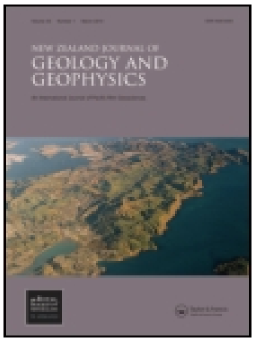

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New Zealand Journal of Geology and Geophysics

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

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To cite this article: Yoko Ota , Alan G. Hull , Nozomi Iso , Yasutaka Ikeda , Ichio Moriya & Torao Yoshikawa (1992) Holocene marine terraces on the northeast coast of North Island, New Zealand, and their tectonic significance, New Zealand Journal of Geology and Geophysics, 35:3, 273-288, DOI: 10.1080/00288306.1992.9514521

To link to this article: http://dx.doi.org/10.1080/00288306.1992.9514521

0028–8306/92/3503–0273 $2.50/0

Holocene marine terraces on the northeast coast of North Island, New Zealand, and their tectonic significance

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Abstract As many as seven Holocene marine terraces are preserved between Raukokore River and Gisborne on the northeast coast, North Island, New Zealand. Six terraces up to 20 m above present mean sea level (a.m.s.l.) are dated at c. 300, 600–700, 900–1200, 1600–2000, 4500, and 6000 radiocarbon yr B.P. to the west of East Cape. Seven terraces are preserved up to 27 m a.m.s.l. near Pakarae River mouth, and the higher six terraces have radiocarbon ages of c. 1000, 1600, 2500, 3900, 5500, and 7000 yr B.P. The coastal region from Waiapu River to Tolaga Bay has only two to three marine terraces, the highest attaining a maximum height of c. 8 m.

Sponge Bay Terrace is generally the highest preserved marine terrace, and it is underlain by more than 10 m of estuarine deposits that record the rapid rise of postglacial sea level. The terrace surface records the culmination of this sea-level rise at 5500 yr B.P. or slightly younger in areas of low average uplift rate (<1.5 m/1000 yr) and c. 7000 yr B.P. in areas of high average uplift rate (>2 m/1000 yr). Lower terraces are usually abrasion platforms with a veneer of intertidal marine deposits, and are interpreted to have been preserved as a result of uplift accompanying large earthquakes.

Three tectonic regions are identified on the basis of the height and the deformation of Sponge Bay Terrace. Region A in the northern Raukumara Peninsula is characterised by rapid Holocene uplift in the east and a westerly tilt toward the eastern Bay of Plenty. Much of the study area lies within Region B that is marked by a low (<1.5 m/1000 yr) average uplift rate and the preservation of only one or two terraces below Sponge Bay Terrace. Region C is confined to a small area 20 km northeast of Gisborne and is defined by one of the highest known average rates of coastal uplift (c. 4 m/1000 yr) in New Zealand. Boundaries between regions are poorly defined but suggest the locations of major, active geologic structures.

Keywords North Island; radiocarbon dates; Holocene; marine terraces; Sponge Bay Terrace; postglacial sea-level rise; tectonic tilt; coseismic uplift

INTRODUCTION

Tectonic setting

The North Island of New Zealand is situated in the Southwest Pacific along the boundary of the Australian and Pacific lithospheric plates (Le Pichon 1968). Along the eastern coast of the North Island of New Zealand, the Hikurangi margin extends southwest toward the northern South Island. Seismic studies of the Hikurangi margin (Adams & Ware 1977; Reyners 1980; Bannister 1988) beneath Hawke Bay reveal a very shallow dip (5–10°) for the northwest-dipping Pacific plate, and geologic structures in the overlying Australian plate are typically northwest-dipping imbricate thrust faults and east-verging folds (Lewis & Bennett 1985; Davey et al. 1986).

Geologic studies of the east coast of North Island reveal a complex geological history of late Mesozoic tectonism followed by the emplacement of the East Coast Allochthon in Oligocene–Miocene time along the Raukumara Peninsula (Fig. 1) to the north, and the beginnings of uplift and crustal shortening further south. In Neogene time, the entire east coast of the North Island was subjected to rapid uplift.

The aims of this paper are: (1) to present new data on geomorphology, stratigraphy, height, and age of Holocene marine terraces in the tectonically active coastal regions of eastern Bay of Plenty and Raukumara Peninsula; (2) to

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Received 5 March 1991; accepted 25 March 1992

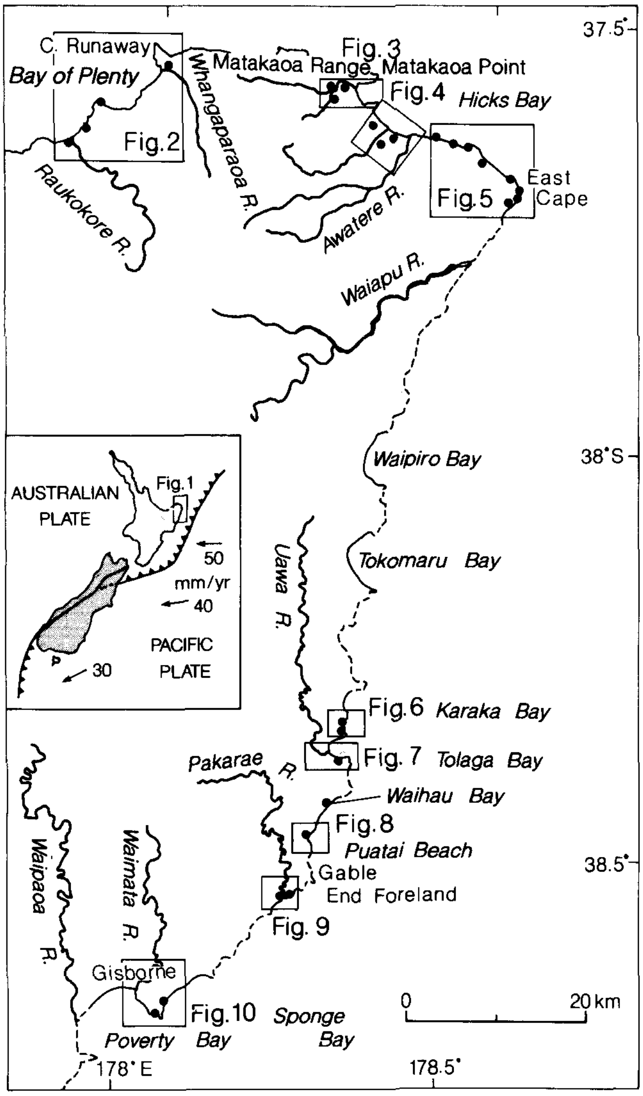

Fig. 1 Map of the coastal area of eastern Bay of Plenty and Raukumara Peninsula examined in this study. The broken line indicates coastal areas where no Holocene marine terrace is preserved. Dots indicate locations where samples for radiocarbon dating were collected. *Inset:* Plate tectonic setting and Pacific plate convergence rates and directions relative to the Australian plate (after Walcott 1978).

establish the Holocene coastal evolution and coastal deformation pattern based on these data; and (3) to consider the tectonic significance of Holocene terraces for comparison with the pattern of late Quaternary tectonics.

The study area covers about 200 km of coastline from the Raukokore River mouth in the northwest to Sponge Bay in the south (Fig. 1).

Previous studies of marine terraces along Raukumara Peninsula

Early geological mapping (Henderson & Ongley 1920; Ongley & MacPherson 1928) identified marine terraces at two levels, and Wellman (1962) described a number of coastal localities within the study area containing late Holocene-aged marine deposits associated with archaeological remains and sea-rafted pumice. Yoshikawa et al. (1980) established that late Pleistocene marine terraces, considered to be 125 000 yr old (Otamaroa Terrace) and 80 000 yr old (Te Papa Terrace), have been uplifted and tilted to the northwest along the coast from East Cape to the Bay of Plenty. They recognised that the maximum uplift rate of 2.4 m/1000 yr occurs near East Cape, and that Holocene coastal landforms between East Cape and Hicks Bay show a deformation pattern similar to that of the late Pleistocene terraces, while Yoshikawa (1988) suggested that the region is divided by a depression south of Hicks Bay into two gently upwarped areas. Yoshikawa et al. (1980) believed that much of the late Pleistocene deformation had probably occurred coseismically, despite the lack of coastal uplift accompanying the 1914 East Cape earthquakes and 1966 Gisborne earthquake.

Sumosusastro (1983) described two Holocene marine terraces near the Raukokore River that he interpreted to be the result of coseismic uplift. Several representative sections of Holocene marine deposits with radiocarbon ages from the present study area were presented by Ota et al. (1983). The coseismic origin of some Holocene terraces within the study area has been discussed by Berryman et al. (1989) and Ota et al. (1991), but no systematic study of Holocene marine terraces along the Raukumara Peninsula has been presented.

STUDY METHODS

Aerial photographs were used to prepare preliminary maps of coastal landforms for detailed field studies of the distribution and stratigraphy of Holocene coastal landforms and deposits. Samples of organic material were collected and radiocarbon dated (Table 1), and airfall tephra layers and sea-rafted pumice were identified by field character and ferromagnesian mineralogy to provide additional chronostratigraphic control. All heights were measured with automatic level and corrected to mean sea level using Gisborne tide-gauge records that show a tidal range of 1.4 m (difference between mean high water spring and mean low water spring). Fieldwork was carried out in 1981, 1983, and 1985.

RADIOCARBON DATING

Eight samples were radiocarbon dated in both New Zealand (Institute of Geological & Nuclear Sciences [NZ]) and Japan (Gakushuin University [GaK]) (Table 2). Shell samples dated in both laboratories were selected from the same stratigraphic horizon and consisted of shells from a single species (*Austrovenus stutchburyi*) preserved in life position. The one wood sample was selected from the outer part of a large log and divided equally for dating at both laboratories. The dating of samples in both New Zealand and Japan was not carried out as a rigorous inter-laboratory comparison, but rather to establish for this study the degree of comparability between dates determined in Japan and in New Zealand.

Table 2 indicates a consistently younger mean age for samples dated in New Zealand. Differences between the New Zealand ages and Japanese ages range from 740 to 190 radiocarbon years, with an average of 460 years. Japanese dates are calculated by comparing the unadjusted sample count rate to the 0.95 Oxalic Acid Standard (NBS) and an assumed $\delta^{13}C$ value of –25‰ PDB. New Zealand dates are calculated from the New Zealand shell standard of 95.9% of the 0.95 Oxalic Acid Standard (NBS) and a sample count rate adjusted for isotopic fractionation determined from the measured $\delta^{13}C$ value. None of the dates have been corrected

Table 1 Radiocarbon dates on samples collected from the northeastern coast of North Island, New Zealand.

Locality	Sample no. grid ref.(1) and NZ Fossil Record no.	Sample type(2)	Height (m a.m.s.l.)(3)	Laboratory no.(4)	Radiocarbon dates (Libby 1/2 life, yr B.P.) ± 1 SD	References
Hicks Bay	Z14,738893	peat	10.3	GaK10473	5590 ± 140	loc. A, Fig. 3
	Z14,738893	wood	9.1	GaK10474	4470 ± 180	loc. A, Fig. 3
	Z14,738893 f69	shell (A.S.)*	8.3	{GaK10475 NZ5461	7100 ± 170 6710 ± 80	loc. A, Fig. 3
	Z14, 746870	peat	c. 21	GaK10476	3170 ± 130	loc. C, Fig. 3
	Z14, 746870	tree*	c. 19	GaK10477	4840 ± 110	loc. C, Fig. 3
	Z14, 746870	wood	c. 19	GaK10478	5470 ± 160	loc. C, Fig. 3
	Z14, 761890	wood	c. 4 m	GaK10472	5630 ± 290	loc. B, Fig. 3
	Z14, 851002 f180	peat	c. 4 m	NZ7052	730 ± 55*	*minimum age of middle terrace
Te Araroa plain	Z14, 793850	wood	c. 4	GaK7919	1900 ± 140	loc. C, Fig. 4
	Z14, 792850	soil	9.1	GaK10479	530 ± 80*	loc. H, Fig. 4 *minimum age
East of Te Araroa	Z14, 860827 f102	shell (C.S.)	3.7	NZ5459	578 ± 34	loc. A, Fig. 5
	Z14, 860827 f103	shell (C.S.)	3.2	NZ5460	700 ± 59	loc. A, Fig. 5
	Z14, 876824 f181	shell	4.3	NZ7041	1140 ± 55	loc. B, Fig. 5
	Z14, 898818 f188	shell	2.5	NZ7038	280 ± 40	loc. C, Fig. 5 lowest terrace
	Z14, 903817 f187	shell	3.4	NZ7005	1030 ± 55	loc. D, Fig. 5 second lowest terrace
	Z14, 925813 f184	shell	2.5	NZ7042	<250	Profile A–B, Fig. 5 lowest terrace
East Cape	Z14, 981771	shell (A.S.)	3.5	GaK10482	1560 ± 150	loc. E, Fig. 5
	Z14, 981771 f182	shell	3.5	NZ7051	1700 ± 60	loc. E, Fig. 5
	Z14, 994755	shell*	4.4	GaK10485	6330 ± 280	loc. F, Fig. 5
	Z14, 994755	shell*	2.4	GaK10486	7020 ± 160	loc. F, Fig. 5
	Z14, 993756 f185	shell (I.E.)*	2.4	NZ6995	6590 ± 110	loc. F, Fig. 5
	Z14, 993756 f186	peat	2.0	NZ7054	6900 ± 90	loc. F, Fig. 5
	Z14, 994754 f183	shell	5.3	NZ6987	5650 ± 30	loc. G, Fig. 5
	Z14, 987746	wood	GL1.2	N3197	3230 ± 85	loc. H, Fig. 5
	Z14, 979755	wood	GL3.3	GaK10481	1730 ± 260	
	Z14, 975730	tree*	8.3	GaK10483	5580 ± 170	loc. I, Fig. 5
Karaka Bay	Z17, 753096 f22	shell	1.5	NZ7139	6270 ± 100	loc. A, Fig. 6
	Z17, 753041	shell (A.S.)	1.4	GaK10448	4950 ± 140	loc. B2, Fig. 6
	Z17, 753042 f23	shell (C.S.)	1.7	NZ7165	1790 ± 50	loc. B2, Fig. 6
	Z17, 753041 f4	shell (A.S.)*	2.2	{GaK10449 NZ5581	6930 ± 170 6330 ± 140	loc. B1, Fig. 6
Tolaga Bay	Z17, 741994 f2	shell (M.L.)*	2.0	{GaK10452 NZ5579	6020 ± 170 5830 ± 130	loc. B, Fig. 7 lower shellbed
	Z17, 741994 f3 f8	shell (A.S.)*	2.4	{GaK10453 NZ6465 NZ5580	4910 ± 120 4130 ± 80 4490 ± 90	loc. B, Fig. 7
	Z17, 41994	peat	2.8	GaK10455	3430 ± 120	loc. B, Fig. 7
	Z14, 741994 f5	wood	3.5	{GaK10454 NZ5582	4110 ± 110 3600 ± 60	loc. B, Fig. 7
	Z17, 722997 f24	wood	c.44	NZ7199	2920 ± 60*	loc. A, Fig. 7 *unreliable
	Z17, 722997 f26	wood	c.3.4	NZ7210	5230 ± 60	loc. A, Fig. 7
Puatai Beach	Z17, 705895	shell	13.5	GaK10450	2640 ± 130	Fig. 8 highest terrace
	Z17, 705895	shell	10	GaK10451	1830 ± 170	Fig. 8 middle terrace

(continued)

Table 1 *(continued)*

Locality	Sample no. grid ref.(1) and NZ Fossil Record no.	Sample type(2)	Height (m a.m.s.l.)(3)	Laboratory no.(4)	Radiocarbon dates (Libby 1/2 life, yr B.P.) ± 1 SD	References
Okitu	Y18, 519687	wood	GL 5.5	NZ5577	7390 ± 120	
	f160					
	Y18, 519687					
	f161	wood	GL 3	NZ5578	7830 ± 110	
Wainui Beach	Y18, 510663	shell (A.S.)	c. 3	NZ6143	7180 ± 150	Fig. 10. L.J. Brown
	f213					(pers. comm.)
	Y18, 510663	shell (A.S.)	3.4	NZ1881	7590 ± 80	Fig. 10. J. Gibb
						(pers. comm.)
	Y18, 517683	shell	11.4	NZ4433	4460 ± 70*	Fig. 10
	f1					*younger terrace?
	Y18, 519681	shell	1	NZ5440	7370 ± 470	Fig. 10
	f147					
	Y18, 530688	tree*	1.7	NZ5099	8410 ± 120	Fig. 10
	f50					
Sponge Bay	Y18, 498658	shell (A.S.)*	1.3	GaK10467	8760 ± 310	loc. A, Fig. 10
	f155			GaK10973	8270 ± 190	
	f155A			NZ5573	7330 ± 200	
		shell		NZ6306	7530 ± 110	
	Y18, 498658	wood	1.5	NZ5575	7970 ± 110	loc. A, Fig. 10
	f158					
	Y18, 498658	shell (A.S.)*	2	GaK10468	7790 ± 150	loc. A, Fig. 10
	Y18, 498658	shell (A.S.)*	2.9	GaK10469	8020 ± 150	loc. A, Fig. 10
	f156			NZ5574	7680 ± 180	
	Y18, 498658	wood	3.5	NZ5576	7250 ± 110	loc. A, Fig. 10
	f159					
	f214	shell (A.S.)	2	NZ6144	7480 ± 100	L.J. Brown
						(pers. comm.)
	Y18, 502663	shell (A.S.)	5.5	NZ6145	6250 ± 100	Fig. 10. L.J. Brown
	f217					(pers. comm.)
Gisborne City	Y18, 463704	shell (A.S.)	1	NZ6147	3640 ± 40	L.J. Brown
	f221					(pers.comm.)
	Y18, 490684	shell	7	NZ6146	2000 ± 100*	L.J. Brown
	f220					(pers.comm.)
						*reworked

(1)Grid reference with respect to New Zealand topographical map (1:50 000, NZMS 260).
(2)Abbreviations for shell species are as follows: C.S. *Cookia sulcata,* N.M. *Nerita melanotragus,* A.S. *Austrovenus stutchburyi,* I.E. *Irus elegans,* M.L. *Macomona liliana.*
Asterisk indicates samples in life position.
(3)GL: depth in metres below the ground surface.
(4)Laboratory codes: N, Japan Isotope Corporation; GaK, Gakashuin University, Japan; NZ, Institute of Geological & Nuclear Sciences, New Zealand.

Table 2 Comparison of radiocarbon ages, measured by Gakushuin University, Japan, and Institute of Nuclear Sciences, DSIR, New Zealand.

Gakushuin no.	NZ no.	$\delta^{13}C$(1) w.r.t. PDB	Calcite(2) (%)	NZ age (yr B.P.)	GaK age (yr B.P.)	Mean age difference (yr B.P.)	NZ age with $\Delta^{14}C = 0$ $\delta^{13}C = 0$	Mean age difference after recalculation
10449	5581	−1.0	0.3	6330 ± 140	6930 ± 170	600	6590 ± 150	340
10452	5579	−0.1	0.2	5830 ± 130	6020 ± 170	190	6170 ± 125	170
10453	5580	−0.5	0.1	4490 ± 90	4910 ± 120	420	4790 ± 80	120
10454	5582	−27.5	N/A	3600 ± 60	4110 ± 110	510	N/A	N/A
10457(3)	5572(3)	−1.4	0.1	6740 ± 150	7380 ± 230	640	7100 ± 140	280
10475	5461	−0.1	0.1	6710 ± 80	7100 ± 170	310	7040 ± 90	60
10973	6306	−1.7	–	7530 ± 110	8270 ± 190	740	7900 ± 100	370
10469	5574	−1.4	–	7680 ± 180	8020 ± 150	340	8000 ± 160	20

(1)$\delta^{13}C$ only measured at NZ laboratory.
(2)Calcite % measured by X.R.D.
(3)From Ota et al. (1991).

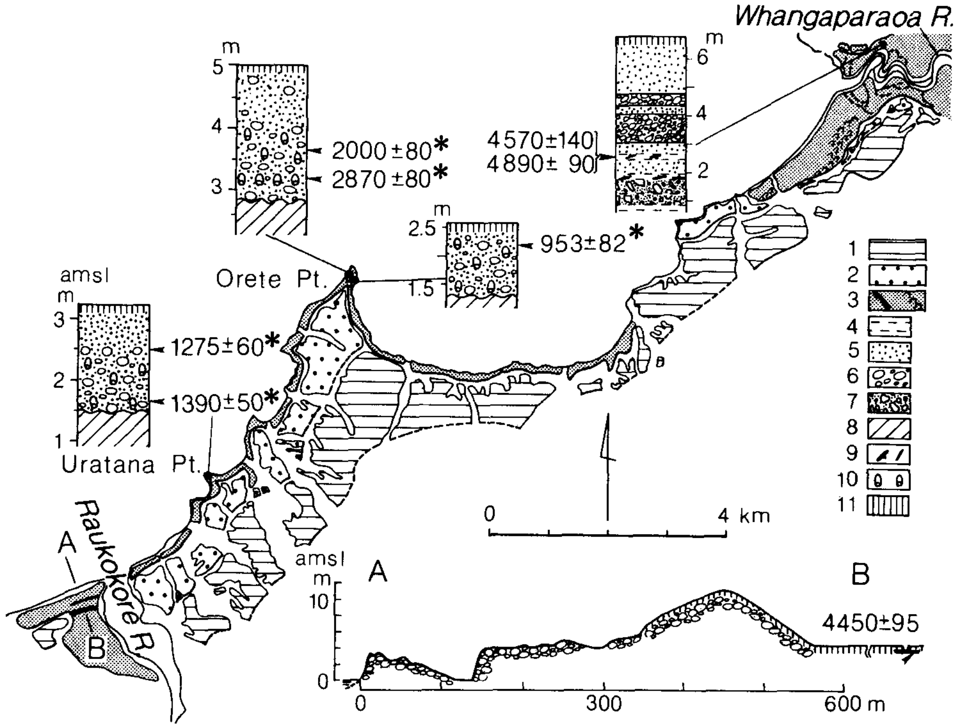

Fig. 2 Late Pleistocene and Holocene marine terraces in northeastern Bay of Plenty. Four sections show the stratigraphy of Holocene marine terraces and age of radiocarbon-dated samples (heights are metres a.m.s.l.). Ages marked by an asterisk were dated in New Zealand and others were dated in Japan. The A–B profile and distribution of late Pleistocene terraces are from Yoshikawa et al. (1980). 1, Otamaroa Terrace; 2, Te Papa Terrace; 3, Holocene terrace with beach ridge and sand dune; 4, silt; 5, sand; 6, beach gravel; 7, fluvial gravel; 8, bedrock; 9, wood; 10, shell,; 11, topsoil.

for secular variation in atmospheric ^{14}C because they are not conventional radiocarbon dates as defined by Stuiver & Polach (1977). The use of the New Zealand shell standard of $\Delta^{14}C$ –41‰ provides a reservoir correction of –336 years when compared to the use of the 0.95 Oxalic Acid Standard (Jansen 1984). No reservoir correction has been applied to Japanese dates, and the degree of age reduction for New Zealand dates varies with $\delta^{13}C$ value. The difference in sample preparation procedures in Japan and New Zealand is considered to have little effect on the calculated age, because isotopic fractionation during gas preparation is insignificant (Kigoshi pers. comm. 1984), and XRD-determined calcite percentages did not indicate the need for surface etching for samples dated in New Zealand (Jansen pers. comm. 1984).

After recalculation of New Zealand dates on the same basis as in Japan, all New Zealand shell sample ages fall within 2 standard deviations of the mean Japanese age for the same sample (Table 2). The wood sample, however (GaK10454, NZ5582; Table 2), does not require a reservoir correction, and the large age difference between New Zealand and Japanese dates cannot be explained easily.

It is not possible to apply a simple arithmetic correction factor to convert Japanese ages to New Zealand ages and vice versa because of the adjustment to count rates and use of different standards at the two laboratories. Table 1 only shows dates as received from each laboratory, and these are used throughout the text.

DESCRIPTION OF HOLOCENE MARINE TERRACES

The Holocene marine terrace is recognised throughout the study area along the base of sea cliffs fringing late Pleistocene marine terraces or hilly lands. Erosion has eliminated any Holocene terrace from the coast south of East Cape to Waipiro Bay. Localities studied are shown in Fig. 1; radiocarbon ages obtained for this study are summarised in Table 1. The morphology and stratigraphy of the Holocene marine terraces are described below.

Raukokore River mouth (Fig. 2): Holocene marine terraces are preserved immediately above present sea level from the mouth of the Raukokore River to Cape Runaway (Fig. 1). On the west side of the Raukokore River mouth, a series of emergent beach ridges is preserved (profile A–B). The innermost ridge, composed of coarse, rounded gravel, reaches c. 11 m a.m.s.l. Buried peaty soil from the back-marsh lowland behind this ridge was dated at 4450 ± 95 yr B.P. (Yoshikawa et al. 1980).

Orete Point and Uratana Point (Fig. 2): North of the Raukokore River mouth, two marine terraces are preserved. The lower terrace is up to 3 m a.m.s.l. and is better preserved. At Orete Point, a higher terrace (5–6 m a.m.s.l.) is underlain by up to 2 m of rounded gravel and sand that contains intertidal shell species ranging in age from 2870 ± 80 yr B.P. to 2000 ± 80 yr B.P. (Sumosusastro 1983). A 2 m step separates this terrace from a lower terrace that is underlain by rounded gravel and sand with shell fragments (953 ± 80 yr B.P.; Sumosusastro 1983). On the lower surface, sea-rafted Taupo Pumice (c. 1800 yr B.P.; Healy et al. 1964) and Loisels Pumice (c. 600 yr B.P.; McFadgen 1985) are interbedded with marine gravel that overlies a wave-cut platform up to 1.5 m a.m.s.l. The lower terrace at Uratana Point is dated at 1275 ± 60 yr B.P. to 1390 ± 50 yr B.P. (Sumosuastro 1983).

Whangaparaoa River mouth (Fig. 2): Near the mouth of the Whangaparaoa River, a terrace, c. 6 m a.m.s.l, extends for several kilometres inland. It is underlain by a silt bed containing a brackish-water diatom assemblage and wood, dated at 4570 ± 140 yr B.P. (GaK) (Yoshikawa et al. 1980). Exposures in the banks of the Whangaparaoa River and a small tributary show fluvial gravel at river level overlain by

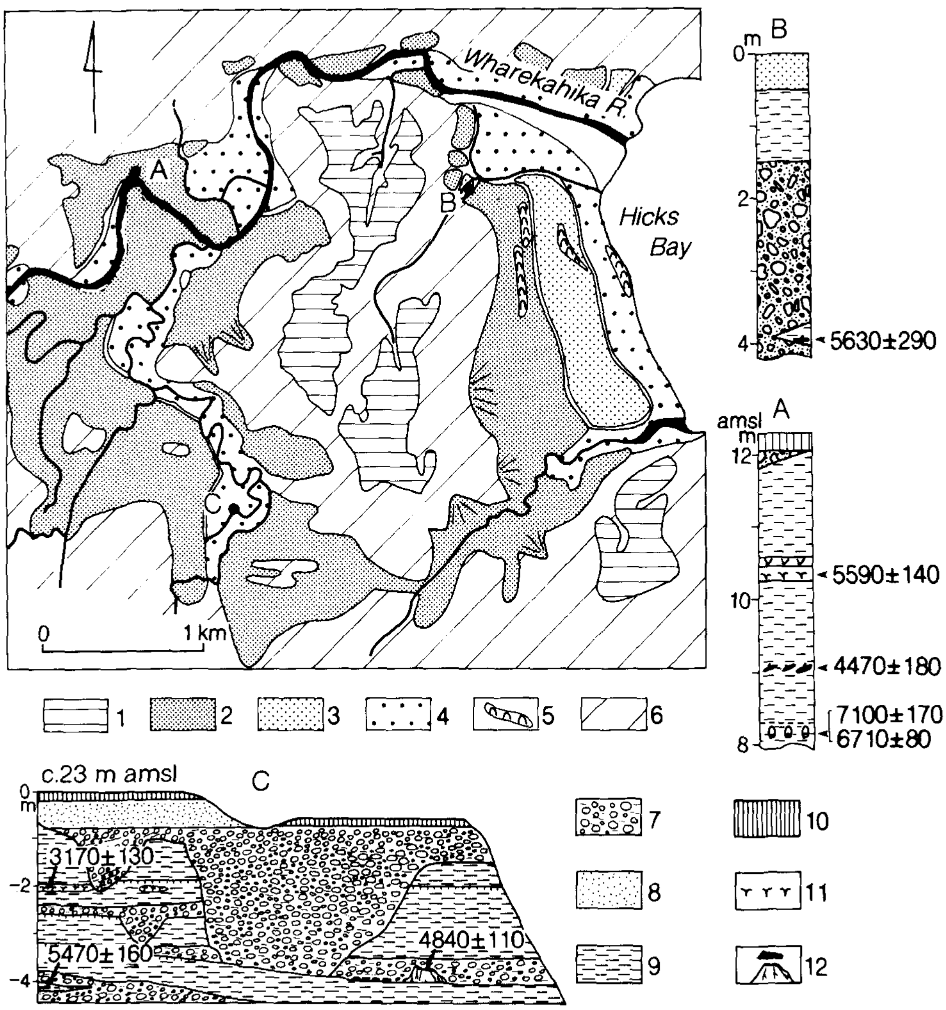

Fig. 3 Geomorphological map of Hicks Bay area. Sections A and B show stratigraphy of Holocene deposits and their radiocarbon dates. Estuarine deposits (loc. A) extend up-valley, well beyond the present coastline. Section C is a sketch of fluvial terrace deposits exposed along a tributary of the Wharekahika River. The tree in growth position (4840 ± 110 yr B.P.) is considered to have been killed by a rise of the local water table induced by relative sea-level rise at the nearby coastline. 1, Otamaroa Terrace; 2, highest Holocene terrace; 3, middle Holocene terrace; 4, lowest Holocene terrace; 5, sand dune; 6, mountain and hill. 7, fluvial gravel; 8, sand; 9, silt; 10, soil horizons; 11, peat; 12, tree in growth position.

0.5 m of estuarine mud enclosing wood, twigs, and leaves, that is in turn overlain by 2–3 m of thick eolian sand. Wood from within the lower part of the mud has a radiocarbon age of 4850 ± 70 yr B.P., which is similar to the ages from the terrace near the coast. Wood from the upper part of the mud horizon has an age of 1930 ± 65 yr B.P. (Sumosusastro 1983).

Matakaoa Point and Omuruiti Point (Fig. 1): Matakaoa Peninsula is composed of volcanic rocks that permit good preservation of emergent coastal features such as sea caves and benches. Coastal landforms fringing the late Pleistocene Te Papa Terrace can be classified into three groups near Matakaoa Point: (1) sea caves and associated benches at c. 6 m a.m.s.l; (2) marine notches and associated benches at c. 4 m a.m.s.l; and (3) a subhorizontal rock platform at c. 3 m a.m.s.l. Similar landforms are preserved at Omuruiti Point south of Hicks Bay at c. 11 m a.m.s.l. (flat-topped stack), c. 8 m a.m.s.l. (abrasion platform), c. 5 m a.m.s.l. (marine notch at the base of a cliff fringing an abrasion platform), and c. 3 m a.m.s.l. (abrasion platform). Datable material was not found from any of these erosional landforms.

Hicks Bay (Fig. 3): At Hicks Bay a well-defined Holocene marine terrace can be subdivided into three levels separated by low but distinctive terrace risers parallel to the present coastline. The highest terrace is overlain by fan deposits at its inner margin, and the height of the back-marsh lowland behind the largest beach ridge on this terrace is c. 10 m a.m.s.l. The middle and lowest terraces are also characterised by beach ridges overlain by eolian sand, and terrace heights are c. 4 m and c. 2 m a.m.s.l., respectively. Wood from beneath a fluvial terrace below the highest terrace (loc. B, Fig. 3) has an age of 5630 ± 290 yr B.P., indicating emergence above sea level of the highest terrace at some time before this date.

The highest terrace can be traced farther inland through a narrow gorge along the Wharekahika River. Exposure along the left bank of the Wharekahika River (loc. A) reveals a shellbed composed entirely of *Austrovenus stutchburyi* in life position, dated at 7100 ± 170 yr B.P. (GaK) or 6710 ± 80 yr B.P. (NZ), within blue-grey silt from near the base of the section. Peat resting on the probable upper limit of marine deposition has an age of 5590 ± 140 yr B.P. and is overlain by Whakatane Tephra (c. 4850 yr B.P.; Froggatt & Lowe 1990). No dates have been obtained from beneath the middle and lowest terrace in the Hicks Bay area, except for 730 ± 55 yr B.P. from peat immediately underlying the middle terrace. This date provides only a minimum age for the terrace formation.

An exposure along a tributary of the Wharekahika River (loc. C) reveals a record of deposition and erosion within late Holocene fluvial and estuarine deposits. Wood from the lowest fluvial gravel bed (5470 ± 160 yr B.P.) is of similar age to wood taken from fluvial gravel north of Hicks Bay (loc. B). A tree stump up to 0.7 m in diameter, buried in

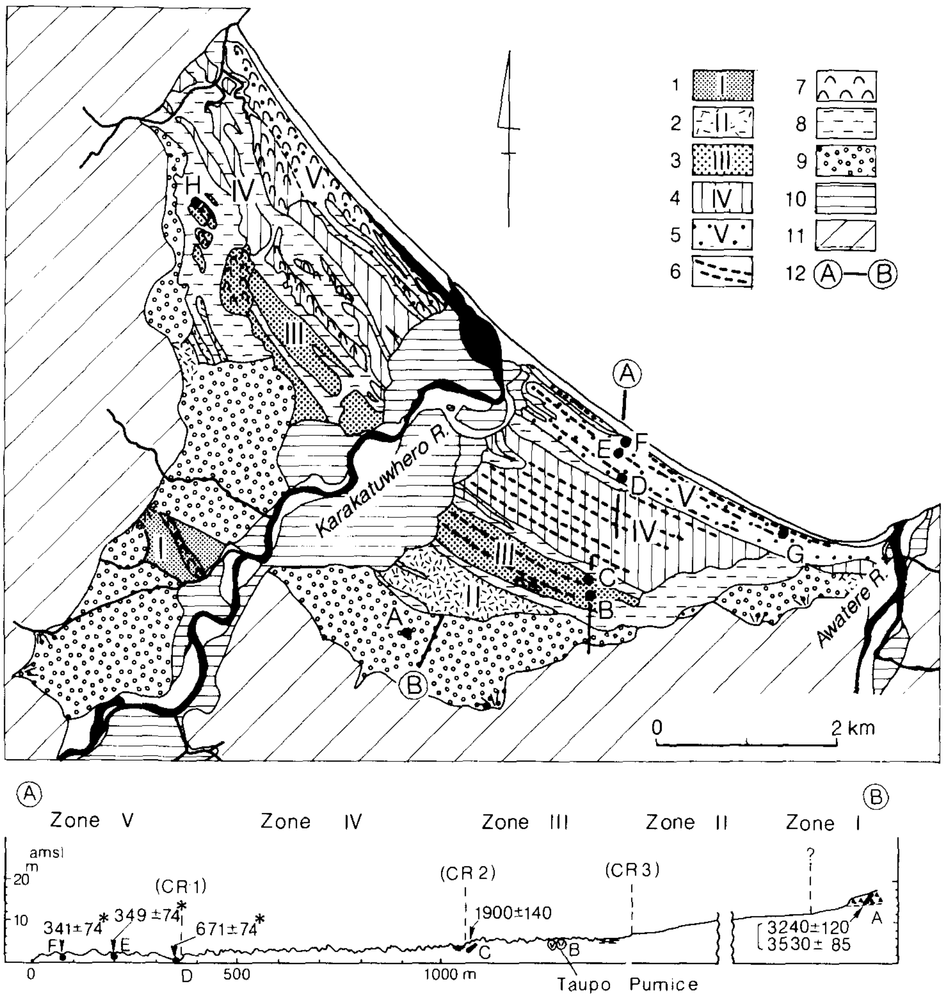

Fig. 4 Geomorphological map of Te Araroa plain showing location of dated samples and profile of gravel ridges. 1–5, Holocene terraces of Zone I to Zone V; 6, major beach ridge; 7, sand dune; 8, back-swamp lowland; 9, alluvial fan; 10, river floodplain; 11, mountain and hill; 12, location of profile. A–F and H are the locations of radiocarbon samples (see Table 1); asterisk from Garrick (1979). G is the location of a c. 300 year old tree. CR1, CR2, and CR3 are "coastal revisions" of Garrick (1979).

growth position (4840 ± 110 yr B.P.), occurs in the second-lowest gravel bed.

Te Araroa plain (Fig. 4): Te Araroa plain, northwest of the Awatere River, preserves more than 50 beach ridges composed largely of well-rounded, coarse, clean gravel, reworked from the Karakatuwhero and Awatere Rivers. Garrick (1979) estimated a coastal progradation rate of 0.46 m/yr, and argued that Te Araroa plain had been formed since 3850 yr B.P., based upon two radiocarbon ages of shell fragments taken from younger beach ridges. Garrick (1979) inferred three periods of "coastal revision" (CR1–CR3): CR1 and CR2 were attributed to coastal erosion; CR3 to coastal emergence.

In this study, Te Araroa plain is divided into five zones judged by the continuity of beach-ridge heights:

Zone I The innermost part of Te Araroa plain that is covered by fan deposits overlying beach ridges. Wood from within the fan deposits (loc. A) is dated at 3240 ± 120 yr B.P. (Yoshikawa et al. 1980) to provide a minimum age for the formation of beach ridges in Zone I.

Zone II Zone II is <10 m a.m.s.l., exists only along the right bank of the Karakatuwhero River, and is undated.

Zone III Zone III consists of about 20 beach ridges <6 m a.m.s.l. traceable on both sides of the Karakatuwhero River. A scarp, c. 2 m high, occurs between the outer edge of the zone and a back-marsh lowland of Zone IV. Blocks of sea-rafted Taupo Pumice are preserved (loc. B), and wood from the outer margin of Zone III (loc. C) has an age of 1900 ± 140 yr B.P. Accordingly, this zone is regarded to have been formed by c. 2000 yr B.P.

Zone IV The surface comprising this zone is <4 m a.m.s.l. and composed of about 20 beach ridges of unknown age. A scarp, c. 2 m high, separates Zone IV from the lower Zone V.

Zone V Zone V comprises the outermost group of beach ridges c. 2 m a.m.s.l. Dates from this zone range from 671 ± 74 yr B.P. at the inner part to 341 ± 74 yr B.P. (Garrick 1979) at the outer margin close to the present coast (loc. D, E, and F). A large pohutukawa tree (*Metrosideros excelsa*), known from historical records to be in excess of 300 years old, occurs at the seaward margin of this zone (loc. G). Zone V, therefore, must be >250 radiocarbon yr B.P.

Awatere River to East Cape (Fig. 5): Along the modern sea cliff on the west side of Maruhou Point (loc. A), beach deposits 1 m thick underlie the lowest marine terrace surface at c. 4 m a.m.s.l. and have dates from enclosed shell material of 578 ± 34 yr B.P. to 700 ± 59 yr B.P. Shell fragments from beach deposits comprising the lowest terrace (c. 4.5 m at the outer margin) west of Wharariki Point (loc. B) have an age of

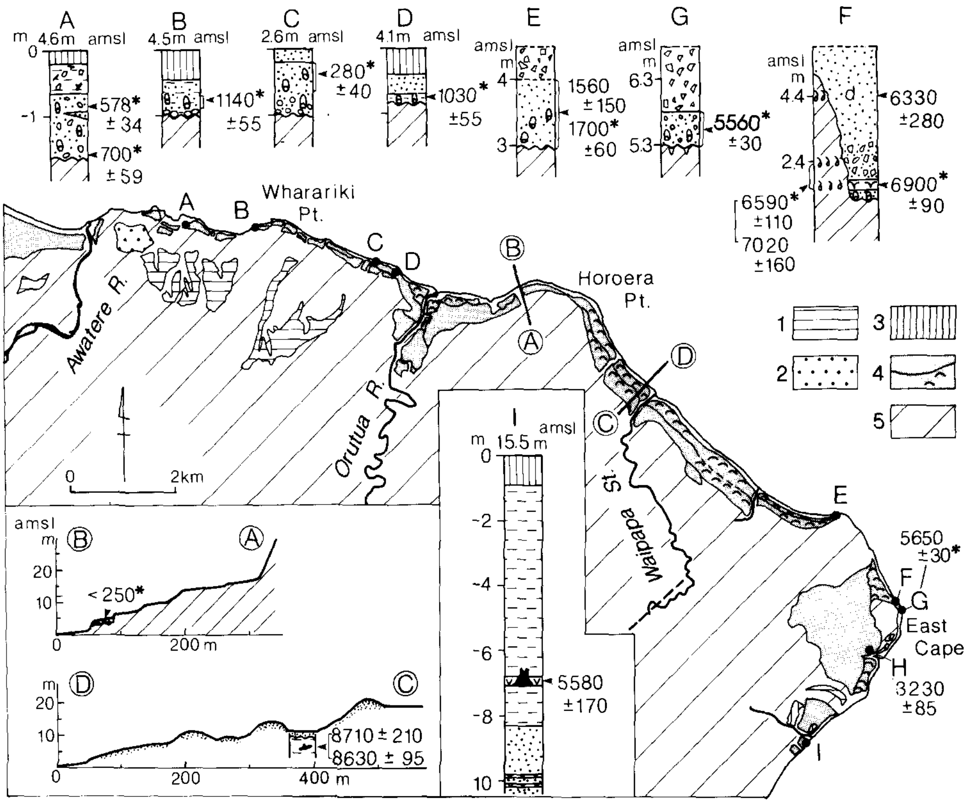

Fig. 5 Distribution of Holocene marine terraces, their stratigraphy (sections A–I), and radiocarbon ages between Awatere River and East Cape. The A–B profile is measured with an electronic distance meter; the C–D profile is measured with a handlevel (after Yoshikawa et al. 1980). 1, Otamaroa Terrace; 2, Te Papa Terrace; 3, undifferentiated terrace; 4, Holocene terrace, major former shoreline, and sand dune; 5, mountain and hill.

1140 ± 55 yr B.P. and are older than the terrace of similar height at Maruhou Point.

Four Holocene marine terraces are preserved near the Orutua River mouth. The highest terrace (up to c. 25 m a.m.s.l.) can be traced inland along the river, but thick eolian sand makes clear definition of the terrace surfaces difficult. The observed upper limit of an abrasion platform of the highest terrace is c. 20 m. Shell from the second-lowest terrace at c. 3 m a.m.s.l. has an age of 1030 ± 55 yr B.P. (loc. D), and the lowest terrace (loc. C) at 2.5 m a.m.s.l. has an age of 280 ± 40 yr B.P.

Five well-defined Holocene marine terraces occur at c. 18, 14, 10, 7, and 5 m a.m.s.l. near Horoera Point (A–B profile). All are wave-cut terraces, judged by their flat abrasion surfaces and former shorelines parallel to the present coast. The highest terrace can be traced to the Orutua River area. Only one sample (dated at <250 yr B.P.) was obtained from the lowest terrace.

Holocene marine terraces are covered by sand dunes southeast of Horoera Point, but several terrace levels at c. 18, 10, and 6 m a.m.s.l. can be recognised near the mouth of the Waipapa Stream (C–D profile). A blue-grey silt containing marine and estuarine diatoms is exposed on the left bank of the Waipapa Stream, and it contains wood dated at 8710 ± 200 yr B.P. (Yoshikawa et al. 1980). Further south, to the west of Te Wharenaonao, coarse sand and shelly gravel overlies a wave-cut platform at c. 3 m a.m.s.l. (loc. E) dated at 1560 ± 150 yr B.P. (GaK) and 1700 ± 60 yr B.P. (NZ).

Rock-boring shells (*Barnea (Anchonasa) similis* and *Notopaphia elegans*) in life position are preserved at two levels (c. 4 m and c. 2 m a.m.s.l.) along the sea cliff near East Cape (loc. F) and have dates of 6330 ± 280 yr B.P. for the upper shells, and 7020 ± 160 yr B.P. (GaK) or 6590 ± 110 yr B.P. (NZ) for the lower shells. A peat bed overlying beach sand with shells at almost the same height as the lower rock-boring shells has a date of 6900 ± 90 yr B.P. The age of shells from beach deposits resting on an abrasion platform at c. 5 m a.m.s.l. (loc. G) is 5560 ± 30 yr B.P.

An extensive Holocene terrace, partly covered by sand dunes, is preserved west of East Cape. The top of the marine deposits is at c. 6 m a.m.s.l. and is overlain by fluvial silt from which a wood sample dated at 3230 ± 85 yr B.P. (loc. H) provides a minimum age for the emergence of the marine sequence. At loc. I south of East Cape lowland, beach sand, c. 2 m a.m.s.l. at the base and c. 7 m a.m.s.l. at the top, is covered by fluvial silt overlain by Whakatane Tephra (c. 4850 yr B.P.). A tree stump from within the silt is dated at 5580 ± 170 yr B.P.

Waipiro Bay and Tokomaru Bay (Fig. 1): At Tokomaru Bay, a terrace at 7–8 m a.m.s.l. can be traced about 2 km inland along the major stream of the area. The terrace is underlain by shelly beach sand or rounded gravel about 2–3 m thick that unconformably overlies Tertiary siltstone. A lower terrace is poorly preserved at about 4 m a.m.s.l. Two surfaces at Waipiro Bay are c. 7–9 m and c. 3–5 m a.m.s.l. Datable material was not found at either locality.

Kaiaua Bay and Karaka Bay (Fig. 6): In the Kaiaua Bay and Karaka Bay area, two Holocene marine terraces are recognised. The higher terrace is well preserved and is traceable c. 1.5 km inland along small streams. The lower terrace is only preserved near stream mouths. At loc. A, shells immediately above the wave-cut platform of the higher terrace are dated at 6270 ± 100 yr B.P. At loc. B1, the higher terrace is underlain by blue-grey silt that contains shells in life position (*Austrovenus stutchburyi* and *Macomona liliana*), dated at 6930 ± 170 yr B.P. (GaK) or 6330 ± 140 yr B.P. (NZ), and the apparent upper limit of marine sediments at loc. B1 is about 3 m a.m.s.l. Relative sea level at the time of the formation of the terrace was probably slightly higher than 4.3 m a.m.s.l.,

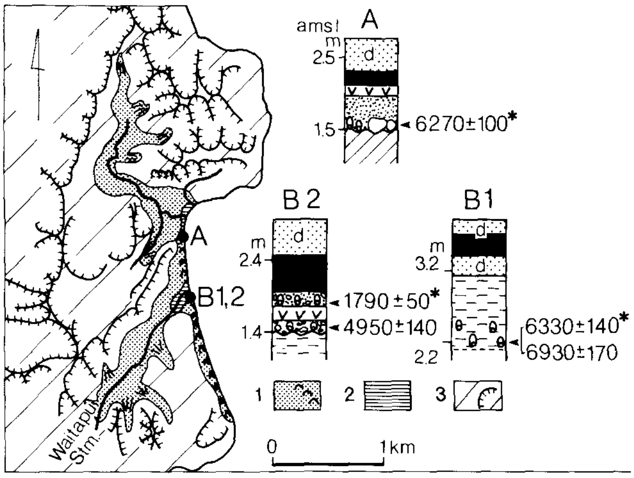

Fig. 6 Geomorphological map and Holocene marine terrace stratigraphy with radiocarbon ages at Karaka Bay. 1, Higher Holocene terrace and sand dunes; 2, lower Holocene terrace; 3, hill.

judged by the height of a flat, wave-cut stack 10 m east from loc. B1 that is partly covered by shelly beach sand.

The lower terrace deposits (c. 2 m a.m.s.l.) consist of a bed of shelly sand and gravel unconformably overlying blue-grey estuarine silt (loc. B2). *Austrovenus stutchburyi* shells from the basal part of the sand and gravel bed are dated at 4950 ± 140 yr B.P. Shells from the upper part of the sand and gravel bed dated at 1790 ± 50 yr B.P. occur immediately above a water-laid coarse tephra (Waimihia Lapilli, 3280 ± 20 yr B.P.; Froggatt & Lowe 1990). This date for shells in the gravel bed is significantly younger than that from the basal part, but the c. 1800 yr B.P. age is consistent with the presence of the underlying Waimihia Lapilli.

Tolaga Bay (Fig. 7): Pullar & Rijkse (1977) estimated the location of former shorelines within the coastal plain near Tolaga Bay at c. 3400 yr B.P. and c. 1800 yr B.P., based on the presence of airfall Waimihia Lapilli, and Taupo Pumice (c. 1850 yr B.P.; Froggatt & Lowe 1990). We classified Holocene marine terraces in this area into three levels:

Terrace I reaches c. 5 m a.m.s.l. and can be traced inland along stream valleys. Wood from 1.6 m below the terrace surface is dated at 5230 ± 60 yr B.P. at loc. A. Wood from 1 m below the surface is dated at 2920 ± 60 yr B.P. This age is inconsistent with the presence of Waimihia Lapilli stratigraphically above it and is not considered to represent the age of estuarine deposits or the terrace surface.

Terrace II is c. 4 m a.m.s.l. and composed of sandy beach ridges. Exposure at loc. B shows the relationship between Terrace II deposits and underlying older (Terrace I) deposits where blue-grey silt (enclosing shells of mostly estuarine *Macomona liliana* in life position, with an age of 6020 ± 170 yr B.P. [GaK] or 5830 ± 130 yr B.P. [NZ]) is unconformably overlain by sand and gravel containing shells of *Austrovenus stutchburyi*, *Paphies donacina*, and *Macomona liliana* in life position (4910 ± 120 yr B.P. [GaK] or 4490 ± 90 yr B.P. [NZ] and 4130 ± 80 yr B.P. [NZ]). A peat bed containing wood fragments, with an age of 4110 ± 110 yr B.P. (GaK) or 3600 ± 60 yr B.P. (NZ) overlies a sand bed resting on the dated shells. At the top of this section, eolian sand with Waimihia Lapilli rests on the peat bed. Thus, the upper part of this section, deposited c. 4600–3500 yr B.P., represents marine deposits of Terrace II, which unconformably overlie the transgressive deposits of Terrace I. The marine limit for this terrace is c. 3.5 m a.m.s.l.

Terrace III is 2–3 m a.m.s.l. and composed of beach ridges containing sea-rafted Taupo Pumice.

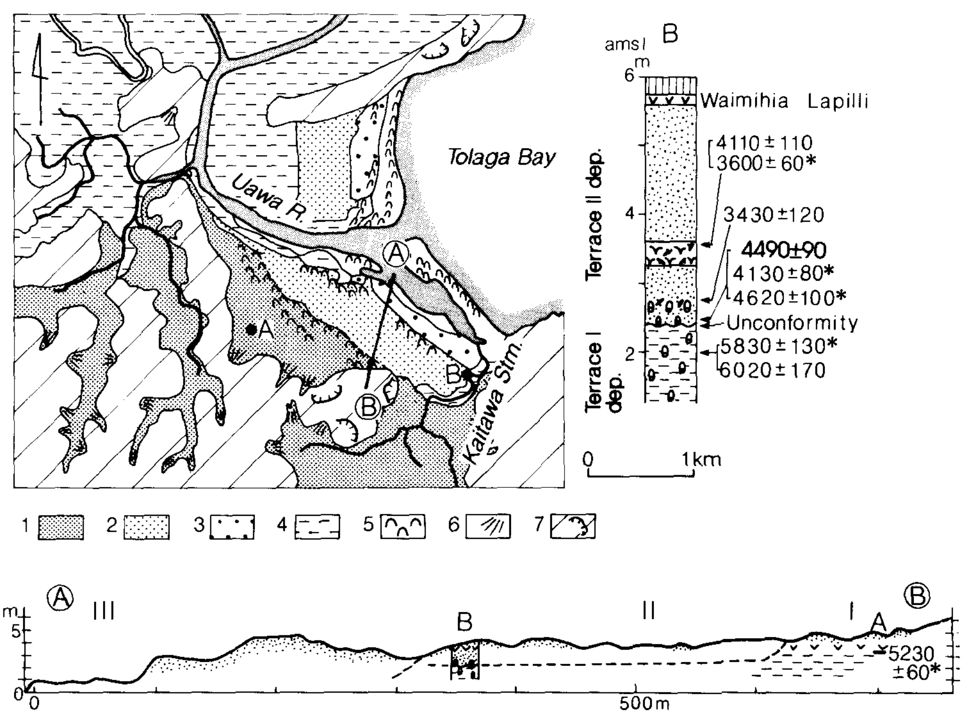

Fig. 7 Geomorphology and Holocene marine terrace stratigraphy near Tolaga Bay. The valley-filling nature of the highest marine terrace suggests a rapid relative sea-level rise. The section at loc. B is projected onto the A–B profile to show the relation between Terrace II deposits and Terrace I deposits. 1, Terrace I; 2, Terrace II; 3, Terrace III; 4, fluvial lowland; 5, sand dune; 6, alluvial fan; 7, hill and landslide.

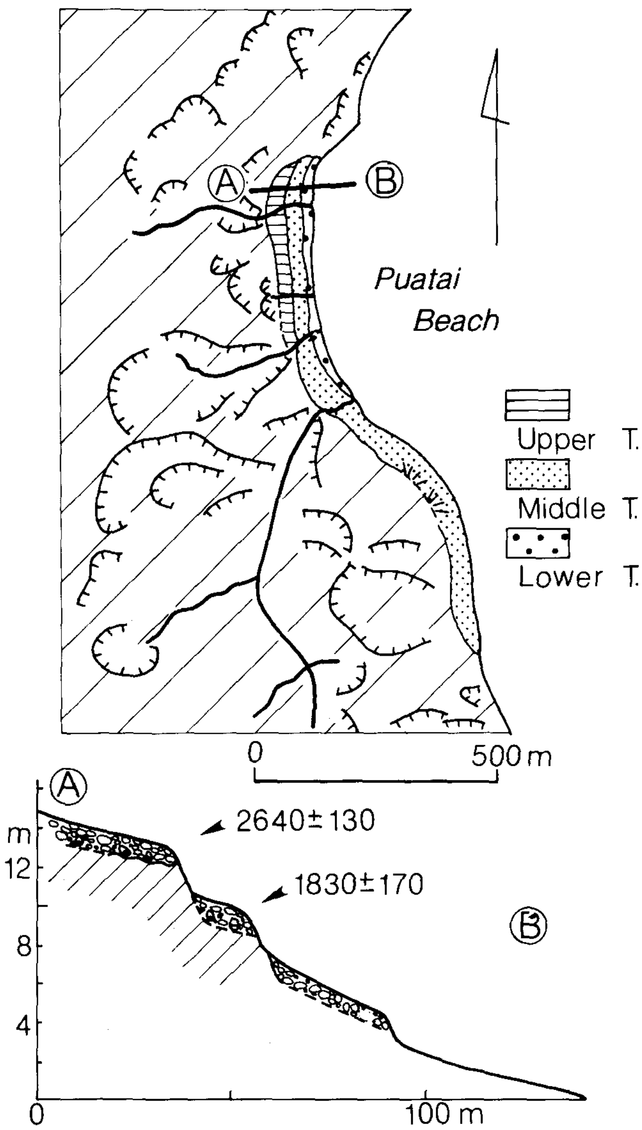

Fig. 8 Map and profile of three Holocene marine terraces preserved near Puatai Beach.

Waihau Bay: The higher of two terraces preserved at Waihau Bay that can be traced to 12 m a.m.s.l. along streams is underlain by a silt bed containing wood and estuarine shells in life position dated at 7450 ± 320 yr B.P. (3.2 m a.m.s.l. in the south) and at 6770 ± 100 yr B.P. (2.5 m a.m.s.l. in the north) (Ota et al. 1987, 1988, 1991). The lower terrace is underlain by 1–2 m thick beach sand and gravel with sea-rafted Taupo Pumice, and is covered by dune sand or slope deposits in many places. Tree trunks in growth position are exposed along the present beach and one has been dated at 8220 ± 60 yr B.P. (Ota et al. 1988).

Puatai Beach (Fig. 8): At Puatai Beach, about 5.5 km north of Gable End Foreland, three narrow Holocene terraces are preserved c. 14, 11, and 6 m a.m.s.l. in the north and 18, 13, and 6 m a.m.s.l. in the south (Ota et al. 1991). Each terrace is underlain by a 2–3 m thick bed of beach sand and gravel containing shell fragments of intertidal rocky shore species that have dates of 2640 ± 130 yr B.P. from the higher terrace and 1830 ± 170 yr B.P. from the middle terrace. The age of the lower terrace is unknown.

Pakarae River area (Fig. 9): Seven Holocene marine terraces are well preserved on both sides of the Pakarae River mouth, northeast of Whangara (Ota et al. 1983). This sequence of terraces has been described in detail by Ota et al. (1991), and indicates rapid and episodic coastal emergence since c. 10 000 yr B.P. Terrace surfaces range in height from 27 to 3 m a.m.s.l. and in age from c. 7000 to 1000 yr B.P., as determined by dating the estuarine and beach fauna preserved on each terrace.

Sponge Bay area (Fig. 10): To the east of Poverty Bay, the Holocene marine terrace extends inland along streams, resulting in an irregular pattern for the former shoreline. Deposits underlying this terrace were first described by Wellman (1962), and they are at present exposed in the sea cliff along Sponge Bay (loc. A). Rounded gravel at the base of the cliff interfingers with blue-grey silt containing shells of *Austrovenus stutchburyi* and *Macomona liliana* in life position. The marine silt is overlain by a massive silt bed that is in turn overlain by airfall Waimihia Lapilli. Radiocarbon dates from shells and wood from several horizons near the base of the section range from c. 8000 to 7000 yr B.P., and ages generally young toward the top of the section. The exact position of the upper limit of marine deposits cannot be determined at loc. A without detailed paleoenvironmental analysis. In the Sponge Bay and Wainui Beach areas, several other radiocarbon ages have been obtained (Table 1), and most are consistent with ages determined from Sponge Bay. The youngest date from this marine terrace is 6250 ± 100 yr B.P. from near the top of the marine deposits (c. 5.5 m a.m.s.l.) and probably represents the age of the culmination of sea-level rise in this area.

DISCUSSION

Ages of Holocene marine terraces

Classification of Holocene marine terraces

The Holocene marine terraces can be subdivided into a maximum of seven surfaces (Fig. 11, 12), each representing a former relative sea-level position. The highest — Sponge Bay Terrace — is defined by its age, wide distribution, and characteristic stratigraphy, and is named after the highest terrace in the Sponge Bay area. Terraces younger than Sponge Bay Terrace are grouped together as the Lower Terraces.

Sponge Bay Terrace (Fig. 11): Sponge Bay Terrace is usually underlain by relatively thick (>10 m) deposits of a marine transgressive facies that contain fossil shells preserved in life position ranging in age from c. 10 000 yr B.P. near the exposed base to c. 5500–7000 yr B.P. near the terrace surface. Where the age of the highest terrace is unknown, it is correlated with Sponge Bay Terrace, based on its valley-filling distribution pattern and the preservation of marine transgressive deposits beneath the terrace surface. Sponge Bay Terrace is preserved as a zone of marine-bored rocks above the present high-tide level and as a wave-cut platform on rocky coasts (cf. East Cape). The marine transgressive facies of the Sponge Bay Terrace shows that it was formed at the culmination of the postglacial sea-level transgression that varies in

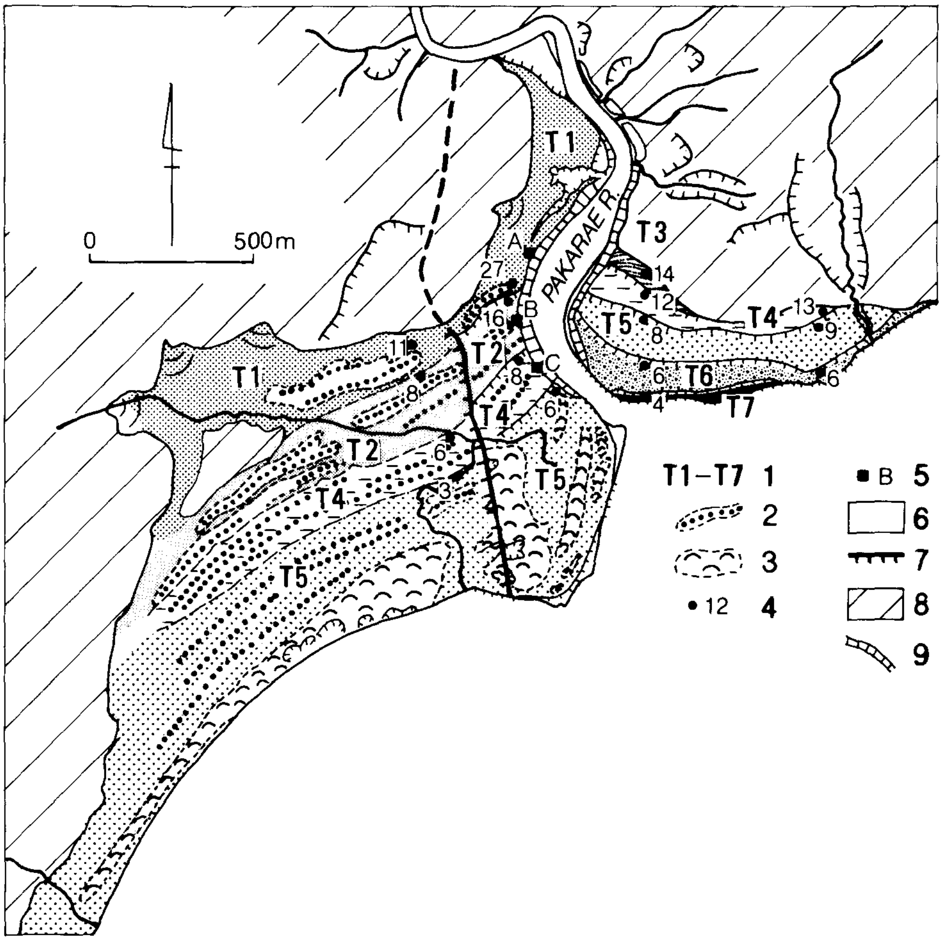

Fig. 9 Distribution and heights of Holocene marine terraces at Pakarae River mouth. 1, Name of terraces; 2, beach ridge; 3, sand dune; 4, former shoreline height (metres); 5, sampling site from Ota et al. (1991); 6, fluvial terrace; 7, active fault trace; 8, hill and landslide; 9, terrace riser.

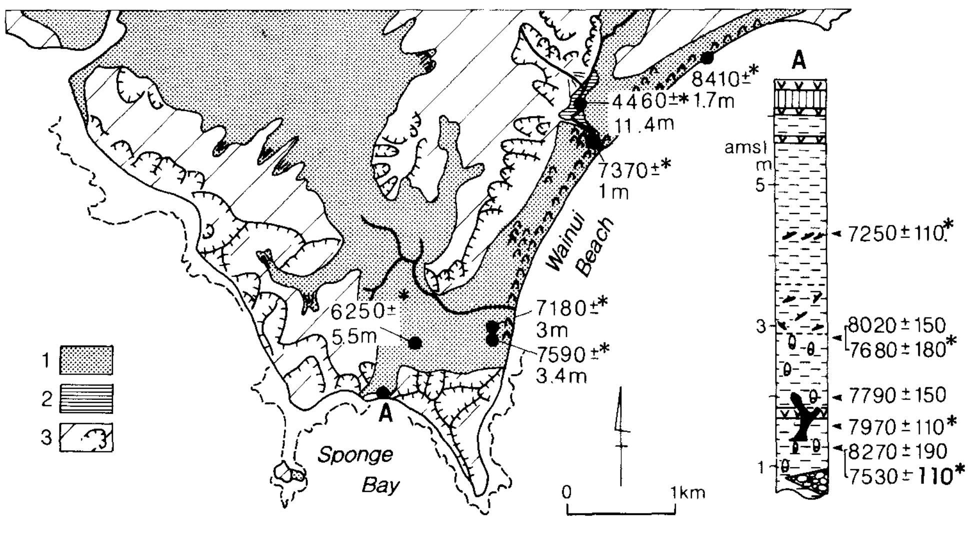

Fig. 10 Distribution and stratigraphy of Holocene marine terraces at Sponge Bay and Wainui Beach. Radiocarbon ages are from this study, L. J. Brown (pers. comm. 1984), and J. G. Gibb (pers. comm. 1985). 1, Higher Holocene terrace; 2, lower Holocene terrace; 3, hill and landslide.

age from c. 5500 to c. 7000 yr B.P. (Fig. 11). These ages are close to the c. 6500 yr B.P. Holocene sea-level culmination age determined from many tectonically stable regions of New Zealand by Gibb (1986). The Holocene sea-level culmination age determined in this study is older than c. 3900 yr B.P. at Miranda, North Island (Schofield 1960), c. 4500 yr B.P. at Christchurch (Suggate 1968a), and c. 4700 yr B.P. at Rapahoe, North Westland, South Island (Suggate 1968b). The significance of this age range for the culmination of the postglacial sea level is discussed below (Tectonic Deformation of Holocene Marine Terraces).

Lower Terraces: There are several dated terraces below Sponge Bay Terrace (Fig. 11). These terraces can be subdivided into a maximum of six levels with different ages: c. 300, 600–700, 900–1200, 1600–2000, and 4500–5000 yr B.P. to the west of East Cape; and <600, 1000, 1600, 2500, 3900, and 5500 yr B.P. at the Pakarae River area. As they are

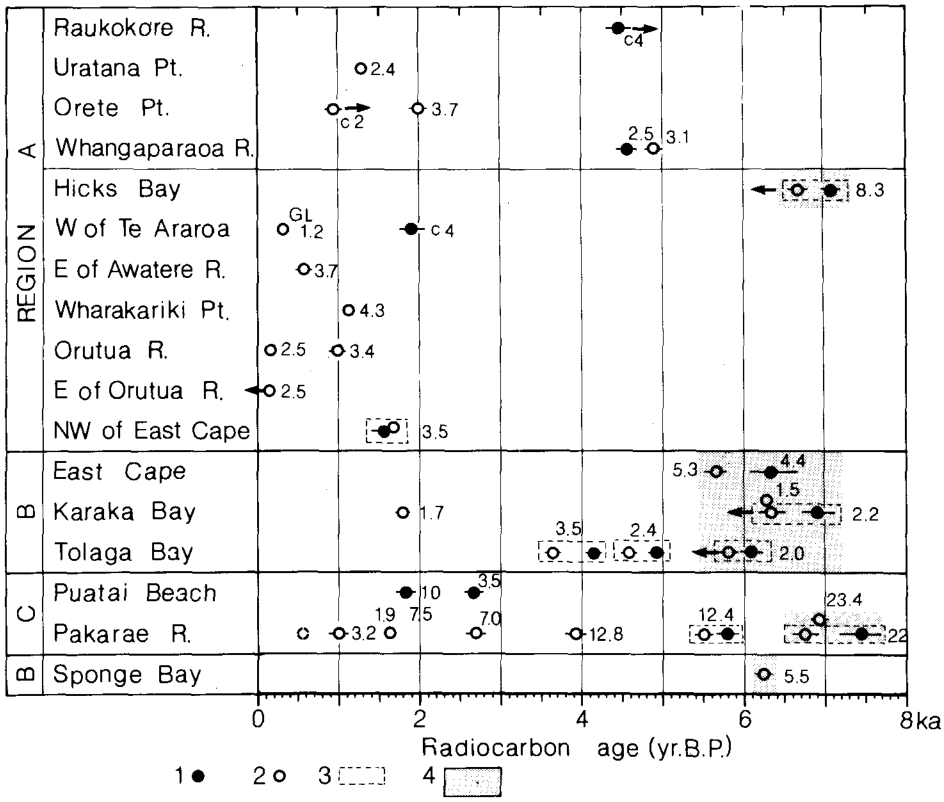

Fig. 11 Distribution of radiocarbon ages of Holocene marine terrace deposits from the study area. Only ages from samples at or near the top of marine deposits or wave-cut platforms are shown. Error bars are 1 standard deviation of radiocarbon counting statistics. Figures beside dated samples show their height above mean sea level. 1, Dated in Japan; 2, dated in New Zealand; 3, duplicate sample; 4, Sponge Bay Terrace. The dashed circle indicates the age was estimated from stratigraphic position associated with a dated tephra layer.

underlain by only thin marine deposits and are of limited areal extent, they are of probable tectonic origin.

TECTONIC DEFORMATION OF HOLOCENE MARINE TERRACES

Height distribution of Sponge Bay Terrace and classification of tectonic regions

Sponge Bay Terrace at c. 5500–7000 yr B.P. is well preserved throughout the study area and is, therefore, a general indicator of the amount of vertical tectonic movement. The terrace height ranges from c. 4 to 27 m a.m.s.l, indicating differential uplift over the study area. From the present variation in height of Sponge Bay Terrace, three distinct tectonic regions can be defined (Fig. 12).

Region A is characterised by uplift and westerly tilting. The vertical deformation pattern of Sponge Bay Terrace in Region A is concordant with that for Otamaroa (last interglacial) Terrace determined by Yoshikawa et al. (1980). The westward tilt of Otamaroa Terrace (9.4 m/km) is greater than that of Sponge Bay Terrace (0.4 m/km) (Fig. 12), suggesting progressive westward tilting for at least the last c. 125 000 years. There are five terraces lower than Sponge Bay Terrace where the average Holocene uplift rate is higher (3 m/1000 yr), and only one or two where the rate is lower (1 m/1000 yr).

Only two Holocene terraces are recognised in **Region B**, located to the east and south of Region A. Sponge Bay Terrace is usually less than 7–8 m a.m.s.l., and no systematic vertical deformation pattern is apparent in Region B. A 13 m discontinuity in the height of Sponge Bay Terrace between Regions A and B also coincides with a sudden height discontinuity of c. 200 m for Otamaroa Terrace. This change takes place in a small zone immediately west of East Cape and indicates the location for a major tectonic boundary (Fig. 12).

Region C is characterised by a high rate of average uplift from c. 2 m/1000 yr at Waihau Beach in the north to c. 4 m/1000 yr at Pakarae River to the south. Although Sponge Bay Terrace is not preserved at Puatai Beach (Fig. 9), the presence of Holocene marine terraces up to 18 m a.m.s.l. and dated at c. 2600 yr B.P. confirms the high rate of uplift and that Puatai Beach is located within Region C.

The age of culmination of the postglacial transgression varies in each of three tectonic regions. The oldest age of c. 7000 yr B.P. is found in Region C with the highest average uplift rate of c. 7–8 m/1000 yr (Ota et al. 1991), suggesting that emergence in this area took place earlier than the other tectonic regions because of rapid uplift. Culmination of postglacial sea level at c. 5500 yr B.P. in Region B and the western part of Region A occurs with an average uplift rate of <1 m/1000 yr. In these areas of lower average uplift rate, sea level rises at a faster rate than tectonic uplift between c. 6000 and 7000 yr B.P., so the culmination of sea level occurs later than in regions of higher average uplift rate. This feature has been recognised throughout the east coast of North Island by Ota et al. (1988).

Coseismic origin for the formation of the Holocene marine terrace sequence

Regions A and C preserve Holocene marine terraces that clearly show discontinuous, stepped profiles (Fig. 5, 8, and 9). The formation of such a discontinuous coastal terrace profile can be interpreted as resulting from uplift accompanying large earthquakes. That the uplift is coseismic is supported by three lines of evidence (Berryman et al. 1989; Ota et al. 1991): (1) characteristic stepped-terrace morphology with emergent

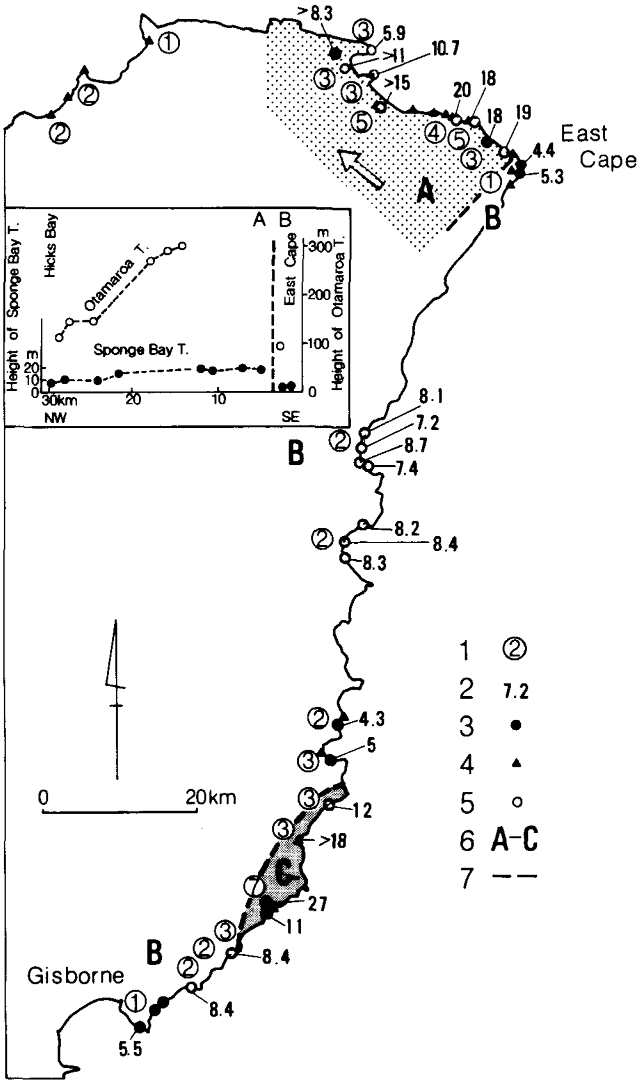

Fig. 12 Number of preserved Holocene marine terraces in the study area. Classification into three tectonic regions is based on the height distribution of Sponge Bay Terrace. Location of boundary between Region B and Region C is uncertain. 1, Number of preserved Holocene terrace; 2, height of Sponge Bay Terrace (metres); 3, location where radiocarbon ages from Sponge Bay Terrace were obtained; 4, location where radiocarbon dates from younger Holocene terraces were obtained; 5, location where no datable material was found; 6, tectonic region; 7, inferred location of boundary between tectonic regions. *Inset:* Comparison of heights between last interglacial (c. 125 000 years ago) Otamaroa Terrace and Sponge Bay Terrace along the coast between Hicks Bay and East Cape.

subhorizontal abrasion platforms; (2) clustering of ages of terrace deposits with significant gaps between successive terraces; and (3) historical occurrence of coseismic coastal uplift in New Zealand in 1855 (Ongley 1943) and 1931 (Henderson 1933). Numerous examples of historic coseismic uplift are found in other areas close to subduction zones: Middleton Island, Alaska (1964) (Plafker 1969); central Chile (1960) (Plafker 1972; Kaizuka et al. 1973); New Hebrides Islands (1965) (Taylor et al. 1980); Kermadec Islands (Doyle et al. 1979); and the Pacific coast of central and southwest Japan (e.g., 1703, 1923, 1946) (e.g., Yoshikawa 1970; Yonekura 1975; Matsuda et al. 1978). Repeated coseismic uplift in these areas produced landward tilting that is well recorded by Holocene marine-terrace deformation and is inferred to have produced a similar vertical deformation pattern for late Pleistocene marine terraces.

The coastal area east of the Raukumara Range has been interpreted by Yoshikawa et al. (1980) as one of active seismic deformation, judged by the progressive landward tilt of marine terraces away from the Hikurangi margin. No historical coseismic marine terraces are known for this part of New Zealand, however. The 1931 Hawke's Bay earthquake (M_s = 7.8) was accompanied by a maximum of 2.7 m uplift and affected 100 km of coastline to the south of the study area (Henderson 1933). Berryman (1983) has inferred that five Holocene marine terraces at Mahia Peninsula, North Island, with ages ranging from c. 300 to 3500 yr B.P., have resulted from episodic uplift probably associated with large earthquakes. He argued that the relative height difference between each terrace is too large when compared to the estimated Holocene eustatic sea-level fluctuation (Gibb 1986), and the terraces must, therefore, have been tectonically uplifted. Hull (1987) established from Cape Kidnappers, North Island, where a c. 2300 yr B.P. marine terrace is preserved up to 6 m a.m.s.l., that the nature of marine deposits overlying a former abrasion platform and its enclosed fauna is best explained by sudden, coseismic uplift. From comparison with the evidence above, it is concluded that most of the Holocene marine terraces within the study area also result from coseismic uplift. On this assumption, a minimum of five to six earthquake events are preserved in Regions A and C since the culmination of the postglacial sea-level rise.

Radiocarbon ages from Region A indicate that large earthquakes probably occurred at least <300, 600–700, 900–1200, 1600–2000, and 4500 yr B.P. No ages are available for some of the terraces. In Region B, only two uplift events, c. 1800 and 4500 yr B.P., are known. In Region C, six uplift events (<600, 1000, 1600, 2500, 3900, and 5500 yr B.P.) have been identified in this study. Ages of uplift in Region C are different from those in Region A, Mahia Peninsula, and Cape Kidnappers and imply that local large earthquakes form unique terrace sequences (Berryman et al. 1989).

The number of uplift events estimated from terrace sequence records is the minimum number of large earthquakes resulting in coastal uplift, because erosion may have removed several terraces. However, there are usually less than six terraces preserved in the 6000–7000 years since the culmination of the postglacial transgression: approximately one every 1000 years. However, the inferred earthquake recurrence interval varies from only 300 years to more than 1500 years, not only between different tectonic regions, but also within a single tectonic region.

Tectonic implications

Recognition of the three tectonic regions indicates that throughout Holocene time, and probably the late Quaternary, significant but variable tectonic movements have occurred along the coastal regions of the Raukumara Peninsula. A number of general tectonic models summarised by Pettinga (1982) have been proposed for the geological structure and evolution of the region west of the Hikurangi Trough. Pettinga rejected the extensional, normal faulting model of Katz (1974) and strike-slip-dominated folding model of Kingma (1958) in favour of a model requiring the eastern part of the North Island to have been dominated by east–west compressional stresses since the late Miocene. Post-Miocene tectonic deformation is thus dominated by crustal shortening and uplift at west-dipping reverse faults within the accretionary sedimentary wedge of the Australian plate above the active subduction zone (Lewis 1980; Davey et al. 1986).

Any model adopted for the deformation of this part of the North Island must explain the ubiquitous uplift throughout the Raukumara Peninsula. All regions defined in this study have undergone uplift throughout the Holocene and probably for much of the Quaternary. Walcott (1987) attributed uplift in Hawke's Bay to underplating of sediments in the subduction zone; Cashman & Kelsey (1990) considered that uplift and extension was related to local development of the outer-arc high. Estimates from earthquake travel-time inversion studies of crustal thickness for the subducted Pacific plate (Robinson 1986; Bannister 1988) suggest that it is thicker and more buoyant than normal oceanic crust of its inferred age. Subduction of thicker oceanic crust beneath the Raukumara Peninsula would have a similar effect to underplating in producing a regional uplift (Smith et al. 1989). Variation in the regional uplift pattern could then be produced by local structures that accommodate shortening within the accretionary wedge. Thus, we believe that the average uplift rate of c. 1 m/1000 yr recognised in Region B may reflect the regional uplift for this part of the Raukumara Peninsula, and the higher average uplift rate in Region C is the effect of uplift from the growth of local structures superimposed on the regional uplift rate.

The boundaries between the tectonic regions are of interest because they may indicate the presence of these active geological structures. The boundary between Regions A and B occurs over a narrow area immediately west of East Cape. The marked height change of Sponge Bay Terrace from c. 20 m to c. 6 m suggests that the boundary may be the trace of a west-dipping, perhaps northeast-striking reverse fault. No recent fault scarps are apparent, however, either on land or from the bathymetry immediately offshore (van der Linden 1968).

No known geologic structure is apparent at the boundary between Regions B and C, either exposed along the coastal section or in inland areas. This boundary may not be a major structural discontinuity; rather, it records the zone where the rate of uplift associated with the growth of a fault/fold offshore is about the same as the more regional uplift rate associated with this part of Region B.

Recent work in Hawke's Bay by Cashman & Kelsey (1990) and Cashman et al. (in press) has shown that strain associated with the oblique compression of the Australian plate in the last c. 2 Ma has been partitioned into discrete domains of extension, contraction, and strike-slip. Distinct boundaries that mark the location of major faults occur between these domains, and the regions identified in this study may be similar to the domains recognised further south in Hawke's Bay.

The c. 7000 years of tectonic deformation revealed in this study represent only a small fraction of the evolution time for this structurally complex area above an active subduction zone. The deformation pattern probably varies in both time and space, but the three different tectonic regions recognised in this study provide some constraints to structural geological models for this part of the New Zealand region. Further detailed studies of the nature of the regions' boundaries and the style of strain accommodation within different regions are warranted.

CONCLUSIONS

Detailed stratigraphy, chronology, and elevation of Holocene marine terraces on the northeast coast of New Zealand determine the pattern of Holocene tectonic uplift adjacent to the boundary between the Pacific and Australian plates. Three distinct tectonic regions are apparent, and near East Cape (Region A), progressive tectonic uplift and northwestward tilting during the Holocene can be demonstrated for at least the last c. 125 000 years.

The Sponge Bay Terrace records the local culmination of postglacial sea level in this part of New Zealand. Thick transgressive deposits testify to a rapid rise of sea level from c. 10 000 to c. 6000 yr B.P. The age of postglacial sea-level culmination varies with average rate of tectonic uplift; higher uplift rate areas have a culmination age at c. 7000 yr B.P., while in lower uplift rate areas, postglacial sea level culminated at c. 5500–6000 yr B.P. Culmination time in the higher average uplift rate areas is probably dependent upon the timing of individual uplift events that must occur more frequently or must be of greater magnitude than in lower average uplift rate areas.

Much of the tectonic history of New Zealand during the last 10 000 years has been deduced from the study of active faults. In the northeastern part of New Zealand, however, few active faults are known. Our study demonstrates that valuable information on the vertical tectonic history during the Holocene is recorded in the coastal deposits. Interpretation of the distribution and age of these deposits can provide the chronology of relative sea-level changes and the recurrence interval of large earthquakes producing coastal uplift. The deformation pattern in northeastern New Zealand, as deduced from the Holocene coastal terrace chronology, can contribute to the understanding of the crustal deformation mechanism for this part of New Zealand.

ACKNOWLEDGMENTS

Data for this study were collected mainly in 1981 and supplemented by additional fieldwork in 1983 and 1985. Financial support from Ministry of Education, Science, and Culture, Japan, in 1981, 1982, 1985, and 1986 (Project numbers: 56041026, 57043023, 60041029, and 61043025; Project Leader Yoko Ota) and New Zealand Geological Survey are gratefully acknowledged. Unpublished dates have been kindly provided by Len Brown and Jeremy Gibb. This paper has been improved from reviews by Pat Suggate, Kelvin Berryman, Len Brown, Colin Mazengarb, Dick Walcott, and one anonymous reviewer. We are also grateful to Graeme Blick, Takahiro Miyauchi, Kenichiro Yamashina, and Masumi Sawa for assistance with fieldwork and for discussion. This study would not have been possible without the friendly co-operation of the many land owners in the study area.

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