125
BR3	continuous broad	18.0	15.1	2220	9.1	0.0	9.1	10.1	2547[2] (2810)[2,3]
BR4	continuous narrow	24.9	21.9	4767[2] (5030)[2,3]	5.5	–1.3	6.8	12.6	1999[2] (1735)[2,3]
BR5	discontinuous narrow	30.8	27.9	6765	3.0	–4.3	7.3	13.8	2233[2] (1535)[2,3]
Pre-BR5[6]	not preserved	–	–	c. 9000[2] (c. 8400)[2,3]	?	<–20.0	?	?	?

[1]Average of 3 sections.
[2]Estimate from slip-predictable model.
[3]Estimate ignoring eustatic sea-level changes affecting BR4 and BR5.
[4]Interpolated from Fig. 1 of Peltier (2002).
[5]Between Orongorongo and Wainuiomata Rivers (Fig. 2).
[6]Beach ridge not preserved but event age estimable from uplift of BR5.

Table 4 Comparison of ages (BP) estimated for beach ridges found at Turakirae Head.

	Wellman (1969)	Moore (1987)	Stevens (1975)	Hull & McSaveney (1996)	This paper (stable sea)	This paper (preferred model)[1]
BR0	0	0	0	0	0	0
BR1	95	95	95	0	0	0
BR2	c. 600	c.450	490	95	95	95
BR3	c. 3100	c.3100	c. 3100	2220	2220	2220
BR4	c. 4900	c. 5000	c. 4900	5450	5030	4767
BR5	c. 5600	c. 6000	c. 5600	7300	6765	6765
pre-BR5[2]	–	–	–	c. 8400	c. 8400	c. 9000

[1]Model incorporates eustatic sea-level change for estimating uplift of BR4 and BR5.
[2]Beach ridge not preserved, but event age estimable from uplift of BR5.

Table 5 Tea Creek Road trench ^{14}C dates of Van Dissen & Berryman (1996).

NZ laboratory number	^{14}C age (yr BP ± 1 σ)	Calibrated age (cal. yr BP)	Material	Related Turakirae Head beach
Wk-1919	1620 ± 50	1330–1570	Small branches, twigs	BR3 accumulating, no uplift
Wk-1792	2730 ± 70	2560–2960	Bark, small branches	May relate to uplift of BR3
Wk-1794	4200 ± 80	4420–4870	Small branches	May relate to uplift of BR4
Wk-1793	5540 ± 80	6040–6480	Bark, twigs, seeds	BR4 accumulating, no uplift

This contrasts with BR1–BR3, which are generally broad in cross-profile and have large landward declivities along most of their lengths (Fig. 4A). A simple explanation of the contrasts is that beaches formed in rising sea level scour on the seaward face, and accrete dominantly on the crest, and so stay narrow, while those formed in stable sea level accrete on the seaward and landward faces, and much less on the crest, and so become broad. The similarity of BR4 and BR5 supports our use of the Peltier (2002) sea-level curve showing rising sea after BR4 had ceased to evolve, when this could not be inferred from other New Zealand data (e.g., Gibb 1986).

Average return period of uplift

Beach ridge uplift and age are highly correlated (Fig. 5), with cumulative uplift at the crest of the Rimutaka Anticline explaining 99.8% of the variance in the beach age, exclusive of BR4. At the anticline crest, the uplift rate for the past 7000 yr has been a very steady 3.32 ± 0.17 mm/yr. Our revisions of beach-ridge ages eliminate all of the variation in uplift rate over time discussed by Moore (1987). The high correlation between age and uplift extends also to the flanks of the anticline. Between the mouths of the Orongorongo and Wainuiomata Rivers at profile 1 (Fig. 2, 4), an uplift rate of 1.31 ± 0.15 mm/yr explains 99% of the variance in beach age (Fig. 5). The slip-predictable relationship allows the time of uplift of BR4 to be interpolated as 4769 ± 395 yr BP. Hence, BR4 probably first rose above the fetch of waves at 2160–3470 BC when it was raised 6.8 m (allowing for a sea level 1.32 m lower than today, interpolated from Peltier 2002) near Barney's Whare (Fig. 2). In addition, we can also extrapolate back in time and infer that the previous uplift event occurred c. 7050 BC (c. 9000 yr BP; Fig. 5). This estimate does not date the time of formation of BR5 because sea level was rising rapidly around that time (Gibb 1986; Peltier 2002). When global sea level rose faster than the land, the storm beach was mobile and easily able to maintain a fixed elevation relative to the rising sea.

The new estimated age of BR4 provides some direct support for applying sea-level corrections. In the adjusted model, uplift of BR4 coincides with a dated rupture of the Wairarapa Fault inferred from trench stratigraphy (Van Dissen & Berryman 1996). If we were to use this date (WK-1794, Table 5) as closely dating the rupture that formed BR4, our slip-predictable relationship would be strengthened, without changing any conclusion. However, we dispute other aspects of the Van Dissen & Berryman (1996) trench interpretation (see later section) and so choose not to include this date in our model.

The relationship between accumulated uplift and elapsed time suggests that coseismic uplift of a given amount is proportional to (and driven by) accumulated elastic strain energy since the previous earthquake. The repeating uplifts appear to be on a buckle of definable size, but driven by release of accumulated strain in unspecified, variable volumes of crustal rock. Hence, the geometric response of uplift to strain will be nonlinear. This implies that the probability density function of uplift magnitudes (Fig. 6) should be lognormal rather than Gaussian. The data from the axis of the anticline provide an acceptable fit to a lognormal distribution (F = 99, 1% probability that the model should be rejected, but a Gaussian model would not be rejected either). In such a model, the mean axial uplift per event is 7.3 ± 0.7 m, and the most frequently occurring (modal) uplift is 7.1 ± 0.9 m. The relationship between uplift and elapsed time indicates a mean recurrence interval of uplift of 2194 ± 117 yr; the modal interval is shorter at 2122 ± 193 yr (Fig. 6). The difference is significant only because of the high covariance between mean and mode. Since our dated events are very few ($n = 4$), their average is likely to poorly approximate the true mean of the long-term population because they are more likely to be samples from the more frequently occurring events and thus be centred about the mode. Because the difference is small, we have not compensated for this bias.

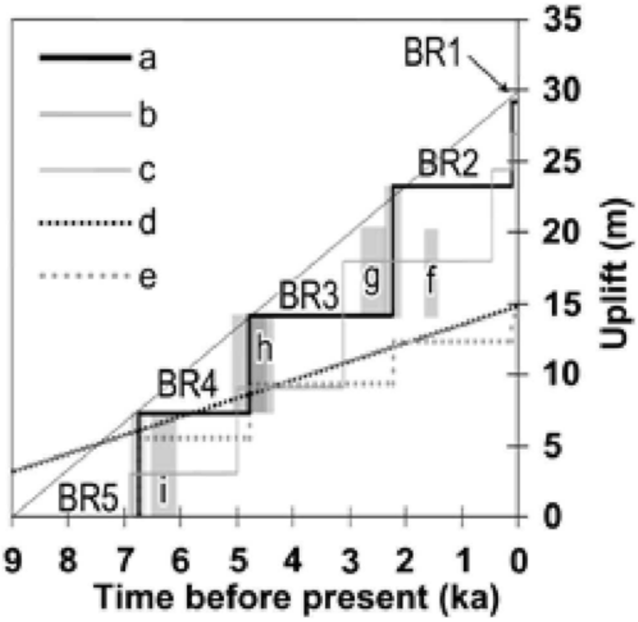

Fig. 5 Cumulative uplift of the Rimutaka Anticline near Turakirae Head since the formation of BR5. Stepped line **a** is at the crest of the anticline at the Palliser Bay shoreline (average uplift of profiles 12, 13 and 14 on Fig. 2, 4). BR1–BR5 indicate the intervals when these beach ridges formed. Stepped line **b** is the older interpretation of Moore (1987) after Wellman (1967). Line **c** is best fit uniform rate of uplift (3.32 ± 0.17 mm/yr). Line **d** is best fit uniform rate of uplift (1.31 ± 0.15 mm/yr) at profile 1 (Fig. 2, 4). Stepped line **e** is uplift history at profile 1 between the mouths of the Wainuiomata and Orongorongo Rivers (Fig. 2). Risers on steps correspond to uplift in great earthquakes involving simultaneous flexure of the Rimutaka Anticline and rupture of the Wairarapa Fault. Shaded areas are 95% confidence limits on age determinations of earthquake timing. Shaded areas **f**, **g**, **h** and **i** are 95% confidence limits on Tea Creek Road ^{14}C dates (Table 5) interpreted by Van Dissen & Berryman (1996) to closely date times of rupture of the Wairarapa Fault (heights and positions of these areas with respect to the uplift axis have no significance).

The last event at 5.98 m uplift (average of three measurements near the anticline axis) is not significantly smaller than either the mean or the mode, suggesting that the previous three events that raised Turakirae Head were great earthquakes of at least similar magnitude to that of AD 1855 (M_w 8.1–8.2, Eiby 1989).

Comparison with earlier age estimates

Beach-ridge age estimates vary somewhat between workers (Table 4). Differences for BR1 and BR2 are fully accountable through the earlier mis-identification now corrected. The age of BR3 now is well constrained by replicated ^{14}C dating that was unavailable before Hull & McSaveney (1996). BR4 has always been estimated on the basis of its relative uplift, and

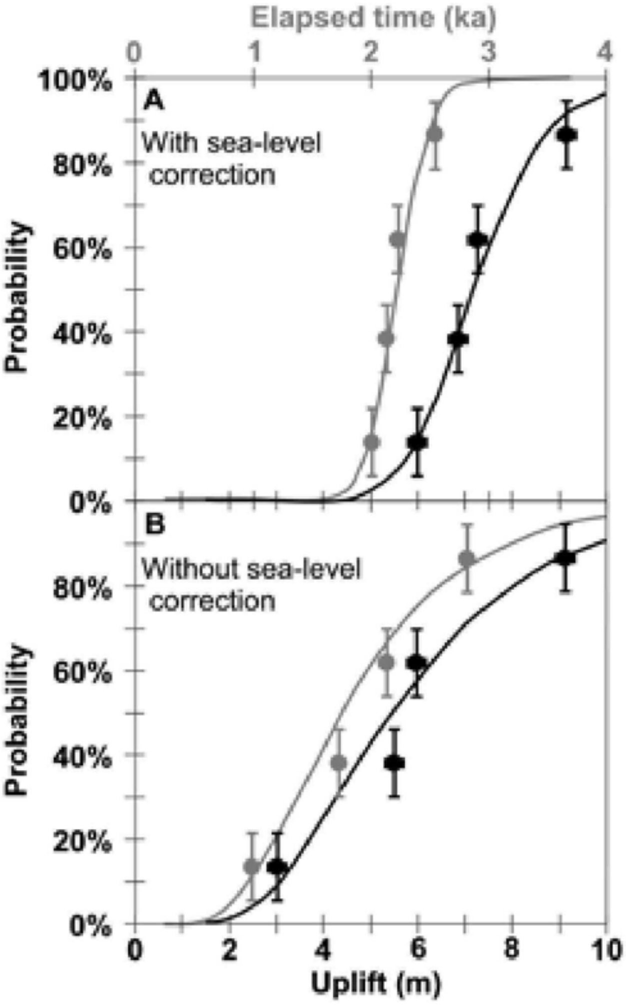

Fig. 6 Cumulative probability-density distributions for uplift (black) at the crest of the Rimutaka Anticline and intervals-between-uplift (grey) at Turakirae Head. Fitted distributions are lognormal. **A**, Our preferred model including correction for eustatic sea level. **B**, Model ignoring eustatic sea-level changes affecting BR5 and BR4, showing how interpretation of the uplift record at Turakirae Head depends on having an accurate sea-level history.

so its age varies as the ages used to calibrate it vary. Hull & McSaveney (1996) and this paper estimate the age of BR5 using ^{14}C dates presented in Moore (1987), and so variations in the age of BR5 between Moore (1987), Hull & McSaveney (1996), and this paper arise through differences in interpretation and selection of available dates (and a smaller amount due to changes in ^{14}C calibration). The selection of dates used here differs from those used in Moore (1986) and Hull & McSaveney (1996), and is made for the reasons stated earlier.

No earlier worker has concluded that eustatic change in sea level had affected the Turakirae record. While not affecting the age of BR5, the effect of rising sea level is to increase the estimate of tectonic uplift of BR5 and so affect the estimates of the age of BR4 (the uplift of which is also affected by a lesser rise of sea level), and the time since the previous uplift event (pre-BR5 of Table 4). This accounts for differences between Hull & McSaveney (1996) and the preferred ages of BR4 and pre-BR5 in this paper.

Limitations of the tectonic evidence

Turakirae Head is not only on the flank of the Rimutaka Anticline, but also on the edge of several other possibly independent tectonic structures: a sedimentary basin in Palliser Bay, and the tectonic trough of Cook Strait (Fig. 1). The entire area overlies the active Hikurangi Subduction Zone, and it is possible that the AD 1855 rupture included slip on the subduction interface (Darby & Beanland 1992). Interseismic subsidence is recorded for other active subduction zones, particularly immediately following coseismic uplift (e.g., Plafker et al. 1991). Hence, it is conceivable that Turakirae Head could be affected independently by coseismic and interseismic subsidence.

Because of the way the beach ridges form from sediment carried up the beach by waves, transgression of the sea onto the land as a result of land subsidence would move the active beach ridge in its entirety farther up the platform, hence we would not be able to detect episodic subsidence directly from the evidence we gathered. The indirect evidence of the remarkably uniform apparent uplift rate for the past 7000 yr (Fig. 5), however, argues strongly against a superimposed subsidence record. Post-seismic subsidence certainly has not occurred in the past 150 yr, because we confirm Edward Roberts' AD 1855 measurement (cited in Lyell 1856) at a site near Mukamuka Stream (locality 17, Fig. 2). If there were subsidence in the area before AD 1855, it must have occurred in a pattern preserving a tight-fitting linear relationship between time and net uplift. The simplest such pattern is zero subsidence, and so we conclude that there has been no subsidence in the past 7000 yr; if the area were affected by episodic subsidence, it must have a longer recurrence interval than 7000 yr. The heights of older marine-cut platforms, however, suggest that the long-term uplift rate between the Orongorongo and Wainuiomata River mouths has changed over time only at a very slow rate (Fig. 7). This suggests that the area is not subject to episodic subsidence.

Bedrock-platform cutting

The sea has been cutting a new bedrock platform in the vicinity of Turakirae Head since AD 1855, but it has yet to cut anything in the rock that could be described even as the beginning of a cliff. This is in marked contrast to the steeply cliffed coastline northeast of Mukamuka Stream (Fig. 2). In the vicinity of Turakirae Head, when sea level has remained stable relative to the land for hundreds to thousands of years along the preserved lengths of the beaches, a gravel ridge has formed and prograded seaward at a rate determined by the local supply of sediment to the beach. Where there has been minimal along-shore sediment supply, the sea has eroded a shallow notch in the bedrock and formed an ill-defined beach. Although the present notch is still being eroded, no coastal cliff has been cut in the bedrock during any of the past four intervals of relative stability between earthquakes and uplift. What then were the conditions here for the sea to cut a cliff in bedrock such as is found in subdued form behind BR5 and on the higher slopes shown in Fig. 3 behind the terraces marked *Imt*?

Whether the coastline erodes and can be cliffed, or progrades with beach-ridge growth, is determined predominantly by along-shore sediment balance. Most sediment is supplied currently to the beach from Orongorongo River, with Wainuiomata River and easily eroded alluvial fans of minor streams draining the Rimutaka Range supplying lesser amounts (Fig. 2, 3). Remobilisation of pre-existing sediment on the coastal plain must have been important during the rapid postglacial rise of sea level, as was sediment eroded from the foot of the Rimutaka Range by wave erosion and landsliding until BR5 was raised above the sea. During times of rising sea level, the sea was able repeatedly to attack the land behind the beach. In addition, the rising base level of Orongorongo and Wainuiomata Rivers induced channel aggradation and reduced channel gradients near the coast and hence must have reduced the supply of coarse alluvial sediment to the coast. On such a storm-lashed coast, a large reduction in gravel supply from the rivers is likely to have induced coastal erosion. Hence, the times of most active erosion of the shore platform must have been during the intervals when sea-level was rising faster than the land. The discontinuity of BR5 appears to be an example of this; although some of its lack of visibility along the coast is attributable to its burial by colluvium and landslides, it also is missing from some localities where it could not have been buried. At Turakirae Head, tilting of beach ridges and shore platforms demonstrates a range of rates of land uplift, whereas the eustatic sea-level rise was uniform. Hence, on the very rapidly rising rock mass in the crest of the anticline, opportunities for shore-platform erosion must have been more limited than elsewhere where uplift was slower.

These effects are illustrated by modelling the apparent sea-level height against the land over time (Fig. 7), combining a history of global sea level with that of inferred local uplift. The first-order fluctuations in sea level for the past 780 k.y. can be modelled from the published smoothed $\delta^{18}O$ data of Imbrie et al. (1984). This assumes that: (1) the range of $\delta^{18}O$ over the past 18 k.y. results largely from changes in the volume of ice sheets and glaciers that caused a global sea-level change of c. 130 m, and (2) any non-linearity in the relationship between $\delta^{18}O$ and sea level is adequately represented in the record of the past 130 k.y. presented by Shackleton (1987). A model sea-level reconstruction has been undertaken by Lea et al. (2002), but we wanted a model over a longer time span and in digital form so that we might manipulate it. In detail, the $\delta^{18}O$ value of marine microfossils varies with other factors as well as the global ice volume. Additionally, global sea level varies with other factors as well as the quantity of water locked up in ice (see Lea et al. 2002, Milne et al. 2002, and Peltier 2002). These other factors, however, are lesser effects (Shackleton 1987) and are partly compensated for in an empirical calibration. They may modulate the amplitude and to a lesser extent the timing of the sea-level fluctuations against the land shown in Fig. 7, but they would not alter the fractal and stepped pattern in the curve. The pattern shape is important here, and not the precise detail of timing and amplitude. Our "sea-level" reconstruction is similar to that of Lea et al. (2002) for the last 370 k.y., but is more generalised because of the smoothing of the original Imbrie et al. (1984) $\delta^{18}O$ record.

It is unrealistic to assume that Rimutaka Range uplift has been at a constant rate over geological time, and so it has been modelled as increasing at an exponentially decreasing rate from zero to its present value over the past 1.0 m.y. The decay constant of -3.448×10^{-6} yr^{-1} is chosen arbitrarily to align one of the peaks in the synthetic sea-level curve with the highest of the Ota et al. (1981) marine terraces (Fig. 7). The model indicates ages of the Ota et al. (1981) terraces, but they are only likely to be close to the true ages over the past c. 300 k.y. where the various models have little opportunity to stray far from reality.

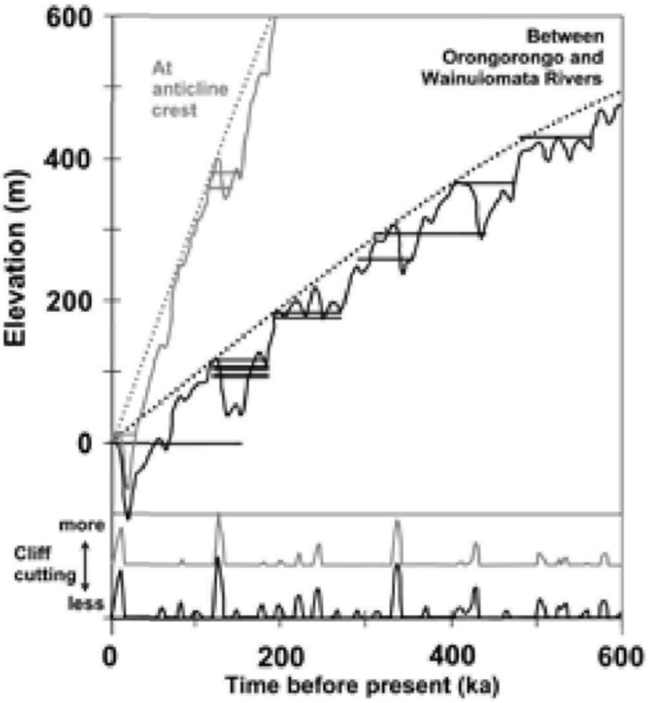

Fig. 7 Model of time versus today's elevation of past levels of the sea, relative to the rising rock mass of the Rimutaka Anticline. The upper plots give directly the age of a raised marine platform of a given elevation, or conversely the current elevation of a former marine platform of a given age. The rock-uplift model (dotted lines) is one of increasing uplift rate rising from zero at c. 1 Ma to today's values with an exponential decay rate of -3.448×10^{-6} yr^{-1} as described in the text. The superimposed sea-level curve is derived from the published smoothed $\delta^{18}O$ data of Imbrie et al. (1984) calibrated against sea-level data in Shackleton (1987). Horizontal lines indicate the intervals when the shore platforms and beach deposits of Ota et al. (1981) may have formed. Lines in grey are at the crest of the Rimutaka Anticline where it reaches the sea. Lines in black are for the flank of the anticline between Orongorongo and Wainuiomata Rivers. Lowest (bottom) curves model times when sea level was rising faster than the land, simultaneously reducing sediment load to the sea from nearby rivers and allowing the sea to frequently overtop beaches and erode cliffs in the bedrock. These curves compare "intensity of cliff-cutting opportunities" between the two sites, and are offset by an arbitrary amount to facilitate comparison.

At the lower uplift rate on Fig. 7, the prominent marine terraces (the modern coastal plain and those marked *Imt* on Fig. 3) correspond to levels that have been repeatedly occupied as shorelines. For the higher uplift rate, the time for platform cutting is very brief. Between Wainuiomata and Orongorongo Rivers (Fig. 2), the modern platform could have been cut, in part, during the penultimate glaciation between c. 140 and 155 ka before being trimmed back in the Holocene. In contrast, the coastal plain at the anticline crest can only have been cut during the postglacial rise of sea level. The efficacy of the cutting process is demonstrated by the width of the cut platform in front of sample site T2 (Fig. 3). At the higher uplift rate, the local sea-level curve is insensitive to the eustatic sea-level model.

Further, we have inferred that the opportunities for cliffing are greater when sea level is rising faster than the land. The models of sea level and uplift can be combined to examine opportunities for cliffing. Since a rising sea both attacks

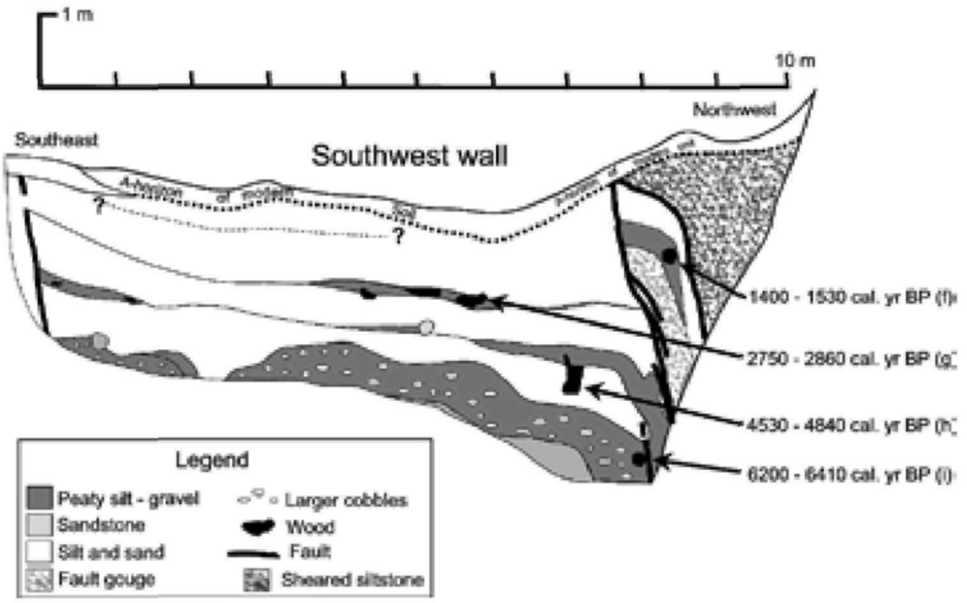

Fig. 8 Stratigraphy of the Tea Creek Road trench (Fig. 1A) excavated across the Wairarapa Fault 80 km north of Turakirae Head (simplified from Fig. 3 of Van Dissen & Berryman 1996; more detailed unit descriptions are given in their legend and not repeated here). Labelled ages refer to calibrated ages of ^{14}C dates in Table 5. Letters f–i refer to Fig. 5.

behind the beach and reduces sediment supply from the rivers, we might assume that intensity of cliffing opportunity scales with relative rate of rise, and with duration of rise, and hence eroded mass might be proportional to the area under the curve of rise rate versus time. These differ between the crest of the anticline and its flanks. To facilitate comparing the two (bottom curves on Fig. 7), we have scaled the models such that the area under the rise rate versus time curve for the postglacial sea-level rise between Orongorongo and Wainuiomata Rivers is 1.0. In this model, it is apparent that although there have been more opportunities for cliff cutting on the more slowly rising coast, the intensity of cliffing has been about equal on the two coasts despite widely differing uplift rates. Correspondence between the model times of cliffing and elevations of known past shorelines attests to the vigour of erosion along this coast when the sea is able to attack a steep shoreline starved of long-shore drift. It follows that nowhere along the coast in the area of our study has the shoreline been particularly sediment starved in the late Holocene, but that the cliffed coast immediately east of our proflile 17 (Fig. 2) currently is starved.

Relationship to history of Wairarapa Fault ruptures and ruptures on other faults

The historical demonstration of simultaneous flexure of the Rimutaka Anticline and rupture of the Wairarapa Fault in AD 1855, and the similarity, within the limitations of the data on older events, of the four episodes of anticlinal flexure, leads directly to the inference in this study that there have been four, and only four, ruptures of the Wairarapa Fault since an earlier unrecorded rupture c. 7000 BC. From a trench study 80 km northeast of Turakirae Head (Fig. 1A), however, Van Dissen & Berryman (1996) interpreted five surface ruptures on the same fault since 4250–4460 BC (6200–6410 cal. yr BP). This is based on the historically observed rupture and four ^{14}C dates (Table 5, Fig. 5, 8) reasoned to closely relate to fault rupture and associated ground disturbance.

Between the two studies, the following ^{14}C dates are statistically identical at the 95% confidence level: NZ4417 and Wk-1919; NZ4746, NZ4419 and Wk-1792; and NZ4414 and Wk-1794. None of these NZ-series ^{14}C dates is inferred to relate to an episode of uplift at Turakirae Head. BR3 was accumulating gravel at the time of growth of the twigs of Wk-1919. At the 95% confidence level, there is complete overlap in time between Wk-1794 and the inferred BR4 uplift (lending some support for our slip-predictable uplift model at Turakirae Head). There also is a 230 yr overlap in time in the calibrated age of Wk-1792 and that for uplift of BR3. BR4 is inferred to have been accumulating gravel at the time of growth of the twigs and seeds of Wk-1793. There is the irrefutable event of AD 1855 known to have affected both sites (but not able to be inferred from the interpreted trench stratigraphy). Thus, there is a possibility of correspondence between the inferred timing of three events between the two studies (Fig. 5). A possible inference from this is that two of the inferred ruptures at Van Dissen & Berryman's (1996) Tea Creek Road site were on a fault segment not associated with flexure of the Rimutaka Anticline. The visible fault geometry suggests that this is possible, but we do not believe that such intermittent segmentation is a useful interpretation of current knowledge. A significant piece of evidence against segmentation is the record from two great (≥8.0) earthquakes at Turakirae Head that were not inferred from the Tea Creek Road trench—indicating that a reinterpretation of one or both records may lead to a simpler hypothesis.

If there were only four Wairarapa Fault ruptures since c. 7000 BC, we would infer that the trench stratigraphy (Fig. 8) records at least two dated sedimentation events unrelated to fault rupture (Van Dissen & Berryman (1996) considered this hypothesis, but rejected it as unlikely). These non-rupture events might relate to the creation of sediment sources by storms. All of the sedimentation must be due to storms, because storm runoff is required to transport sediment to the rupture-generated reservoir. Thus, all of the trench dates relate to storms that mobilised sediment from available sources (which may have been newly created by storms or earthquake shaking). The average interval (c. 1500 yr) between such events measures the joint frequency of sediment-source creation and burial of organic matter (by earthquake damage, debris avalanching, and major forest wind-throw) within the small, formerly forested drainage basin above the trench site. Some of these events may (and probably do) relate to fault rupture at the site, but it is noteworthy that the best known rupture event (the AD 1855 fault movement) is not interpreted as a datable sedimentation event in the stratigraphy. This contrasts strongly with the evidence from warping at Turakirae Head, where the AD 1855 deformation is the defining model.

If the trench dates were interpreted in terms of direct relationships between dated horizons and fault movement, we would infer:

(1) at least one rupture since AD 550–420 (which could equate with the AD 1855 uplift of BR2);
(2) at least two ruptures, and possibly more before AD 550–420; and
(3) one of the earlier ruptures was between 4350–4460 BC and 2580–2890 BC (which may equate with the uplift of BR4 at 2160–3470 BC).

While our interpreted coastal-uplift chronology is largely incompatible with the previously published interpretation of the Tea Creek Road trench, it is fully compatible with the above interpretation. Hence, we reason that our study presents a more likely chronology of ruptures of the Wairarapa Fault along the segment active in AD 1855 than that inferred in Van Dissen & Berryman (1996). Although we infer fewer rupture events, this implies earthquakes of larger magnitude.

There is a possibility that warping of the Rimutaka Anticline occurs only in the larger Wairarapa Fault ruptures, and that the smallest ruptures pass unrecorded at Turakirae Head. Such an interpretation would imply that coastal uplift does not occur in a small proportion (c. 33%) of the ruptures, and by implication these ruptures are on segments of the fault that do not affect the south Wellington coast. The size of events recorded at Turakirae Head (mostly larger than the event of 1855), however, precludes that the fault near the trench site does not rupture when Turakirae Head rises, yet the trench apparently does not record all of the Turakirae events. Are we to believe that completely different faults can rupture and still produce similar patterns of uplift at Turakirae Head?

The poor agreement between the rupture histories inferred from the Turakirae Head beaches and the Tea Creek Road trench should not be so surprising. The record from Turakirae Head is a composite record from many individual sites, whereas there is, as yet, only a single trench record. The mass of age data from Turakirae Head (Table 1) enabled individual dates to be examined in comparison with others purporting to date the same event. Many dates from Turakirae Head were inferred to relate to intervals between uplift events, and we used only those inferred to most closely bracket the uplift. There is a need for further trenching to compare with the two interpretations and so better constrain the times of rupture of the Wairarapa Fault, before there can be usefully informed discussion on how segmentation between the two sites has arisen.

There are many other faults in the Wellington region (Fig. 1A,B), but the available data suggest that the Turakirae sequence does not hold evidence of the activity of those that do not participate in the distribution of strain during ruptures of the southern end of the Wairarapa Fault. It is unlikely that rupture of the Wellington Fault, for example, could cause local flexure on the Rimutaka Anticline in a similar pattern to that seen in AD 1855. If there were regional uplift associated with rupture at Wellington, we would expect it to be areally uniform at Turakirae Head, and such uniform uplift is not seen. Likewise, we recognise no signal in the data from Turakirae Head that could be inferred to arise from rupture of the subduction interface beneath the area, unless this simultaneously involves rupture of the Wairarapa Fault and folding of the Rimutaka Anticline. We already have noted that local or regional subsidence there could pass undetected, but if it occurred, it must have been very peculiarly distributed in time.

Stevens (1969) inferred BR2 to date from the Haowhenua earthquake of local Māori oral tradition, interpreted by Best (1918, 1923) as occurring sometime in the 15th century, c. AD 1460. In our interpretation of the Turakirae record, the 15th century was marked by continued accretion of BR2 at a stable height. There is no possibility of uplift occurring at Turakirae Head around this time, and hence our record has no bearing on this possible earthquake.

Darby & Beanland (1992) compared a number of inferred models of the AD 1855 Wairarapa Fault rupture with the then-known pattern of uplift, which did not include the large local uplift now recognised at Turakirae Head. If this local pattern is now included, the observed pattern of uplift for the AD 1855 earthquake closely follows that predicted by Darby & Beanland's (1992) flexed-Wairarapa Fault model, but the significant (8 km) left step apparently 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 & Mazengarb (1996). The excellent qualitative fit to this model implies that the AD 1855 earthquake probably did not involve significant (if any) slip on the subduction interface. Darby & Beanland (1992) did not pursue this model further because it predicted local amounts of uplift grossly in excess of any then known in the AD 1855 earthquake literature.

Further work

The interpretation of Turakirae Head beach ridges presented here is a remarkably complete record of just four great earthquakes that have raised this section of the south Wellington coastline in the past 9000 yr. The interpretation is at variance with previously accepted interpretations for the area (Moore 1987, Hull & McSaveney 1996), with previously accepted interpretation of the paleoseismology of the Wairarapa Fault (Van Dissen & Berryman 1996), and with the previously accepted eustatic sea-level curve for New Zealand (Gibb 1986). We believe that the evidence supporting our interpretation is compelling, but accept that it is dependent on accurate knowledge of the local sea level, which is poorly constrained, particularly about a time when the rate of rise was slowing rapidly. There is circumstantial evidence at the head for rising sea level at the time of formation of BR5, but it may be the wrong environment to expect evidence to be there to constrain the amount of change. Rising sea level directly increases the amount of uplift indicated by the relative positions of BR5 and BR4 by an amount equal to the rise, and hence it affects our estimate of the age of BR4. There is need for further work on the New Zealand Holocene eustatic sea-level curve, in particular incorporating geophysical modelling of the associated isostatic response of land to rising sea, and constraining with new data portions of the curve currently poorly constrained. Further development of cosmogenic isotope surface-exposure dating may enable BR4 to be directly dated in the future, or organic material for ^{14}C dating may be found to constrain the time it ceased forming. This will resolve uncertainty about its age, but it may not resolve the uncertainty about its uplift unless it dates from a time of well constrained, stable, sea level similar to today's. Trenching across the ridges may show stratigraphic differences between those accreting laterally at stable sea levels and those accreting vertically with rising sea level, but even BR1 has to have accreted vertically at an even faster rate to have reached its present height before c. AD 1910. The variance with fault trenching studies is most readily resolved by further fault trenching at different localities; there is little likelihood of resolving it completely with further studies at Turakirae Head. It may be that the differences are real, and then structural reasons such as fault segmentation can be considered.

CONCLUSIONS

1. The hypothesis first put forward in Aston (1912) that the lowest beach ridge (BR1) along the coast at Turakirae Head was raised 2.7 m by the AD 1855 earthquake is unequivocally refuted by:
   (1) occurrence of modern beach flotsam in BR1;
   (2) continued evolution of BR1 since photographed by Aston c. 1910;
   (3) a lack of deformation of BR1, which subparallels modern sea level;
   (4) mid 19th-century ^{14}C dates from BR2 and associated former tidal pools;
   (5) labelling of BR2 on AD 1856 maps as being the former shoreline of AD 1855;
   (6) variation in uplift at Turakirae Head in AD 1855 from 1.8 m west of Wainuiomata River to 6.4 m east of Barney's Whare, with >4 m of uplift along >3.5 km of coastline.
2. BR1 formed quickly after the co-seismic uplift of 23 Jan 1855. It will continue to evolve at about its present range of heights until the next uplift event.
3. BR2 began to form 110–430 BC and first rose above the fetch of waves on 1855 Jan 23^{d} 2130^{h}, when it was raised a maximum of 6.4 m near Barney's Whare.
4. BR3 first rose above the fetch of waves 110–430 BC when it was raised a maximum of 10 m near Barney's Whare, and probably began to form 2760–3400 BC.
5. BR4, dated by assuming a uniform rate of uplift and a global sea level 1.32 m below present sea level, first rose above the fetch of waves 2760–3400 BC when it was raised 6.8 m near Barney's Whare. BR4 began to form 4660–4970 BC when BR5 first rose above the fetch of waves.
6. BR5 began to form c. 7000 BC, but continued to rise with rising sea level, until it rose 7.3 m above the fetch of waves near Barney's Whare.
7. Sea level continued to rise after formation of BR5, moving BR4 up the exposed coastal platform, reducing the apparent uplift of BR5. The sea may have continued to rise but at a greatly reduced rate after formation of BR4, but probably had stopped rising before BR3 ceased to evolve.
8. Beach-ridge uplift at Turakirae Head fits a lognormal probability density distribution with a mean of 7.3 ± 0.7 m (1 σ error) and mode of 7.1 ± 0.9 m. The AD 1855 event is not significantly smaller than the mode, suggesting that the raised beach ridges at Turakirae Head are evidence of great earthquakes of at least similar magnitude to that of AD 1855.
9. Beach-ridge uplift and age are highly correlated. The mean recurrence interval of 2194 ± 117 yr is little different from the mode of 2122 ± 193 yr. The pattern of slip-predictable uplift appears to have persisted for hundreds of thousands of years.
10. The pattern of shoreline uplift for the AD 1855 earthquake is closely described by the flexed-Wairarapa Fault model of Darby & Beanland (1992), but the significant (8 km) left step that raised the head 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 & Mazengarb (1996). This model does not involve slip on the subduction interface.
11. There have been four great earthquakes involving rupture of the Wairarapa Fault and flexure of the Rimutaka Anticline in the past 9000 yr, which contrasts with the five fault ruptures in the past 6500 yr inferred from a trench study by Van Dissen & Berryman (1996). One or more of the organic horizons at the trench site may not have arisen from an event that raised the coastline at Turakirae Head.
12. Away from the crest of the Rimutaka Anticline, a part of the modern coastal platform may have been inherited from a coastal platform cut during the low stand of sea level in the penultimate glaciation. At the crest of the anticline, however, the entire platform can only have been cut during the postglacial rise of sea level until 5080–5480 BC.
13. New Zealand's eustatic sea level was still rising significantly after 4660–4970 BC, and at a greatly reduced rate after 2760–3400 BC. It had stopped rising before 110–430 BC.
14. The open-ocean radiocarbon reservoir correction (δR) for 10 ^{14}C dates of coastal marine shells that died in January 1855 at Turakirae Head is 3 ± 14 cal. yr BP.

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APPENDIX 1

Macrofauna of raised beaches at Turakirae Head

ALAN G. BEU

INTRODUCTION

After recognition by the late Bruce Dix that well-preserved fossil macrofaunas from AD 1855 were to be found beneath large boulders (1–2 m diam.) lying in the former tidal pools of BR2 at Turakirae Head, two visits were made to collect them at several suitable sites (in the vicinity of profile localities 7 and 8, Fig. 2 of main text). A bag of sediment also was collected at most sites to obtain micro-molluscs for study. The sediment samples consisted of friable, peaty, sandy soil with a large number of present-day plants, insect, and terrestrial snail remains. The samples were wet-sieved, dried, and sorted in the conventional manner.

The macrofaunas from all localities (Table 6) consist of 97 species of Mollusca, 4 of barnacles (Cirripedia), and a few representatives of 5 other phyla or classes (crabs, echinoids, ophiuroids, polychaete tubes, and fish). Names of the Mollusca have been updated from those in Powell (1979) following Beu & Maxwell (1990), Coovert & Coovert (1995), Spencer & Willan (1996), Marshall (1998a,b), Williams et al. (2003), and Beu (2004). The faunas listed in Table 6 are from six localities (Fig. 2):

1. GS15119, R28/f62, fauna visually dominated by large "paua", *Haliotis iris*, in a hollow beneath a large boulder c. 400 m east of Turakirae Head, on the AD 1855 intertidal slope, about midway between beach ridges BR1 and BR2, NZMS 260 grid ref. R28/70417266. (This locality yielded the diverse fauna of micro-molluscs.)
2. GS15120, R28/f61, monospecific *Diloma nigerrima* fauna beneath a large rock a few metres below (seaward of) BR2, c. 400 m east of Turakirae Head; R28/70427270.
3. GS15121, R28/f72, fauna visually dominated by "white limpet", *Gadinia conica*, beneath a large rock between beach ridges BR1 and BR2, c. 100 m north of the south boundary of the Turakirae Head scientific reserve, on profile 12, R28/71487349.
4. GS15122, R28/f62, fauna visually dominated by lepadomorph barnacles, c. 10 m east of GS15119, on BR2 intertidal slope c. 400 m east of Turakirae Head, R28/70407349.
5. GS15123, R28/f64, polychaete tube crust on the underside of a large rock on BR3 intertidal slope, c. 50 m seaward of BR3 crest and c. 50 m southwest of a sharp bend in the old quarry track, R28/70437288.
6. GS15124, R28/f71, polychaete tube crust on the underside of a large rock on the western side of a large (former) stack on the BR3 intertidal slope, c. 200 m southwest of GS15123, R28/70187288.

ECOLOGY

The ecological conditions inhabited by the listed faunas have been determined partly from the author's experience of molluscs in the Wellington area, partly from examination of the shores around Turakirae Head for comparison with the uplifted faunas, and partly from reference works including Morton & Miller (1968), Foster (1978), and Powell (1979). The faunas are largely those expected around Wellington at present, at or just below the low-tide line on extremely exposed rocky shores, allowing for transport into the deposition site of molluscs and barnacles from higher up the shore.

The AD 1855 fauna associated with BR2

The fauna found closest to BR2 is GS15120 (R28/f61) from beneath a large rock just seaward of BR2 and c. 400 m east of Turakirae Head, which consists of *Diloma nigerrima* in large numbers. An identical living fauna was observed recently on a nearby shore, near the high-tide line among rocks east of the mouth of the Orongorongo River, 2 km NNW of Turakirae Head. Here, very large numbers of *D. nigerrima* live on top of one another in deep, narrow channels (weathered out softer beds) between the rocks. The same fauna occurs near the high-tide line at Red Rocks, between Owhiro Bay and Sinclair Head, west of Wellington Harbour. The fauna in GS15120 therefore represents the AD 1855 normal marine high-tidal fauna of an exposed rocky shore, preserved in its original relationship to the storm beach ridge behind it. *D. nigerrima* also occurs in small numbers in some other collections (GS15119, GS15121) and these specimens evidently have been transported into the deposition site from higher up the shore.

The faunas in GS15119 and GS15121 are similar to each other, and both are taxonomically diverse collections from similar situations well seaward of BR2. The visually dominant molluscs of these two sites are different—*Haliotis iris* in GS15119 and *Gadinia conica* in GS15121. However, *G. conica* is the most abundant mollusc at both sites, and the apparent difference results from the much smaller number of *Haliotis iris* at GS15121 than at GS15119. Evidently this is a function of the much lower exposure of the GS15121 site, 2 km farther from Turakirae Head than GS15119. The other major difference between the sites is the lower diversity of the micro-molluscs in GS15121 than in GS15119. At GS15119, the floor of the hollow had a shallow but obvious accumulation of peaty, fine-grained sediment, from which the micro-molluscs were sorted. In contrast, the site of GS15121 was floored with coarse, highly porous gravel, from which most of the micro-molluscs presumably have been removed either by leaching or by washing down into the gravel.

Other abundant to common molluscs, beside the dominant two species, in both collections are chitons (particularly the intertidal "snake's skin" chiton, *Chiton pelliserpentis*, common on all New Zealand rocky shores); limpets (16 taxa of limpet-shaped gastropods, including 8 "true" limpets, 2 *Haliotis* species, 3 fissurellids, and 3 pulmonate limpets); the irregularly coiled "worm-shell" gastropod *Serpulorbis zelandicus*, which is still cemented to sheltered rocks at both sites; littorinids, the characteristic worldwide exposed rocky

Table 6 Macrofauna of raised beaches BR2 and BR3 at Turakirae Head. See text for localities; GS15119–15122 are associated with BR2. GS14123 and GS15124 are associated with BR3. Single asterisk (*) indicates species limited to the intertidal or shallow subtidal zones of exposed rocky shores; Double asterisk (**) indicates species limited to the supra-littoral fringe. Abbreviations indicate specimen numbers: A = abundant (>20 specimens); C = common (5–20); R = rare (<5); numbers are listed where there were fewer than four specimens (other than for *Leuconopsis obsoleta*). "Q & G" is used for Quoy & Gaimard.

Locality	GS 15119	GS 15120	GS 15121	GS 15122	GS 15123	GS 15124
Macrofauna						
Mollusca						
Polyplacophora						
Leptochiton inquinatus (Reeve)	1					
Ischnochiton maorianus Iredale*	C		2	2		
Plaxiphora ?biramosa (Q & G)*					2	
Chiton (*Sypharochiton*) *pelliserpentis* Q & G*	C		A		C	
Chiton (*Amaurochiton*) *glaucus* (Gray)*	C					
Onithochiton neglectus (Rochebrune)*	C			1		
Bivalvia						
Linucula sp.	R		1			
Pronucula ?certisina (Finlay)	R					
Glycymeris (*Glycymerula*) *modesta* (Angas)	1					
Lissarca trapezina (Bernard)*	1					
Aulacomya maoriana (Iredale)*	R		1			
?*Perna canaliculus* (Gmelin), umbones*	R					
?*Modiolus* sp., umbo	1					
Xenostrobus pulex (Lamarck)*	1		R			
Ostreidae, indet. Juvenile	1			C	R	R
Borniola ?bidentifera (Powell)*	R		2			
Lasaea "rubra (Montagu)"*	C		C	A	A	A
Myllita (*Zemyllita*) *stowei* (Hutton)*	1					
Melliteryx parva (Deshayes)	1					
Mysella unidentata (Odhner)	R					
Neolepton antipodum (Filhol)	R					
Leptomya retiaria (Hutton)	1					
Pseudarcopagia disculus (Deshayes)*	R		2			
Tawera spissa (Q & G)	1			2		
Caryocorbula zelandica (Q & G)	1					
Hiatella arctica (Linné)	1					
Gastropoda						
Cellana denticulata (Martyn)*	C		R	R		
Cellana ornata (Dillwyn)*	R		C	R		
Cellana radians (Gmelin)*	C		A	C		
Patelloida corticata (Hutton)*	R		R			
Notoacmaea daedala (Suter)*	C					
Notoacmea ?helmsi (Smith)*, corroded	R		R	R		
Radiacmea inconspicua (Gray)*	R		1			
Atalacmea fragilis (Sowerby)*	1			2		
Incisura lytteltonensis (Smith)*	C					
Sinezona iota (Finlay)*	R					
Sinezona laquea (Finlay)*	R					
Sinezona levigata (Iredale)*	R					
Haliotis (*Paua*) *iris* (Gmelin)*	A		R			
Haliotis (*Sulculus*) *australis* (Gmelin)*	2			2		
Scutus antopodes (Montfort)*			1			
Emarginula striatula (Q & G)*	C					
Tugali suteri Thiele*	C		1			
Thoristella chathamensis (Hutton)*	C		R	1		
Cantharidus (*Mawhero*) *purpureus* (Gmelin)*	1					
Micrelenchus (*Plumbelenchus*) *dilatatus* (Sby)*	R					
Diloma nigerrima (Gmelin)*	R	A	R	1		
Diloma (*Fractarmilla*) *bicanaliculata* (Dunker)*	C					
Melagraphia aethiops (Gmelin)*	C					
Herpetopoma bella (Hutton)*	C		R			
Turbo smaragdus (Gmelin)*	C		R	1		
Liotella lissa (Suter)	R					
Liotella polypleura (Hedley)	R					
Austrolittorina cincta (Q & G)*	C		C	C		
Austrolittorina antipodum (Philippi)	C		R	1		
Risellopsis varia (Hutton)*	C		1	C		

(*continued*)

Table 6 (*continued*)

Locality	GS 15119	GS 15120	GS 15121	GS 15122	GS 15123	GS 15124
Eatoniella olivacea (Hutton)*	C		2	1		
Eatoniella roseola (Iredale)*	C					
Eatoniella (*Albosabula*) *lampra* (Suter)*	R					
Eatoniella (*Albosabula*) ?*rakiura* Ponder*	R					
*Eatoniella**, 3 further species	R					
*Powellisetia**, 2 species	R					
Onoba foveauxiana (Suter)*	R					
Onoba insculpta (Murdoch)*	C		2	2		
Pisinna zosterophila (Webster)*	A			2		
Merelina lyalliana (Suter)*	R					
Pusillina (*Haurakia*) *hamiltoni* (Suter)*	R					
Pusillina (*Haurakia*) *infecta* (Suter)*	R					
Anabathron (*Scrobs*) *hedleyi* (Suter)*	R					
Rissoina chathamensis (Hutton)*	A		2			
Suterilla neozelanica (Murdoch)**	1					
Caecum digitulum Hedley	C					
Zeacumantus subcarinatus (Sowerby)**	A					
Stiracolpus sp., apex	1					
Serpulorbis zelandicus (Q & G)*	A					
Curveulima titahica (Suter)	R					
Melanella sp., straight	R					
Buccinulum pallidum Finlay*	1					
Buccinulum vittatum littorinoides (Reeve)*	C		R			
Cominella maculosa (Martyn)*			2			
Haustrum scobina (Q & G)*	R		C	1		
Haustrum haustorium (Gmelin)*	R		C	1		
Xymene aucklandicus (Smith)	R		R	R		
Zemitrella choava (Reeve)*	R					
Austromitra rubiginosa (Hutton)*	2					
Dentimargo cairoma (Brookes)*	R					
Linopyrga rugata (Hutton)	R					
Evalea sabulosa (Suter)	1					
Chemnitzia zealandica (Hutton)	C			1		
Gadinia conica (Angas)*	A		A	C	C	R
Siphonaria cookiana Suter*	R			R		
Siphonaria zelandica (Q & G)*	C		R	R		
Marinula filholi Hutton**	R		1	R		
Leuconopsis obsoleta (Hutton)**	3		3	C	6	1
Arthropoda, Crustacea						
Cirripedia						
Chamaesipho columna (Spengler)*	A		A	A		
Epopella plicata (Gray)*	C		C	C		
Tetraclitella purpurascens (Wood)*	A		A	C	C	R
Calantica ?*spinosa* (Q & G)*	R		R	A		
Macrura						
Crab "fingers"	C					
Echinodermata						
Echinoidea						
Evechinus chloroticus, spines & plates	C		R			
Asteroidea						
Ophiuroid ossicles				R		
Polychaeta						
Spirobidae, tubes	C		R	R		
Salmacina australis, tubes, in crust			C	A	A	A
Vertebrata						
Pisces, bones	C		R	R		

shore high-tidal gastropods of sun-heated rock faces, represented by two species of *Austrolittorina*; and the very diverse minute rissooidean gastropods that are so characteristic of present-day New Zealand rocky shores (17 taxa in GS15119). The other abundant animals in both collections are the most characteristic of all exposed rocky shore animals, the barnacles *Chamaesipho columna* and *Epopella plicata. C. columna* is abundant at present on highly exposed, vertical, wave-splashed rock faces at Turakirae Head, living closely oppressed in sheets that extend up to 3 m above the high-tide line on shaded seaward faces. Specimens occur commonly in the AD 1855 faunas as small segments of sheets. The smaller number of the much larger species *E. plicata* in the AD 1855 faunas is paralleled in the much lower number of specimens of *E. plicata* than of *C. columna* in the present fauna at Turakirae Head. The most abundant barnacle in these two faunas, though, is *Tetraclitella purpurascens*. This very distinctive, low, wide barnacle, with its coarsely tubular shell structure visible from the underside, occurs still attached to pebbles and the undersides of large rocks at both sites, as well as abundantly in the sediment. According to Foster (1978, p. 94) it occurs at present "over the lower half of un-silted shores", in situations "not exposed to excessive desiccation risk", such as under boulders, in crevices, and in caves.

A markedly different ecological situation is represented in GS15119 and GS15121 by *Zeacumantus subcarinatus*, *Marinula filholi*, *Leuconopsis obsoleta*, and the single specimen of *Suterilla neozelanica*. These are all members of the cryptic supra-littoral fringe fauna, which occurs among pebbles and terrestrial plants landwards of the truly marine exposed rocky shore (e.g., observed on the present-day shore east of Island Bay, Wellington). This fauna depends for its survival against desiccation mostly on decaying marine macro-algae cast ashore in storms. *Leuconopsis*, however, may have more complex connotations, as discussed below. Some taxa in GS15119 and GS15121, present as only a few, abraded or immature specimens, represent a more offshore, soft-substrate environment: *Glycymeris*, *Leptomya*, *Tawera*, *Caryocorbula*, *Stiracolpus*, and perhaps *Linucula* and the pyramidellid gastropods *Linopyrga*, *Evalea*, and *Chemnitzia*.

The total faunas, then, are an accumulation of shells from a wide range of environments. Even the intertidal "true limpets" such as *Cellana* are represented mainly by specimens with spirorbid polychaete tubes attached *inside* their shells, demonstrating that they were dead before deposition. Most of the better preserved and all of the abundant molluscs are stated by Powell (1979) to live low in the intertidal or in the shallow subtidal zones. The most abundant mollusc, *Gadinia conica*, is a cryptic species living in widely separated colonies of many closely spaced individuals, in caves and cave-like hollows beneath large boulders at and below low tide on extremely exposed rocky shores, and rarely has been observed or reported living in the Wellington region. However, specimens were abundant living under a large overturned boulder at the low-tide line at Turakirae Head during April 1994, so this evidently is a common species around Turakirae Head at present. The depositional situation represented by the most diverse fauna at Turakirae Head therefore seems to be *in situ* preservation of the fauna that lived and accumulated in large cave-like hollows beneath large perched boulders. The most common *in situ* species are (in decreasing order) *Gadinia conica*, *Tetraclitella purpurascens*, *Serpulorbis zelandicus* and, at the more exposed site at Turakirae Head, *Haliotis iris*. The common supra-littoral fringe and intertidal species of the higher shore areas nearby were carried downslope to the deposition site, and the molluscan microfauna of *Corallina* turf, of surfaces of macro-algae, and of the undersides of boulders was transported in voluminously. A few shells were contributed from more distant offshore soft substrates.

An interesting contrast is provided by the fauna in GS15122, collected only c. 10 m east of GS15119. Large molluscan shells are rare in GS15122, and instead the lepadomorph barnacle *Calantica* is represented by some hundreds of plates sorted from the small sediment sample. Only a few plates of *Calantica* are present in GS15119 and GS15121. The site where GS15122 was collected seems to have been a relatively long, narrow, cave-like hollow beneath a large perched boulder, open at both ends so that the water surged rapidly through the site via wave action. This seems to have provided an ideal sheltered, food-rich site for the attachment of lepadomorph barnacles, but allowed much less shell deposition than at the nearby site where GS15119 was collected.

The BR3 fauna

Two samples (GS15123, R28/f64; GS15124, R28/f71) are from the intertidal slope between BR2 and BR3 (i.e., they are from the next intertidal slope older than AD 1855). They contrast strongly with the AD 1855 fauna, as they consist almost entirely of large accumulations of tubes of a small polychaete (each tube up to c. 30 mm long and c. 2 mm wide) closely intertwined to form a dense calcareous crust up to 70 mm thick and covering up to 70 cm of the underside of large, perched boulders. The polychaete responsible for the tubes appears to be *Salmacina australis*, which is recorded in the present-day fauna by Morton & Miller (1968, p. 126) as "the most slender of all serpulid tubes ... chiefly dredged from sub-tidal grounds ... massed together in firm, upstanding ridges and crests".

No other obvious biota is present at these two sites, and any molluscan shells formerly present on the BR3 intertidal slope evidently have been leached from the peaty soil beneath the boulders. However, both samples of polychaete crust were found to have overgrown and enclosed barnacles, both *Epopella* and *Tetraclitella*, and the limpet *Gadinia conica*, preserving a meagre record of the fauna that formerly occupied the underside of the boulders. This remnant appears to have occupied the same low-tidal to shallow subtidal, sheltered, cave-like hollows beneath large perched boulders as is preserved at the sites of GS15119 and GS15121 on the AD 1855 intertidal slope, and a polychaete crust identical to those in GS15123 and GS15124 is present on the underside of the large boulder where the AD 1855 fauna of GS15122 was collected.

A sample of the polychaete crust was crushed, wet-sieved, and sorted to reveal that the tube meshwork at both sites was inhabited by very large numbers of the small, pink, nestling intertidal bivalve *Lasaea* '*rubra*' (the worldwide taxonomy of this genus is in a state of flux), along with a few other molluscs. The small high-tidal mussel *Xenostrobus pulex* and the tiny supra-littoral fringe snail *Leuconopsis obsoleta* also are present in both GS15123 and GS15124, and a single specimen of each of three other small molluscs was present in GS15123 (*Notoacmea*, *Eatoniella*, and *Austrolittorina*).

Significance of *Leuconopsis* and *Xenostrobus*

A surprising element in the BR3 polychaete crust fauna is *Leuconopsis obsoleta*. This small (c. 3–4 mm high) ellobiid snail was described in detail by Powell (1933, pp. 146, 150) as living "in sheltered harbour bays towards high tide" at Rangitoto Island, Auckland, where it is an "organic-mud feeder which occurs sporadically on the undersides of stones that are in contact with mud". Powell (1933) also noted that on the open coast at Muriwai, West Auckland, he had observed it with the larger ellobiid *Marinula filholi* on cliff faces just above high tide in freshwater seeps. At Island Bay, south Wellington coast, the author has seen *L. obsoleta* in large numbers well above high tide among pebbles behind the rocky shore east of the beach, under moist, decaying marine macro-algae, along with large numbers of *Marinula filholi*, *Suterilla neozelanica*, and *Zeacumantus subcarinatus*. Although an obligate supra-littoral fringe species, *L. obsoleta* evidently is very ecologically tolerant in damp situations, and is able to use a wide variety of foods.

In the faunas studied here, by far the largest number of specimens of *L. obsoleta* was found in GS15122, on the AD 1855 intertidal slope of BR2. At this site, where the fauna is dominated by *Calantica* plates in an elongate hollow beneath a perched boulder, an identical polychaete crust to those beneath large rocks on the BR3 slope is attached to the underside of the boulder. A few pieces of crust, up to c. 10 cm across, have fallen to the floor beneath the hollow. Large numbers of freshly dead, translucent shells of *L. obsoleta* occurred clustered in hollows on the undersides of the crust fragments, attached by mucus to the crust, and in contact with the damp, peaty sediment flooring the hollow. None occurred on the *in situ* polychaete crust still attached beneath the boulder. These specimens therefore appear to be present-day examples of *L. obsoleta*, living under the lime polychaete crust fragments c. 200 m inland from the high-tide line. Specimens in the sediment sample from GS15122 therefore might be either modern or might date from the AD 1855 uplift, but it is likely that all are modern.

This relationship suggests that the specimens of *L. obsoleta* in GS15123 and GS15124, from the samples of polychaete crust under rocks on the BR3 intertidal slope, were part of the supra-littoral fringe fauna living on the crust in AD 1855, and represent another aspect of the living fauna uplifted in AD 1855. However, a more complex scenario is suggested by the occurrence of the small high-tidal mussel *Xenostrobus pulex* in both samples from the BR3 polychaete crust. Four fresh, brightly coloured, articulated shells up to 16.8 mm long were present in GS15123; part of this sample has since been used for AMS radiocarbon dating. It is clear that this obligate high-tidal rocky shore mussel cannot have occupied the same subtidal submerged environment as the polychaete tubes that formed the crust. It is equally clear that no filter-feeding bivalve could occupy the extreme supra-littoral fringe, up to 200 m inland from the high-tide line, suggested here as the habitat of the specimens of *L. obsoleta*. The dated specimens of *X. pulex* have similar ^{14}C ages to those of the polychaete tube crust and *Gadinea conica* specimens from the BR3 intertidal slope (Table 1). The most likely explanation for the occurrence of such ecologically distinct species in the pre-AD 1855 fauna as *L. obsoleta* and *X. pulex* seems to be that a shallow, brackish pool or lagoon existed briefly on the BR3 slope after the uplift, and *X. pulex* and *L. obsoleta* occupied diverse ecological situations on the fringes of the pool.

BIOSTRATIGRAPHIC AGE OF THE SHELLS

As there are no extinct species in any of the Turakirae Head faunas, and all taxa present still live around Wellington, the macrofauna of the uplifted shores at Turakirae Head give no direct biostratigraphic evidence for the date of uplift, other than that it was very recent. However, there are other clues to a very young age. The first is the retention of bright coloration. Although the shells on the AD 1855 BR2 slope have been affected strongly by acidic groundwater in peaty soil, so that many specimens are bleached and corroded, some specimens can be found of all species retaining fresh, bright, original colour. The retention of much of the original colour by specimens of *Haliotis iris* is particularly impressive, as even Holocene fossils and archaeological midden material of this species usually have been bleached to a silvery white.

A second and more compelling indication of a very young age is the retention of molluscan chitinous material (conchiolin). In particular, three specimens of *Haustrum haustorium* in GS15121 retain perfectly preserved, flexible conchiolin opercula in their apertures. The opercula would not be expected to survive for 1–2000 yr and strongly support an AD 1855 date of uplift of shells between BR1 and BR2.

SHELL PRESERVATION POTENTIAL

A geologically important connotation of the Turakirae Head macrofauna is their brief period of preservation. No shells have been found on the floors of hollows on the BR3 intertidal slope, and only the two small areas of polychaete tube crust, adhering to the undersides of boulders above the soil surface, remain to show that this slope had a marine fauna. The soil around and beneath boulders on all uplifted intertidal slopes near Turakirae Head is peaty enough to support a dense flora dominated by flax (*Phormium tenax*), and leaching of calcium carbonate clearly is rapid in this acidic environment. Even in the faunas raised in AD 1855, many specimens are bleached and severely corroded, demonstrating that leaching has progressed rapidly in <150 yr. This beach succession therefore is useful in demonstrating that a diverse, abundant shelly fauna can last for significantly less than 2000 yr in an acidic environment with a moderately high rainfall.