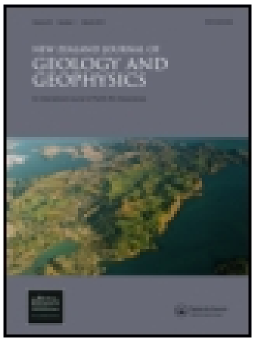


New Zealand Journal of Geology and Geophysics

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

Pleistocene coastal terraces of Kaikoura Peninsula and the Marlborough coast, South Island, New Zealand

Yoko Ota , Brad Pillans , Kelvin Berryman , Alan Beu , Takatoshi Fujimori , Takahiro Miyauchi , Glenn Berger , A.G. Beu & F.M. Climo

New Zealand Journal of Geology and Geophysics, 1996, Vol. 39: 51–73
0028–8306/96/0051 $2.50/0

Pleistocene coastal terraces of Kaikoura Peninsula and the Marlborough coast, South Island, New Zealand

YOKO OTA
Geography Department
Senshu University
2–1–1 Higashi-mita
Tamaku, Kawasaki, 214, Japan

BRAD PILLANS
Division of Archaeology and Natural History
Research School of Pacific Studies
Australian National University
Canberra, ACT 0200, Australia

KELVIN BERRYMAN
ALAN BEU
Institute of Geological and Nuclear Sciences
P.O. Box 30 368
Lower Hutt, New Zealand

TAKATOSHI FUJIMORI
Keio Gijuku Futsubu Junior High School
Kohokuku, Yokohama, 223, Japan

TAKAHIRO MIYAUCHI
Department of Earth Sciences
Chiba University, Chiba, 260, Japan

GLENN BERGER
Quaternary Sciences Center
Desert Research Institute
Reno, Nevada, 89506–0220, U.S.A.

With an appendix

Mollusca from Parikawa locality

A.G. BEU
Institute of Geological and Nuclear Sciences
Lower Hutt, New Zealand

F.M. CLIMO
Museum of New Zealand
P.O. Box 467
Wellington, New Zealand

Abstract Pleistocene marine terraces along the Marlborough coast, South Island, New Zealand, have been re-examined with detailed stratigraphic observations, accurate height data, and amino acid and thermoluminescence (TL) geochronology. Marine terraces range in age from c. 220 ka (oxygen isotope stage 7) to c. 60 ka (oxygen isotope stage 3), in the area from Cape Campbell to Conway River. At Kaikoura Peninsula, five marine terraces are preserved. The marine fauna, loess stratigraphy, and amino acid dating of *Tawera spissa*, from the Kaikoura I (highest) terrace and from the highest terrace at Haumuri Bluffs (Tarapuhi Terrace), indicate a correlation to oxygen isotope substage 5c, with an age of 100 ka.

North of the Clarence River, marine terraces (including the Parikawa Formation) are correlated to oxygen isotope substage 5e of the last interglacial. TL dating of loess supports this interpretation. The Winterholme Formation terrace at Kekerengu is reinterpreted as a last glaciation fluvioglacial terrace graded to a low-stand of the sea. Therefore, we abandon the use of Winterholme and Parikawa Formations and, instead, correlate terraces to the geochronometrically and astronomically tuned oxygen isotope chronology.

Maximum late Pleistocene uplift rates vary from c. 2 m/ka at Conway River, 1.3 m/ka at Haumuri Bluffs, 1.1 m/ka at Kaikoura, and 1.1 m/ka at Clarence River, to c. 0.5 m/ka in the Long Point area, c. 10 km south of Cape Campbell. Local structures, rather than regional uplift related to subduction, appear to be primarily responsible for uplift, and in at least three of the four areas, the causative faults are contractional fault/fold structures between or south of the major strike-slip faults of the Marlborough fault system.

Keywords Pleistocene; marine terrace; fluvial terrace; Kaikoura Peninsula; Marlborough coast; molluscan assemblage; amino acid dating; thermoluminescence dating; tectonic deformation; Quaternary; chronology

INTRODUCTION

The Marlborough coast of the South Island of New Zealand lies within a zone of active faulting and folding at the southern end of the Hikurangi subduction zone (Fig. 1). The rugged coastline and the high Kaikoura Ranges are consistent with rapid tectonic uplift, but rates are difficult to quantify. Pleistocene marine terraces occur intermittently along the coast (Jobberns 1928) and these provide a way of calculating vertical deformation rates. In this paper we use an integrated approach including detailed stratigraphic observations, accurate altitude data, and amino acid and thermoluminescence (TL) geochronology to calculate terrace ages and deformation rates in the area from Cape Campbell to Haumuri Bluffs.

Four major dextral strike-slip faults in the study area accommodate much of the c. 36 mm/a relative plate motion across the Australia–Pacific plate boundary at this latitude (Van Dissen & Yeats 1991), but not all the faults reach the coastline as simple structural features. The seaward-most

G94038
Received 12 August 1994; accepted 28 September 1995

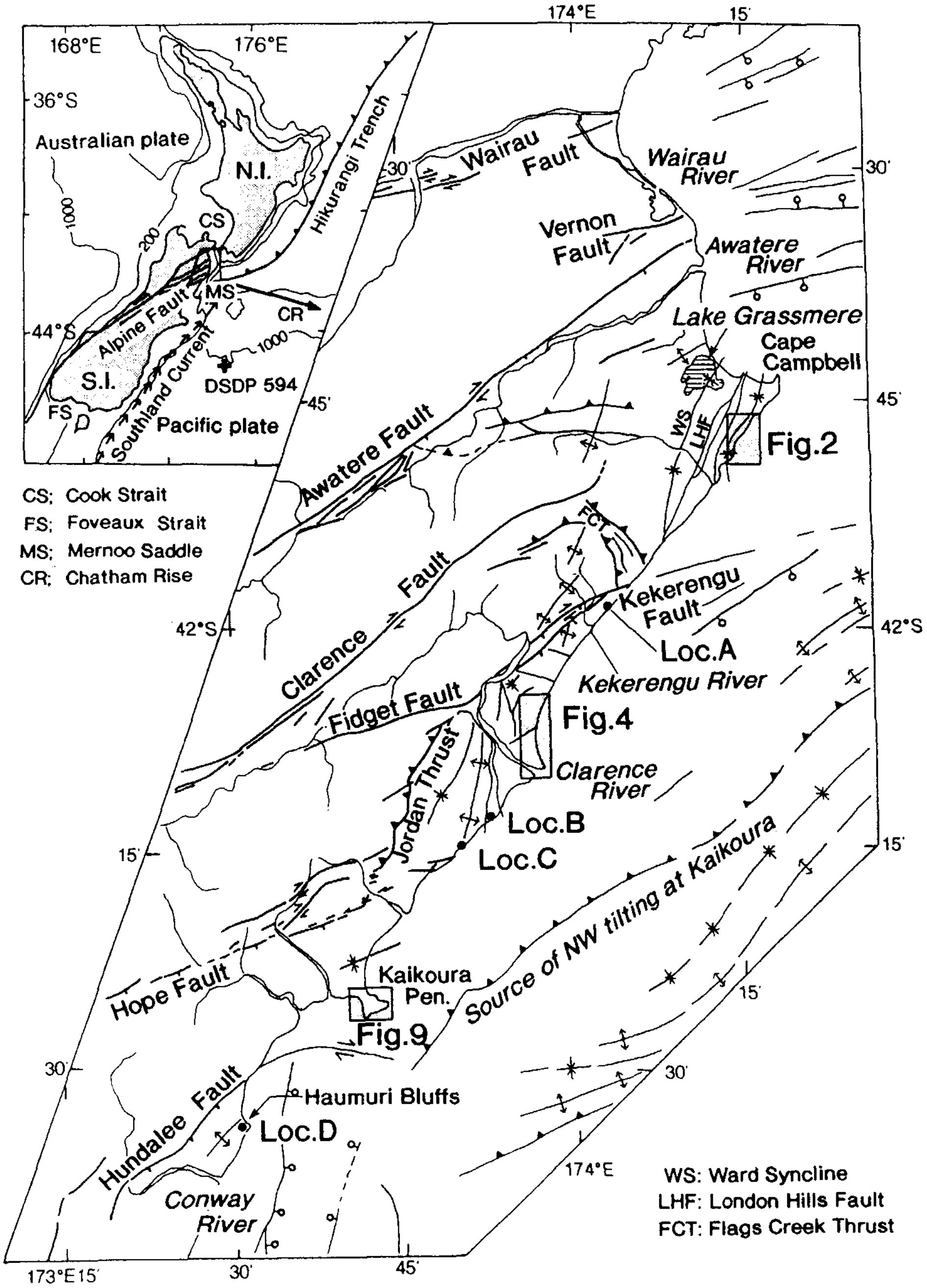


Fig. 1 Map of the northeastern part of South Island, showing the study areas, major Quaternary active faults (heavy lines), and late Cenozoic structures (light lines). *Inset*: Plate boundary and the location of Fig. 1. Abbreviations: N.I. = North Island; S.I. = South Island.

element of the Hope Fault (Fig. 1) has a much lower slip rate than inland sections, and most of the Hope Fault motion is transferred to the Kekerengu Fault via a north-striking fault, the Jordan Thrust (Van Dissen & Yeats 1991). Similarly, the Clarence Fault terminates as a northeast-striking strike-slip fault c. 15 km from the coast (Browne 1992), with the strain probably being taken up in a series of folds and contractional faults (Fig. 1) on which there is, as yet, very little documented Quaternary movement. Some of the strike-slip motion on the northeast part of the Clarence Fault may be transferred to the Kekerengu Fault via the Fidget Fault (Fig. 1) (Reay 1993). The Awatere and Kekerengu Faults reach the coastline c. 5 km north of the Awatere and Kekerengu Rivers, respectively. Lamb & Bibby (1989) presented a kinematic interpretation of how the Marlborough region may have deformed over the past 25 m.y., and Wellman (1979) presented regional uplift rates although no field data were published to justify the uplift rates.

The location and activity of the major dextral strike-slip faults are major controls on the geology, particularly on the distribution of late Mesozoic and Cenozoic cover strata over basement greywacke rocks. Although the major faults are primarily strike-slip, the lesser vertical component has been sufficient to form large tilt blocks, such that the late Mesozoic and Cenozoic cover strata are preserved only on the downthrown sides of the major faults, and east and northeast of the terminations of the Hope and Clarence Faults. Numerous fault and fold structures have been mapped within the cover strata (Lensen 1962; Prebble 1980; Kirker 1989; Rait et al. 1991), and Carter & Carter (1982) and Lewis & Bennett (1985) have made preliminary compilations of offshore structures (Fig. 1). These fold and fault structures as well as the major strike-slip faults may play a role in the deformation of the late Pleistocene marine terraces preserved along the Marlborough coast.

Previous work

Although earlier workers (e.g., McKay 1877, 1886; Cotton 1914, 1916; Henderson 1924) mentioned the presence of high-level marine gravel along the Marlborough coast, the first systematic description was that of Jobberns (1928), who described features between the Wairau River and Christchurch. In the present study area, Jobberns recorded terraces in four main areas: (1) Long Point, at heights up to 160 ft (c. 50 m); (2) Clarence River/Kekerengu area, at heights of 300–350 and 500–550 ft (c. 90–105 and 150–168 m); (3) Kaikoura Peninsula, at heights of 140–160, 250, and 360 ft (c. 43–50, 76, and 110 m); (4) Conway River/Haumuri Bluffs area, at heights of 150–160, 250, 330–380, and 500–600 ft (c. 46–50, 76, 100–116, and 150–183 m) and perhaps higher.

Jobberns concluded that there had been little differential uplift along the whole coast, and proposed correlation, based on terrace heights, to the Mediterranean area and South America.

Suggate (1965) recognised two major groups of marine terraces between Kekerengu and Kaikoura Peninsula. These were named Parikawa and Winterholme Formations, assigned to the penultimate interglacial and last interglacial periods, respectively. Suggate recognised four major terraces at Kaikoura and tentatively assigned one of them (170–200 ft) to the Parikawa Formation. The distribution of the Parikawa and Winterholme Formations is shown on the 1:250 000 geological map of the area (Lensen 1962).

Richly fossiliferous, Pleistocene marine deposits near the top of Haumuri Bluffs were discovered by McKay (1877, 1886). The fauna was also described by Fleming & Suggate (1964) who noted that it contained no extinct species, and, despite its cool aspect, they assigned it to an interglacial predating the Parikawa Formation. Bull (1984, 1985) made brief mention of marine terraces along the Kaikoura coast, and he presented best fit uplift/age estimates for a flight of eight terraces apparently recognised on Kaikoura Peninsula. Bull (1984) showed uplift estimates along a coastal transect between the Wairau River and Kekerengu. In neither interpretaion were field observations presented to support them. Ota et al. (1984) described marine terraces in the Conway River – Haumuri Bluffs area, and tentatively assigned the sequence of terraces to the last three interglacials, based on morphostratigraphical observation.

Study method

Airphoto interpretation (scale c. 1:20 000) enabled preliminary mapping of the study area. Fieldwork produced a terrace distribution map and sections of terrace deposits and coverbeds. Heights of marine deposits, underlying rocks, and terrace surfaces were measured at exposures by digital altimeter. Recorded heights were corrected to sea level or trig stations about every 2 h. The accuracy of measurement is considered to be within ±2 m. In addition to the observation of natural exposures, excavations by hand-auger were carried out at about 20 locations on Kaikoura Peninsula. Wood and shell samples were collected from exposures and from auger holes for paleoenvironmental interpretation and amino acid dating. At one site near Clarence River, two loess units, immediately overlying fluvial gravel, were sampled for TL dating.

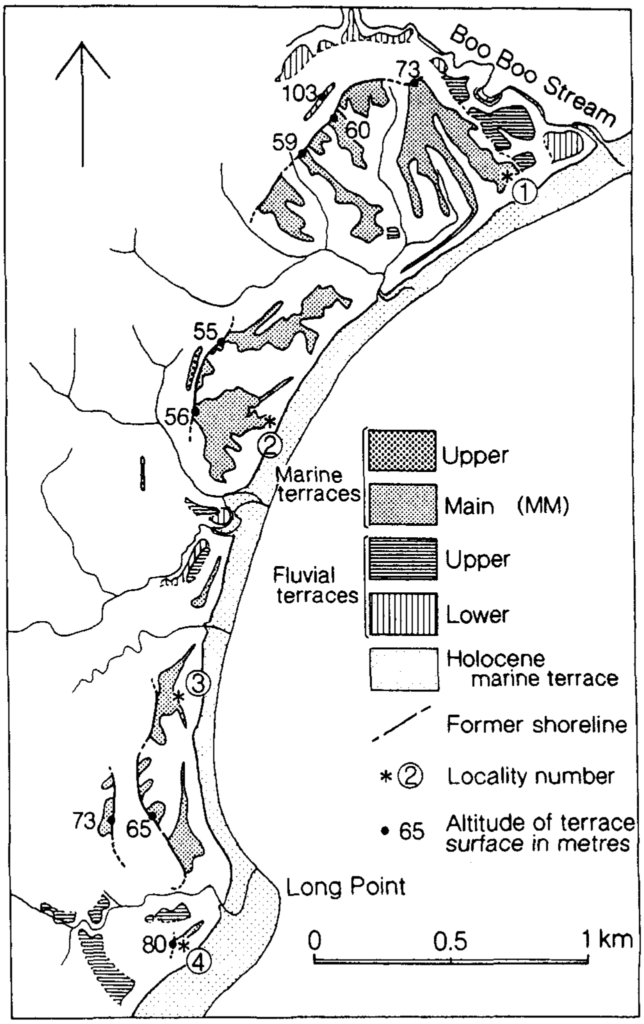


Fig. 2 Distribution of terraces from Long Point to Boo Boo Stream.

TERRACES, TERRACE DEPOSITS, AND COVER BEDS

Long Point to Boo Boo Stream

Main terrace (MM)

A well-defined continuous marine terrace surface is recognised in the coastal area from Long Point north to Boo Boo Stream (Fig. 2). This terrace is especially well preserved in the northern part of the area and is named the "main" terrace. The terrace is in some places preserved as very narrow ridges parallel to the coast, owing to dissection by subsequent streams whose orientation is controlled by structure in the underlying Tertiary rocks.

Marine terrace deposits and overlying cover beds of the main terrace are exposed at the former sea cliff between this terrace and the younger Holocene terrace. Typical exposures are shown in Fig. 3. At Loc. 4 (Long Point), 3 m of well-stratified beach deposits, composed of well-rounded pebbles

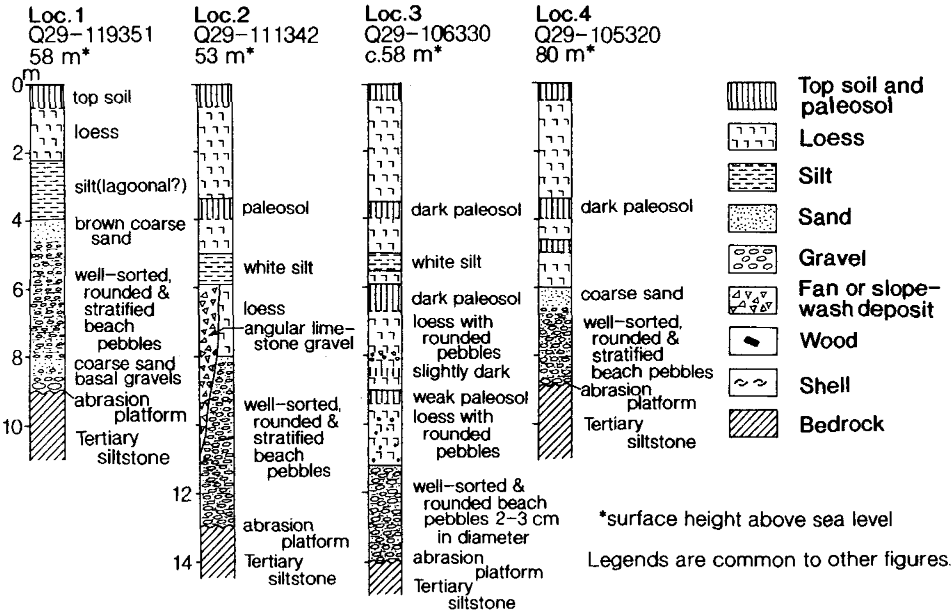


Fig. 3 Representative sections of marine terrace deposits from Long Point to Boo Boo Stream. Localities are shown in Fig. 2.

with coarse sandy matrix, is overlain by 6 m of nonmarine cover beds, in which there are at least two paleosols within loess deposits. The top of the beach deposits is 74 m above sea level (a.s.l.). An excellent section is exposed at Loc. 3, where 3 m of well-sorted and rounded beach gravels, the top of which is 47 m a.s.l., is overlain by 11 m of nonmarine cover beds. At least four loess units with three paleosols are present. We consider this locality is a representative section for the main terrace. At Loc. 2, angular limestone gravel fills a small erosional depression in beach deposits. About 2 m of white silt covers this angular gravel, which in turn is overlain by loess.

The height of the inner margin of the main terrace surface ranges from 55 to 80 m a.s.l. (Fig. 2), with higher elevations at either end of the areas at Long Point, and at Boo Boo Stream.

Other terraces

Inland of the main terrace, very narrow flat ridge-crests at 73–103 m may represent remnants of an older marine terrace (upper marine terrace of Fig. 2). However, beach deposits were not found to confirm this. At least two fluvial terraces are preserved below the main terrace along Boo Boo Stream. The upper fluvial terrace is c. 36 m above the stream near the coast. The lower fluvial terrace was probably graded to sea level at the culmination of the postglacial sea-level rise, and is relatively well developed along the stream, although estuarine deposits were not found.

Clarence River to Kekerengu River

Marine terraces

Marine terraces in this area are divided into three groups: upper (UM); main (MM); and lower (Holocene) terraces (Fig. 4).

Upper marine terrace (UM): Remnants of a high marine terrace are preserved as flat summits above the main marine terrace in at least two locations: at Carrion Hill (west of Loc. 9) and at Loc. 6 (Fig. 4). Pigeon Hill (294 m) may also be a remnant (Fig. 4). At both Loc. 6 and Loc. 9, well-sorted, rounded and stratified beach gravel is exposed. The terrace surface height at Carrion Hill is 222 m, and is c. 190 m at Loc. 6, indicating some northward down-tilting.

An intermediate c. 160 m a.s.l. between Loc. 6 and Loc 7 may also be a marine terrace remnant. However, beach deposits were not found, and no correlative terrace remnants were found elsewhere.

Main marine terrace (MM): This terrace is everywhere covered by thick (often >10 m) slope-wash deposits but its origin as a marine terrace is confirmed by exposures from north of Pigeon Hill to Woodbank Stream (Fig. 4). Marine terrace remnants are also preserved as small flat ridge-crests between deep and steep valley walls, above very steep former sea cliffs rising from the low-lying Holocene terrace. Excellent exposures also occur in some steep valley heads.

At Loc. 10 (Fig. 4), c. 5 m of well-sorted and rounded beach gravel unconformably overlies the abrasion platform truncating Miocene siltstone (Fig. 5) at an altitude of 143 m. These beach deposits include boulders bored by shells and they abut a bedrock cliff just inland of Loc. 10, indicating the exact location of the former shoreline angle. A section at Loc. 9, which is very close to the type locality of Parikawa Formation of Suggate (1965), also represents a typical sequence of terrace deposits and cover beds. About 2 m of beach gravel, with bored boulders up to 0.6 m in diameter, rests on the abrasion platform of Tertiary siltstone (112 m a.s.l.) and is overlain by 6 m of stratified beach pebbles c. 2 cm in diameter containing shell fragments. About 35 m of slope-wash deposits, intercalated with some stratified pebble horizons, overlie these beach deposits. At Loc. 7, estuarine silt, which includes fossil wood and shells, is intercalated with slope-wash deposits, and rests on Tertiary siltstone at c. 90 m a.s.l. The silt is overlain by coarse beach boulders, the base of which is 105 m a.s.l. This stratigraphy indicates that the main terrace was formed in association with sea-level rise, probably corresponding to the last interglacial maximum, judged by the relatively widespread preservation of this marine terrace, and the interglacial fauna in the

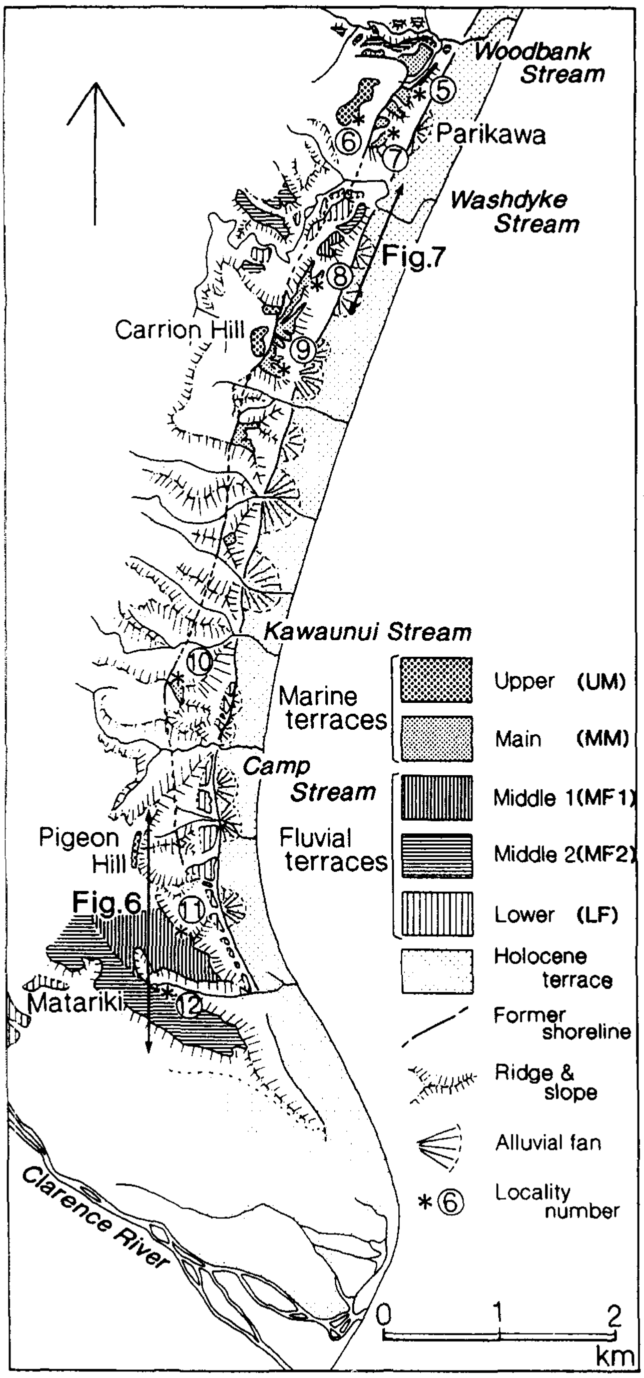


Fig. 4 Distribution of terraces from Clarence River to Woodbank Stream.

transgressive deposits (see later discussion of the fauna). The marine terrace deposits of Parikawa Formation were previously correlated to the penultimate interglacial by Suggate (1965).

The height of the abrasion platform ranges from 143 m in the south to 105 m in the north, indicating a significant component of northward down-tilting.

Fluvial terraces

Fluvial terraces occur along the Clarence River, Washdyke Stream, Woodbank Stream, and the Kekerengu River.

Clarence River mouth: Below the preserved marine terrace remnant of Pigeon Hill on the north bank of the Clarence River there is an extensive flight of fluvial terraces (Fig. 4, 6). Three sets of terraces are distinguished on height and stratigraphic criteria on the north bank of the Clarence River (Fig. 6). Upper surfaces are preserved as narrow ridge crest remnants, underlain by very coarse fluvial gravel. The highest remnant is 284 m a.s.l., c. 10 m below the marine terrace remnant at Pigeon Hill. No loess cover beds are preserved on these upper terraces because of severe dissection and wind deflation on ridge crests.

The middle fluvial terrace set comprises two levels, MF1 (higher terrace at 160–166 m a.s.l. at its outer edge) and MF2 (lower terrace at c. 158 m a.s.l. at its outer edge). Although the riser between MF1 and MF2 is only a few metres, the thickness and coarseness of gravel beds and cover beds are different between the terraces. MF1 is underlain by >20 m of subrounded fluvial gravel, with cobbles c. 0.2 m in maximum diameter. There is up to 7 m of loess cover, containing three paleosols (e.g., Loc. 11, NZMS 260 grid ref. P30/859953, Fig. 5). We collected two samples of this loess for TL dating, results of which are presented below. MF1 terrace is interpreted to be a fill terrace. In contrast, terrace gravel of MF2 is thin (<4 m thick), but very coarse with boulders up to 0.9 m diameter, and is cut into underlying fluvial gravel of MF1. This is interpreted as a lag deposit resulting from fluvial downcutting. Loess and soil cover over MF2 gravel is only c. 0.6 m thick, and no paleosols have been recognised in good exposures such as at Loc. 12 (P30/859950, Fig. 6). Although the geomorphology suggests MF2 is a degradational step below the MF1 fill terrace, the significant difference in loess thickness suggests the MF2 terrace may be substantially younger than MF1.

A lower fluvial terrace (LF) with thin gravel and little loess cover occurs near Matariki at c. 78 m a.s.l. (Fig. 4).

Washdyke Stream: A flight of fluvial terraces is well defined at the south bank of Washdyke Stream (Fig. 4, 7). At least three extensive surfaces are recognised below the marine terrace (MM). The surface of the highest fluvial terrace (MF1) is 89 m a.s.l. and is underlain by c. 15 m thick fluvial gravel. The middle one (MF2) is 73 m a.s.l., and the lower terrace (LF) is at c. 45 m a.s.l.

Kekerengu River mouth: On the north bank of Kekerengu River (Fig. 1), an extensive, well-preserved fluvial terrace occurs at c. 40 m a.s.l. at its outer edge. Suggate (1965) proposed that this terrace was graded to an interglacial highstand and argued that the slightly stratified sandy gravel exposed beneath the terrace at the Winterholme Formation type section (P30/939121) was a nonmarine member of the interglacial formation. At Loc. 1 (P30/938118, Fig. 1), c. 300 m south of the type locality, we found terrace deposits composed of slightly stratified but unsorted subangular to subrounded fluvial gravel c. 20 m thick, with boulders up to 0.4 m in diameter. The gravel is covered by thin loess c. 0.5 m thick. No paleosols were recognised in this thin loess, suggesting an age for the underlying terrace gravels no older than a stage of the last glaciation. No certain marine terraces, at the elevation of the Kekerengu fluvial terrace, occur in the vicinity, and we propose a fluvioglacial origin for the "Winterholme" surface at Kekerengu.

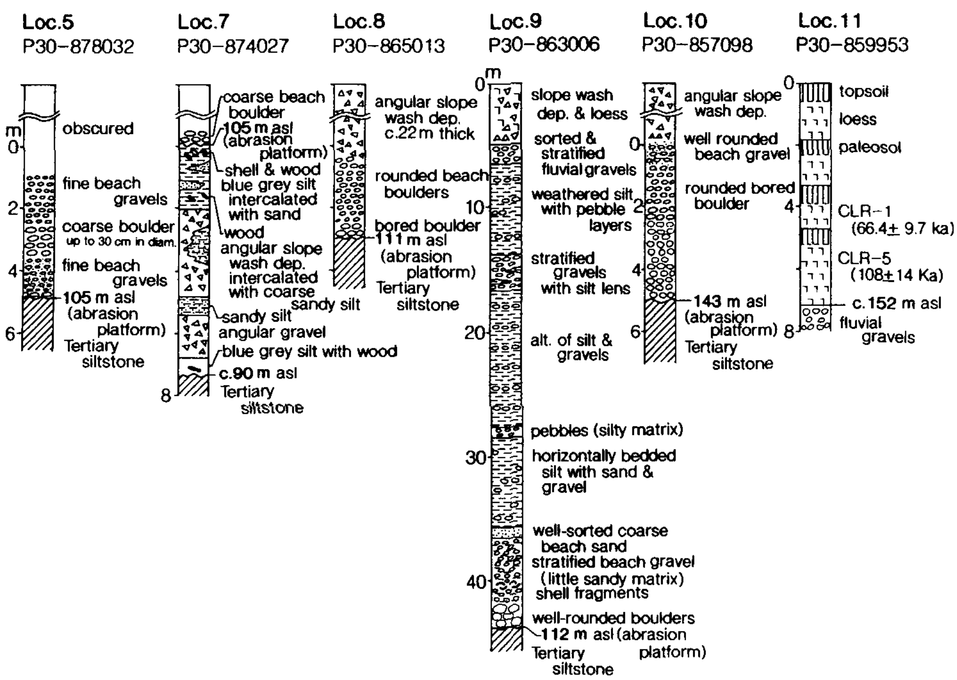


Fig. 5 Representative sections of terrace deposits from Clarence River to Woodbank Stream. Localities are shown in Fig. 4.

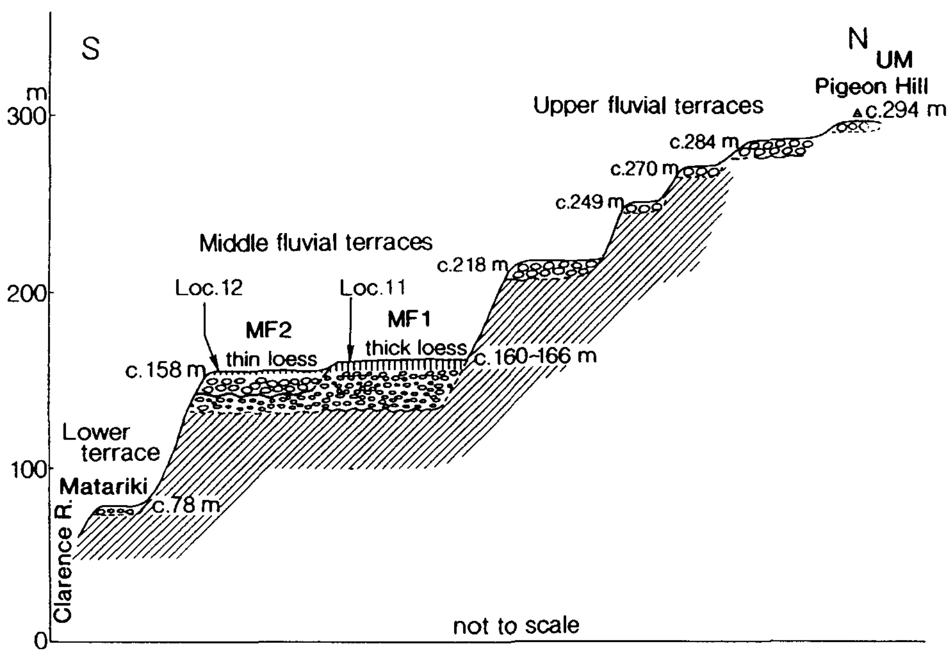


Fig. 6 Schematic profile of terraces at the left bank of Clarence River.

South of the Clarence River

In the area between Clarence River and Kaikoura Peninsula, marine terrace remnants are rare, making correlation and age estimation difficult. Beach deposits were observed on the north bank of Mororimu Stream and on the north side of Half Moon Bay (Fig. 8). At Mororimu Stream (Fig. 1, 8; Loc. B), a flat terrace surface is preserved at c. 90 m a.s.l. at its seaward outer edge. The terrace is underlain by angular fan gravel c. 35 m thick, which overlies 1 m of well-sorted coarse sand including some rounded pebbles of probable marine origin. An unconformity between these beach deposits and bedrock, probably representing a marine abrasion surface, is 61 m a.s.l. A wood sample from the fan deposits was radiocarbon-dated at c. 60 ka (W. B. Bull pers. comm.), but no direct age data are available for beach deposits. Small terrace remnants to the south of this location are probable correlatives, but no exposures of cover beds were found.

On the north side of Half Moon Bay (Fig. 1, 8; Loc. C), c. 0.4 km south of Ohau Point, beach deposits 2 m thick, resting on an abrasion platform 17 m a.s.l., are exposed on a stack just seaward of the main highway. These deposits, composed of well-rounded boulders up to 1 m in diameter, are overlain by slope-wash deposits. Because of the isolated

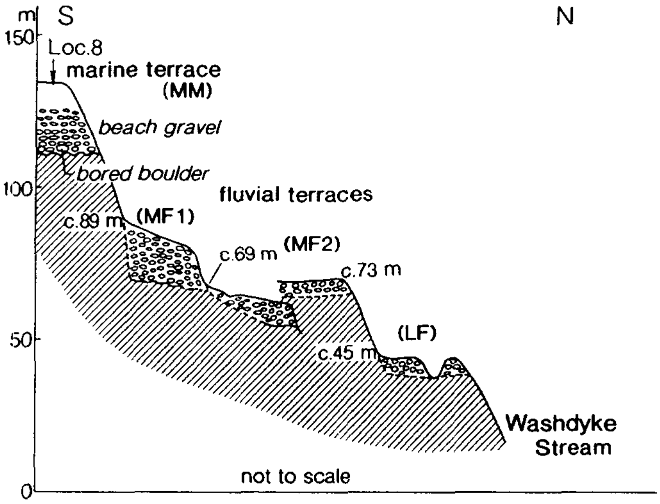


Fig. 7 Schematic profile of terraces at the right bank of Washdyke Stream.

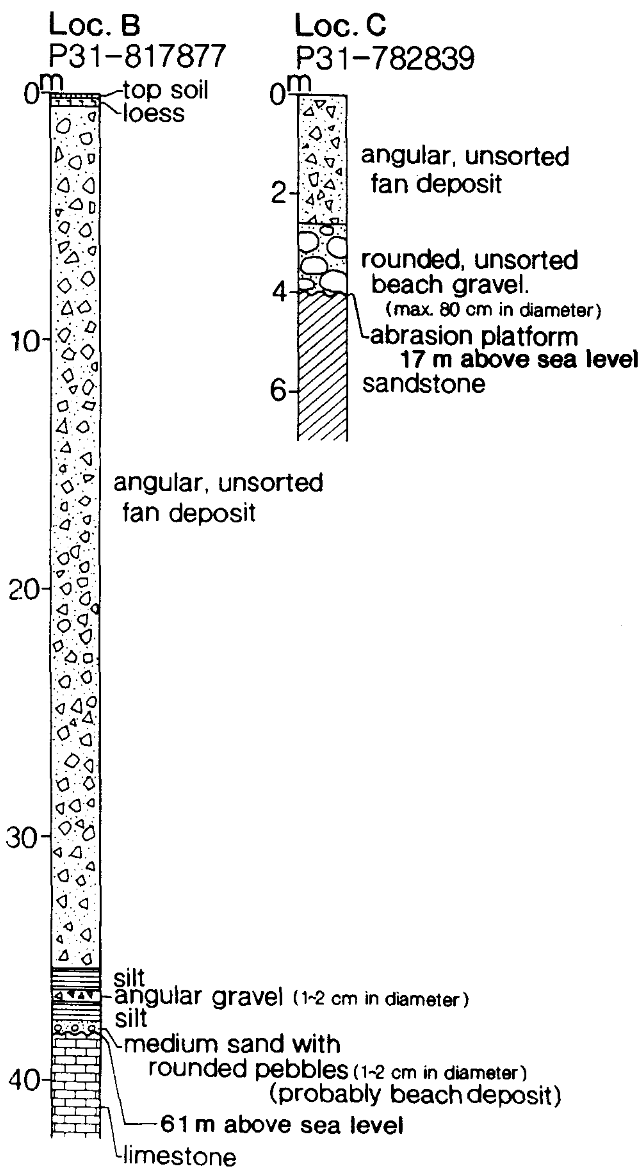


Fig. 8 Sections of terrace deposits south of the Clarence River.

occurrence of these deposits, no age estimation or correlation is possible, although the relatively low elevation suggests a mid-Holocene or late Pleistocene age.

Kaikoura Peninsula

A flight of five marine terraces (labelled I, II, III, IV, and V in order of decreasing elevation and age), comprises much of the surface area of Kaikoura Peninsula (Fig. 9).

Terrace I: Terrace I is preserved in the central, highest part of Kaikoura Peninsula, at elevations of 95–108 m. Limestone underlies the terrace in this area, and two shallow, closed depressions (dolines) appear on the terrace surface. The terrace surface is tilted down to the northwest. An auger hole at Loc. 17 (Fig. 9) penetrated 5 m of mottled, weathered loess overlying 0.5 m of weathered sand and >2 m of pebbly, shelly sand. Mollusca from this auger hole are discussed below. The loess is subdivided into three units on the basis of weathering characteristics, interpreted as three periods of loess accumulation separated by periods of pedogenesis.

Terrace II: This terrace surrounds Terrace I and is also down-tilted to the northwest. It occurs at a maximum height of c. 83 m to the east of Terrace I and c. 75 m to the west. The presence of a low riser across Terrace II to the west of Terrace I suggests it could be further subdivided, and a possible boundary is shown on Fig. 9. The riser cannot be mapped in other places, however, and we consider this riser a secondary feature, perhaps related to an individual coseismic uplift event. The terrace surface is often underlain by 2–4 m of weathered loess, in which we recognise three units separated by paleosols. At Loc. 18 (Fig. 9, 10), 2.5 m of loess overlies c. 1 m of rounded quartz gravel, with pebbles 1–3 cm in diameter, interpreted as beach gravel. A similar sequence was obtained at Loc. 16.

Terrace III: Terrace III occurs at elevations of c. 64 m in the eastern part of the peninsula and c. 35–55 m on the western part, illustrating down-tilt to the northwest. An auger hole at Loc. 20 (Fig. 10) penetrated 2.2 m of weathered loess, subdivided into upper loess and lower loess by a paleosol. At the basal contact between loess and bedrock, rare rounded polished pebbles, interpreted as of marine origin, were present. Beach gravel is also identified at Loc. 13 and Loc. 14.

Terrace IV: A well-preserved, extensive terrace occurs on the eastern half of the peninsula at elevations of between 46 and 58 m. The terrace surface is underlain by 2.0–2.5 m of weathered loess, but in the basal part of an auger hole at Loc. 19 (Fig. 10), sandy clay of possible estuarine origin was encountered. Two loess units are present at this locality.

Terrace V: This terrace is separated by a low cliff from Terrace IV in the eastern part of the peninsula, at c. 38 m elevation.

Other terraces

A Holocene terrace, which can be subdivided into a number of separate levels, fringes the peninsula. These are discussed in a companion paper (Miyauchi et al. in prep. "Age, height and tectonic significance of late Holocene marine terraces along south Marlborough coast, New Zealand"). Small

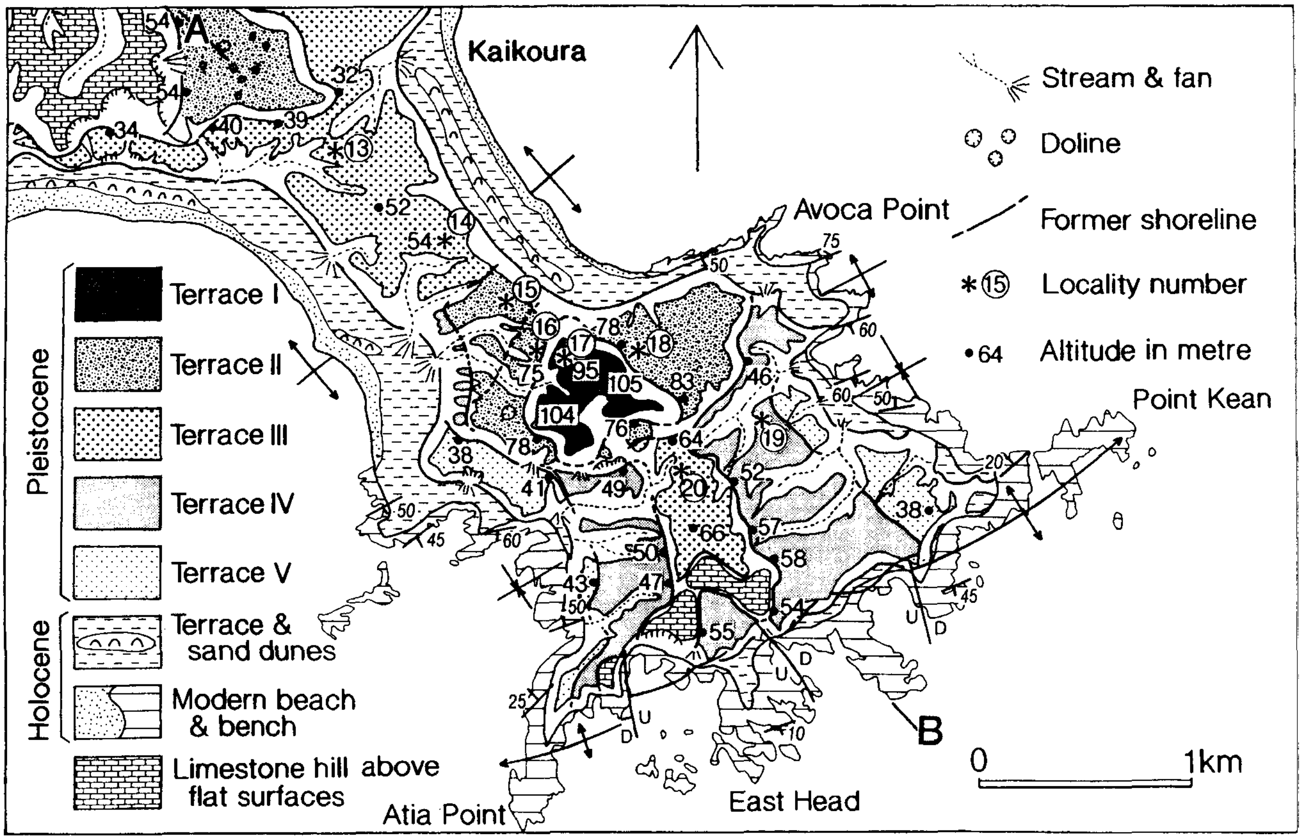


Fig. 9 Distribution of marine terraces on Kaikoura Peninsula. Some terrace height data are omitted in this figure because of the scale of figure. Section line A–B refers to the cross-section shown in Fig. 15. Bedrock structure—folds, faults (with throw indicated by up and down symbols), and dip measurements (numbers in italics)—are from Lensen (1962) and Campbell (1975).

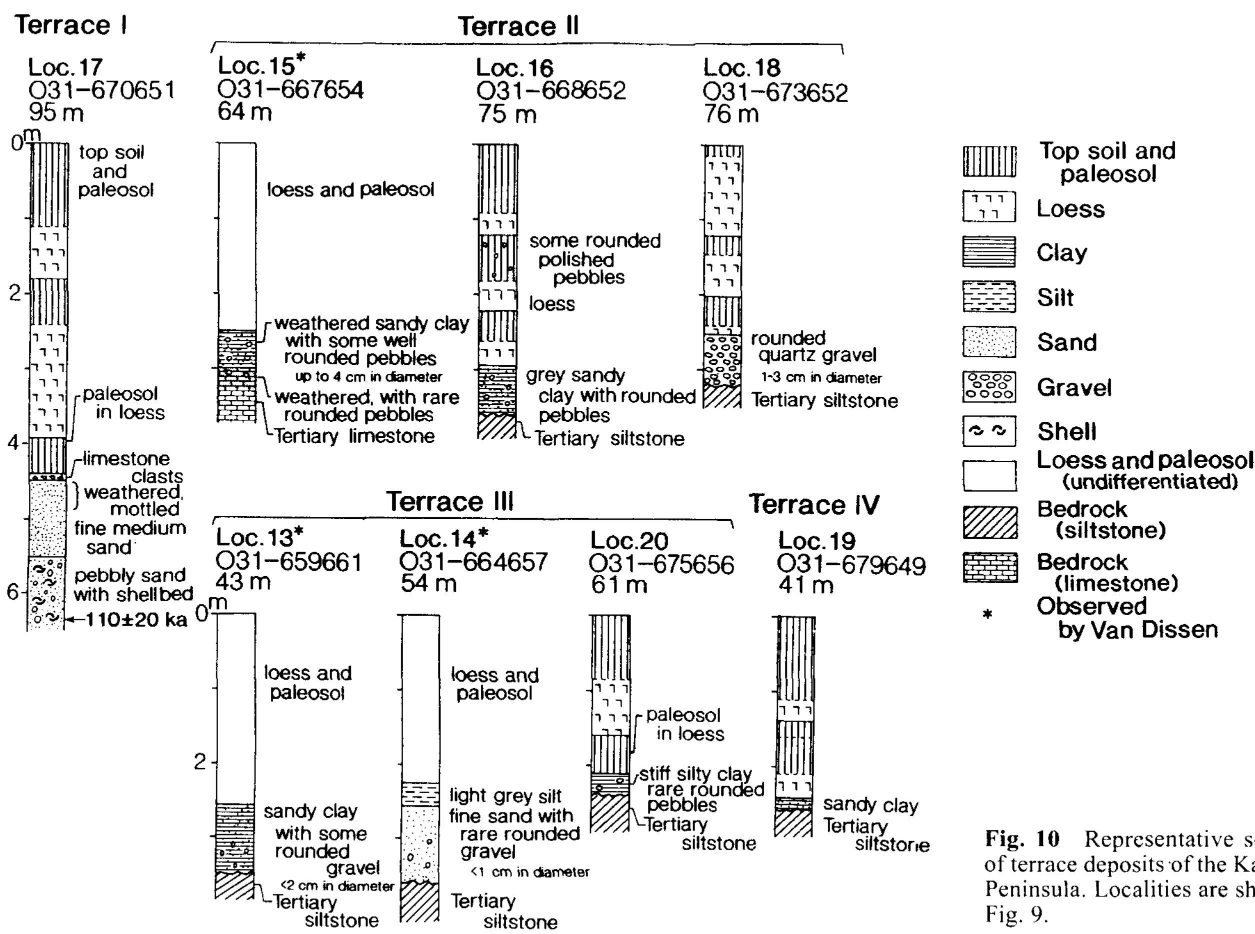


Fig. 10 Representative sections of terrace deposits of the Kaikoura Peninsula. Localities are shown in Fig. 9.

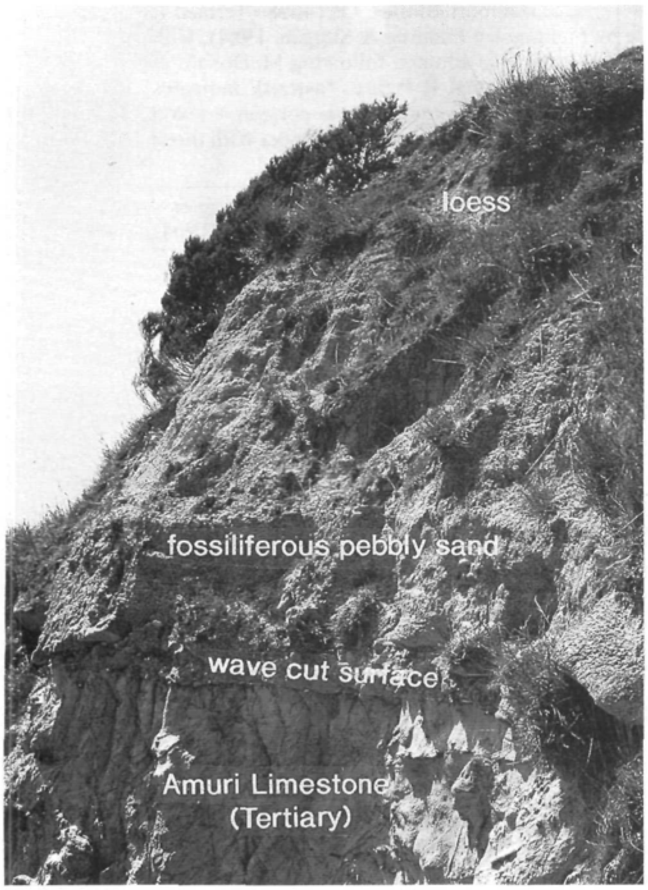


Fig. 11 Marine and terrestrial cover deposits overlying the abrasion platform of the Tarapuhi Terrace at Haumuri Bluffs.

terrace remnants also exist on hilltops to the west of the main highway opposite Kaikoura township at elevations up to c. 108 m. Auger holes penetrated up to 4.5 m of weathered loess overlying bedrock, similar to loess thicknesses of Terrace I on the peninsula, suggesting a similar age for the terrace remnants. No basal marine or fluvial deposits above bedrock were found, thus, we cannot link this area to the marine terrace sequence on the peninsula.

Haumuri Bluffs

At Haumuri Bluffs (Fig. 1) there are two prominent terraces of marine origin. The highest terrace, with an abrasion platform at c. 162 m a.s.l. determined by Ota et al. (1984) (top of marine deposits is 164 m a.s.l. according to Fleming & Suggate 1964), was named the Tarapuhi Terrace by Ota et al. (1984) and was tentatively correlated with the antepenultimate interglacial, following Suggate (1965). The terrace surface is moderately dissected and gently rolling, with, in places, a steep riser along its northern margin down to a lower marine terrace. Beneath the terrace surface there are fossiliferous marine deposits (Fig. 11) previously described by McKay (1877, 1886) and Fleming & Suggate (1964). The marine deposits are c. 2.5 m thick and are capped by loess c. 3.5 m thick. Terrace deposits rest unconformably on Paleocene – Late Cretaceous rocks (Warren & Speden 1977). We re-collected fossiliferous marine deposits from Loc. D (Fig. 1) for environmental interpretation and amino acid dating, the results of which are presented in the following sections.

The lower terrace is at c. 40 m a.s.l., and was named the Amuri Bluff Terrace by Ota et al. (1984). The terrace surface is underlain by c. 3 m of loess, which may be divided into two units by a weak paleosol, and by c. 5 m of marine silt and gravel. The abrasion platform is c. 32 m a.s.l.. The Amuri Bluff Terrace is thus about one-quarter of the elevation of the Tarapuhi Terrace at Haumuri Bluffs, and c. 2 km to the southwest the intermediate level Kemps Hill Terraces are at c. 90 and 110 m a.s.l., or two-thirds the elevation of the Tarapuhi Terrace (Ota et al. 1984, fig. 2, 3).

MOLLUSCAN ASSEMBLAGES AND PALEOENVIRONMENTS

MM (Main Marine) terrace to the north of Clarence River

Mollusca identified by Climo (pers. comm. 1992) from two samples of MM terrace deposits (Loc. 7, Loc. 9, of Fig. 4) are listed and discussed further in Appendix 1. Apart from a small fragment of a bivalve with the external sculpture of *Austrovenus* (the estuarine "cockle"), the samples contain a diverse fauna of terrestrial forest-litter snails. Climo reported that all species present now have a range encompassing eastern Marlborough, where they live today in indigenous forest growing on limestone. This fauna is not inconsistent with an interglacial climate. The matrix of fine sediment, containing many twigs and leaves, and the fragment of *Austrovenus*, suggest that MM terrace deposits were deposited where a quietly flowing forest stream reached the landward margin of an estuary.

Tarapuhi Terrace at Haumuri Bluffs and Terrace I on the Kaikoura Peninsula

Molluscan assemblages and paleoenvironments

The diverse molluscan fauna of the high Pleistocene terrace remnant (Tarapuhi Terrace of Ota et al. 1984) at Haumuri Bluffs has long been well known in Pleistocene paleontology; following initial mentions by its discoverer (McKay 1877; 1886, p. 126), it was discussed in detail, and a fauna of 73 molluscan species was identified by Fleming (in Fleming & Suggate 1964, table 1).

The faunas listed here (Table 1) are from two new collections: (1) re-collection of McKay's Haumuri Bluffs locality (Loc. D, Tarapuhi Terrace, GS14697, O32/f108, grid ref. O32/515505); and (2) a collection from the highest terrace on Kaikoura Peninsula (Loc. 17, GS14698, O31/f431), from a 5–6 m deep hand-augured hole, 20 m south of Lookout Point, at O31/673650, and from Fleming & Suggate (1964).

Fleming (in Fleming & Suggate 1964, table 1) listed a combined molluscan fauna of 73 species in GS158, GS767, GS9014, and GS9015, all from the same locality as GS14697. Of the 73 species, Fleming pointed out that there were only 27 species in their collections, and only 18 of these were in common with McKay's collections. Comparison of our new collection with earlier ones showed that many of the larger species recorded from Haumuri Bluffs are known by only one or two specimens, nearly all present only in GS158. The combined fauna in Table 1 from Tarapuhi Terrace (Loc. D) and Kaikoura Peninsula (Loc. 17) contains

Table 1 Mollusca identified in GS14697 (Tarapuhi Terrace, Haumuri Bluffs), GS14698 (Terrace I, Kaikoura Peninsula), and listed from Tarapuhi Terrace by Fleming (in Fleming & Suggate 1964), with names from Beu & Maxwell (1990); *Mytilus edulis galloprovincialis* adopted following McDonald et al. (1991) and Gardner (1992). Symbols: A = abundant, C = common, R = rare, *asterisk indicates species limited to southern South Island at present; X in Fleming & Suggate (1964) column = taxon present (abundance not recorded); ? indicates uncertainty of identification of Fleming's taxa with those listed here.

	GS14697	GS14698	Fleming & Suggate (1964)
POLYPLACOPHORA			
Leptochiton inquinatus (Reeve)	R		
Leptochiton sp.		R	
**Ischnochiton circumvallatus* (Reeve)	R	R	
Rhyssoplax sp.	R		
Onithochiton neglectus (Rochebrune)	A	C	
?Acanthochitona sp. (decorticated)		R	
BIVALVIA			
Nucula nitidula A. Adams	R	R	X
Pronucula ?certisina (Finlay)	R		
**Austronucula schenki* Powell	R		
Barbatia novaezelandiae (Smith)			X
**Philobrya meleagrina* (Finlay)	C		
modiolus Suter	A	A	X
pinctada (Finlay)	R	R	
?other sp.	R		
Cosa costata Bernard	R	R	X
Verticipronus mytilus Hedley	A	C	
**Lissarca* aff. *pisum* (Suter)	C	R	
*"*Austrosarepta*" *?harrisonae* Powell	C	A	
Mytilus edulis galloprovincialis Lamarck	A	R	X
Aulacomya ater maoriana (Iredale)	C		X
Perna canaliculus (Gmelin)	R		
Chlamys gemmulata (Reeve)	R		
zelandiae (Gray)			X
Tiostrea chilensis lutaria (Hutton)	C		X
Limatula suteri Dall		C	
**Mysella unidentata* Odhner	C	C	
Borniola reniformis (Suter)	R		
* *decapitata* (Powell)	C	R	
**Kidderia (Kidderia)* ?aff. *oblonga* (Smith)	R	R	X
(Costokidderia) costata Odhner	A	A	X
Kellia (Kaneoha) ?minima Ponder	R		
Cyamium (Cyamiomactra) problematicum (Bernard)	R	R	
**Puyseguria* aff. *cuneata* Powell		R	
Lasaea "rubra (Montagu)"	A	C	X
Neolepton antipodum (Filhol)	A	A	X
Mylliteryx parva (Deshayes)		R	
Condylocardia crassicosta (Bernard)	R		X
Purpurocardia purpurta (Deshayes)			X
Cardita aoteana Finlay	R	R	X
Pleuromeris marshalli Marwick		C	
zelandica (Deshayes)	R	R	X
**Gaimardia forsteriana* Finlay	A	C	X
Tellinidae, fragment	R		
Leptomya retiaria (Hutton)	R		
Gari lineolata Gray		R	
Paphies donacina (Spengler)			X
Scalpomactra scalpellum (Reeve)		R	
Tawera spissa (Quoy & Gaimard)	C	A	X
Austrovenus stutchburyi (Gray)			X
Ruditapes largillierti (Philippi)	C	C	X
Protothaca crassicosta (Deshayes)			X
Dosinia sp. juvenile		R	
Hiatella "artica (Linné)"	R	R	
Myadora striata (Quoy & Giamard)			X
Pholadidea suteri (Lamy)	R	R	X
GASTROPODA			
Haliotis sp. fragments	R	R	
Emarginula striatula (Quoy & Gaimard)	R	R	

(continued)

Table 1 (*continued*)

	GS14697	GS14698	Fleming & Suggate (1964)
Sinezona levigata (Iredale)	A	A	X ?
?laquea (Finlay)	R	R	
?lyallensis (Finlay)	R		
Incisura lyttletonensis Hedley	R		
**Cellana strigilis* (Hombron & Jacquinot)	R		
ornata (Dillwyn)	R	R	X
radians (Gmelin)	R	R	X
?flava (Hutton)	R		
stellifera (Gmelin)			X
sp.	R		
Notoacmea cf. *helmsi* (Smith)	R	R	
Zalipais/Liotella, ?2 spp.	A	A	
"*Cirsonella* aff. *parvula* Powell"			X
Brookula (Aequispirella) corulum (Hutton)	R		
**Notesetia* cf. *neozelanica* (Suter)	R	R	
Crossea (Crosseola) sp.	R		
?Lodderia eumorpha (Suter)		R	
?Skeneidae, cf. *Argalista*		C	
Skeneidae, ?aff. *Hyalogyra*, genus 1		R	
genus 2		R	
genus 3		R	
Micrelenchus tenebrosus (A. Adams)	R	C	X
Thoristella chathamensis (Hutton)	C	C	X
Cantharidella tessellata (A. Adams)	C	C	X
Zethalia zelandica (Hombron & Jacquinot), columellae	R	R	X
Calliostoma punctulatum (Martyn)	R		X
cf. *selectum* (Gmelin)			X
Trochus (Coelotrochus) tiaratus (Quoy & Gaimard)		C	X
(Thorista) viridis (Gmelin)			X
Modelia granosa (Gmelin)			X
Nodilittorina cincta (Quoy & Gaimard) (abraded)	R		
Rissoella (Zelaxitas) ?micra (Finlay)	R	R	
Orbitestella sp.	R	R	
**Powellisetia ?porcellana* (Suter)	C	C	
* cf. *gradata* (Suter)	R		
**Eatoniella (Eatoniella) stewartiana* Ponder	A	C	
* *(Albosabula)* cf. *lampra* (Suter)	R		X
* *rakiura* Ponder	C	C	
(Caveatoniella) n. sp. aff. *puniomacer* Ponder	R		
* *(Dardaniopsis)* cf. *aterviscerialis* Ponder	A	C	
* *notalabia* Ponder	A	A	
(Dardanula) cf. *olivacea* (Hutton)	C	A	X
roseola (Iredale)	R	R	
?sp.		R	
Anabathron (Scrobs) hedleyi (Suter)	A	A	
Merelina maoriana Powell	A	A	X
Pisinna impressa (Hutton)	R	C	
*? ?aff. *micronema* (Suter)	R		
rekohuana (Powell)	A	A	X
semisulcata (Hutton)	R	R	
?subfusca (Hutton)	R	R	
Onoba foveauxana (Suter)	A	A	X
?insculpta (Murdoch)	A	A	
?other spp.	A	A	X ?
?Ovirissoa n. sp.? A	R	C	
n. sp.? B	R		
**Pusillina (Haurakia) huttoni* (Suter)		R	
**Rufodardanula (Tubbreva) exigua* (Ponder)	R	R	
Caecum (Fartulum) digitulum Hedley		R	
**Stiracolpus symmetricus* (Hutton)	C	R	X
Maoricolpus roseus (Quoy & Gaimard)	R		X
Sigapatella novaezelandiae (Lesson)	C	R	X
Crepidula monoxyla (Lesson)	R	R	
?Proxiuber australe (Hutton) juvenile	R		X
Argobuccinum pustulosum tumidum (Dunker)	R		X
Brookesena neozelanica (Suter)	R	R	
Xymene ambiguus (Philippi)		R	X
aucklandicus (Hutton)	A	C	X

(*continued*)

Table 1 (*continued*)

	GS14697	GS14698	Fleming & Suggate (1964)
huttoni (Suter)	R		
plebeius (Hutton)	R	C	X
pusillis (Suter)		R	
Lepsithais lacunosa (Bruguière)	A	C	X
**Comptella curta* (Murdoch)	C	R	X
* *devia* (Suter)		R	
?other sp.		R	
Buccinulum littorinoides (Reeve)	C	R	X
* *pertinax finlayi* Powell	R	R	X
Cominella (Cominella) adsepersa (Bruguière)			X
**Cominella (Eucominia) nassoides* (Reeve)	R		X
Austrofusus glans (Röding)	R		
**Zemitrella sulcata* (Hutton)	C	R	X
**Paxula transitans* (Murdoch)	C	C	X ?
Amalda (Baryspira) australis (Sowerby)			X
**Aoteatilia substriata* (Suter)	R	C	
**Haloginella albescens* (Hutton)	R	R	
Neoguraleus sp.	R	R	
Aoteadrillia wanganuiensis (Hutton)	R	R	X
**Comitas trailli* (Hutton)	R		X
Antimelatoma buchanani (Hutton)			X
Duplicaria (Pervicacia) tristis (Deshayes)	R	R	X
Acteon sp. juvenile		R	
*?*Odostomia* sp. A - ?*murdochi* Suter	C		
*? sp. B - ?*acutangula* Suter	R		
*? sp. C - ?*vestialis* Murdoch	C	A	
**Evalea sabulosa* (Suter)	C	C	
* ?*liricincta* (Suter)	R		
Chemnitzia, 2 spp.	R	C	
Linopyrga rugata (Hutton)	R	R	
?*Gumina* sp.	R		
?*Terelimella* sp.		R	
?*Syrnola* sp.	R		X
Triphoridae, fragment	R		
Benhamina obliquata (Sowerby)			X
Siphonaria aff. *zelandica* (Quoy & Gaimard)			X

143 species (117 from Loc. D), but the following 19 species present in Fleming's list are not present in either of the new collections: *Barbatia novaezelandiae*, *Modiolus* cf. *areolatus*, *Chlamys zelandiae*, *Purpurocardia purpurata*, *Austrovenus stutchburyi*, *Protothaca crassicosta*, *Paphies donacina*, *Myadora striata*, *Cellana stellifera*, *Trochus viridis*, *Calliostoma selectum*, *Cirsonella* aff. *parvula*, *Turbo granosus*, *Xymene ambiguus* (present in GS14698), *Cominella adspersa*, *Amalda australis*, *Antimelatoma buchanani*, *Benhamina obliquata*, and *Siphonaria zelandica.* The recorded combined fauna therefore totals 162 species. Almost all the new additions recorded are "micromolluscs" (under c. 5 mm long), extracted by long-continued sorting of sievings from the relatively large samples of c. 2 kg of sediment from each locality. This fauna is most unusually diverse for a New Zealand Pleistocene terrace fauna.

In addition to Mollusca, the sample from Loc. D contains the following taxa (none are present in the augured sample from Kaikoura Peninsula): Crustacea, a few crab "fingers", common barnacle plates, and whole shells of *Eliminius*; Echinoidea, small spines common; Polychaeta, spirorbid tubes common, a few larger tubes; Brachiopoda, *Tegulorhynchia nigricans* common, *Terebratella sanguinea* rare; Vertebrata, a few fish otoliths and dermal spines.

Comparison of faunas

The two faunas listed in Table 1 are remarkably similar in preservation, in their dominant species of large molluscs, in their very high diversity and taxonomic content of micromolluscs, and in overall appearance. They likely demonstrate that the two terrace remnants are of similar or identical age and environment of deposition. The most striking aspect of the initial appearance of both bulk samples was their remarkably low diversity of larger molluscs. Both are dominated by the gastropods *Lepsithais lacunosa* and *Buccinulum vittatum*, oysters (*Tiostrea*), fragments of mussels (mostly *Mytilus*), and the venerid bivalves *Ruditapes* and *Tawera*. A few smaller molluscs (*Xymene aucklandicus*, *Cantharidella tessellata*, and *Micrelenchus tenebrosus*) are also common, but all other molluscs >5 mm across are uncommon to rare in both samples. However, both have a very diverse molluscan microfauna, and some small taxa in both samples are much more abundant than any larger taxa (particularly *Onithochiton*, *Philobrya*, *Verticipronus*, *Lissarca*, *Costokidderia*, *Lasaea*, *Neolepton*, *Gaimardia*, *Sinezona*, *Liotella*, *Eatoniella* (numerous species), *Pisinna*, *Onoba*, *Evalea*, and *Odostomia*). No other New Zealand terrace fauna has been reported with such a diverse microfauna (perhaps reflecting preservation of micromolluscs in an unusual lime-rich matrix), and the ecological and temperature conditions indicated by the fauna can be confidently inferred. The identifications of micromolluscs presented here are preliminary.

Depositional environment

The common species of larger gastropods, some of the less common ones such as *Haliotis*, limpets and *Argobuccinum*, all the common, diverse rissooids, the chitons, the common larger epifaunal bivalves, and most of the common small bivalves are intertidal to shallow subtidal inhabitants of exposed rocky shores, and many of them are common today along the Kaikoura coast. However, the common larger infaunal bivalves do not inhabit rocky shores; *Ruditapes largillierti* burrows in soft sediments in enclosed bays or near the mouths of estuaries, where salinity is lower than oceanic, and *Tawera* is widely distributed in soft substrates on the shelf, extending down from very shallow subtidal depths. In contrast, those infaunal bivalves that are limited to exposed rocky shores at present (*Protothaca* and *Pseudarcopagia*, burrowers in gravel; nestlers such as *Irus*) are rare in these faunas or have not been collected. Many other common taxa in both samples, both large and minute species, live today on or in soft substrates on the inner shelf. These include the nuculids, *Limatula*, *Pleuromeris*, *Scalpomactra*, *Stiracolpus*, *Austrofusus*, and the columbellids, turrids, and pyamidellids. The rock-boring pholad *Pholadidea* occurs in both samples, and a few specimens in each sample represent sandy ocean beach taxa (*Dosinia*, *Gari*, *Myadora*, *Duplicaria*, and, above all, *Zethalia*, represented only by abraded columellae). The fauna seems to result from contributions from a variety of shallow-water environments. The terrace remnant at Haumuri Bluffs is separated at present from the higher hinterland by a gully and, if the gully was present at the time of deposition of the terrace cover, some of the low-salinity taxa such as *Ruditapes* could have lived in the embayment formed by the drowned gully. Similarly, the small terrace remnant at Kaikoura might, at the time of deposition, have partly enclosed a bay to the north or south of the peninsula. However, some shells were transported a considerable distance from a sandy beach, and a significant proportion of specimens were cast ashore from a soft substrate in c. 5–20 m of water.

Temperature regime

The most surprising aspect of the two faunas is the cold temperature regime they indicate. The 37 taxa marked with an asterisk in Table 1 are known at present only from southern New Zealand, mostly from Foveaux Strait or farther south (Powell 1979) where present-day mean summer surface water temperatures are 12–14°C (Heath 1985, fig 3). Present-day summer surface water temperatures in the vicinity of Kaikoura are 15–16°C (Heath 1985). Fleming (in Fleming & Suggate 1964, p. 354) previously noted that "the whole aspect of the fauna is cool", and this is strongly reinforced by the many new additions.

The two warm-water indicators Fleming thought were present have been deleted through subsequent research and reidentification. The bulk of the fauna is composed of temperate, wide-ranging species that are common today in central and southern New Zealand, from the Cook Strait region to Stewart Island. Even among these "background" taxa, many common in the Haumuri Bluffs and Kaikoura terrace faunas are much more common today in southern South Island and the subantarctic islands than they are as far north as Marlborough (e.g., *Philobrya*, *Cosa*, *Verticipronus*, *Kidderia*, *Sinezona*, *Incisura*, the diverse *Onoba* species, and *Argobuccinum*). The most important component of the faunas, however, are the well-known southern species in the modern fauna, limited today to Foveaux Strait and Stewart Island, most notably *Lissarca pisum*, "*Austrosarepta*" *harrisonae*, *Kidderia oblonga*, *Gaimardia forsteriana*, almost all the many *Powellisetia* and *Eatoniella* species, and *Pusillina huttoni*, *Zemitrella sulcata*, *Paxula transitans*, *Aoteatilia*, *Haloginella albescens*, *Comitas trailli*, and *Evalea sabulosa*. These trends are reinforced by the presence of two cold-water larger species, *Cellana strigilis* and *Cominella nassoides*. The overall nature of the fauna is therefore similar to that living in shallow water at present, no farther north than Foveaux Strait.

Interpretation

The presence of a Foveaux Strait molluscan fauna on terraces at Haumuri Bluffs and Kaikoura Peninsula, implies sea-surface temperatures that at first sight suggest the beach deposits were deposited during a cold, even glacial, period. However, the geomorphological evidence and amino acid epimerisation dating point clearly to deposition during a high stand of sea level within oxygen isotope stage 5. Fleming & Suggate (1964, p. 357) accounted for this apparent anomaly by suggesting that, at the time of deposition, "the sea had begun to retreat significantly from the maximum transgression of the eustatic cycle". While this (inferred to mean global cooling) could well be a contributing factor, the temperature regime was so cold that global cooling after the peak of interglacial conditions would not explain the whole of the anomaly.

The Southland current (Fig. 1, inset) (Heath 1972a) was presumably responsible for transport of the Foveaux Strait molluscan fauna northwards to Marlborough, and cold-water conditions in Marlborough sustained the fauna. This cold-water current flows (during the present interglacial) from Foveaux Strait, northwards east of the South Island, through the Mernoo Saddle (at least in part) and then divides, part heading northeastwards around the southern North Island, and the more relevant part continuing close to shore towards Cook Strait. This nearshore current, coupled with wind-driven surface water currents (Heath 1972b), produces an unusual oceanographic feature of the Kaikoura coast: intense upwelling of deep (cold) water close to shore. Seafloor water temperature within 50 km of Kaikoura is as much as 12°C colder than surface water (Ridgeway 1969; Heath 1972a), so enhanced upwelling compared with the present day is a likely reason for the surprisingly cold faunas. We therefore infer the occurrence of a Foveaux Strait fauna on the Kaikoura coast terraces is the result of stronger Southland current flow through the Mernoo Gap at slightly lowered sea-level conditions, perhaps coupled with more windy conditions, particularly southerly conditions that are known to result in substantial lowering of sea-surface temperatures on the north Canterbury and Marlborough coasts (Heath 1970). Nelson et al. (1993), using ^{18}O data from DSDP Site 594 (Fig. 1), have shown that while surface and bottom water temperatures were up to 1°C warmer during stage 5e than at present (consistent with sea level a few metres higher than present), there was a pronounced cooling during stage 5d (c. 110–115 ka).

AMINO ACID DATING

The extent of amino acid racemisation in fossil proteins has been widely used overseas to determine the ages of Quaternary deposits. Well-preserved molluscs are particularly suited to the technique (e.g., Bowen et al. 1985; Hearty et al. 1986).

We have analysed the extent of racemisation (more correctly epimerisation) of the amino acid isoleucine in the venerid bivalve *Tawera spissa* from two sites in the study area—Loc. 17 (Terrace I, Kaikoura Peninsula), and Loc. D (Tarapuhi Terrace, Haumuri Bluffs). Analyses were restricted to *T. spissa* for two reasons: (1) there are variations in racemisation reaction rates between different shell taxa, and for comparative purposes it is important to use the same taxon; (2) the extent of isoleucine epimerisation in *Tawera* shells from the Wanganui Basin, North Island (Pillans & Sykes unpubl. data), provides a means of calculating numerical ages for the Marlborough sites.

Amino acid data for the Kaikoura and Haumuri Bluffs sites are summarised in Table 2. Analyses were carried out by G. Sykes, University of Wales, using techniques described in Bowen et al. (1985). Ages for the Marlborough sites were calculated by using the 80 ka Hauriri Marine Terrace (Pillans 1983) in the Wanganui Basin as a calibration point, using the amino acid age equation, and Arrhenius equation (Table 2) to allow for differences in long-term temperature history between the two areas. Kaikoura area mean annual temperatures (MATs) are 1–2°C cooler than those of the Wanganui Basin at present (New Zealand Meteorological Service 1983), which means that rates of isoleucine epimerisation are some 20–40% slower at Kaikoura than Wanganui.

The calculated ages for the two sites in the study area are: Kaikoura Terrace I, 110 ± 20 ka; Tarapuhi Terrace, 135 ± 35 ka.

Quoted age uncertainties represent combined analytical uncertainties in D/L ratios in both the Marlborough and Wanganui samples. Also included is allowance for variation of up to ±0.5°C in the long-term temperature difference between Wanganui Basin and Marlborough (±0.5°C ≈ ±10% age uncertainty). Within the quoted uncertainties of the amino acid ages above, correlation of the faunas with either isotope stage 5c or isotope stage 5e is indicated.

THERMOLUMINESCENCE DATING

Principles and procedures

TL dating of loess depends on the premise that the detrital grains contain both a light-sensitive and a light-insensitive TL component, and that the former is largely zeroed by daylight exposure just before deposition. Two dominant influences on the accuracy of TL ages of loess are the extent of zeroing of the light-sensitive TL component and the long-term stability of the total TL signal. Even in grains transported only a few kilometres, most of the light-sensitive TL is usually reduced to zero or a low level (Berger 1990). New Zealand loess has provided accurate dates up to at least 800 ka.

For TL measurements, we prepared polymineral 4–11 μm size fractions for each sample using standard procedures (Aitken 1985). The TL signal arises mainly from the feldspar grains. We calculated equivalent-dose (D_E) values from extrapolations of the beta dose-response curves using the total-bleach (TB) and partial-bleach (R-beta) (PB) procedures (Aitken 1985; Berger 1988; Berger et al. 1992), and plotted D_E against readout temperature (D-T plots). From the D-T plots we estimated a plateau D_E value for use in the age equation. We calculated an effective dose rate for the burial history of the sample from present U, Th, and K concentrations and other data (Berger 1988). A TL age then equals D_E /(effective dose rate). We attempted to eliminate or minimise unstable TL introduced by laboratory irradiations with the use of pre-readout heating at elevated temperatures, storage at 150°C for 4 days being chosen. A rationale for such a choice may be found elsewhere (Berger 1994; Berger & Anderson 1994).

Samples and results

We collected two blocks of loess from relatively unaltered horizons at Loc. 11 (samples CLR-1 and CLR-5 in Fig. 5). Resultant dosimetry, TL data, TL ages, and further details are given in Table 3. An example of the extrapolation of dose-response curves to obtain D_E values is shown in Fig. 12A. The calculation of a TL age depends upon the interpretation of the D-T plots shown in Fig. 12B, C. Consistent with results from our earlier TL dating tests on

Table 2 Extent of isoleucine epimerisation in *Tawera spissa* from Marlborough and Wanganui.

Site	Present MAT[a] (°C)	D/L ratio[b] (±1σ)	Age[c] (ka)
Kaikoura Terrace I (Kaikoura Peninsula)	12.3	0.26 ± 0.01	110 ± 20
Tarapuhi Terrace (Amuri Bluff)	12.1	0.30 ± 0.04	135 ± 35
Hauriri Terrace (Wanganui Basin)	13.5	0.24 ± 0.01	80

[a]Present mean annual temperatures (MATs), based on the period 1951–80 (New Zealand Meteorological Service 1983), with corrections for long-term uplift (Kaikoura) and latitude (Tarapuhi). Estimates based on climate data for Kaikoura and Patea.

[b]D-alloisoleucine/L-isoleucine ratio (G. Sykes pers. comm. 1992).

[c]Ages based on amino acid age equation:

$$\log_e\left(\frac{1+(D/L)}{1-K'(D/L)}\right)-\log_e\left(\frac{1+(D/L)}{1-K'(D/L)}\right)_{t=0}=(1+K').K_L.t$$

where K' = reciprocal of eqilibrium constant = 1/1.3
K_L = forward rate constant for isoleucine epimerisation
t = time

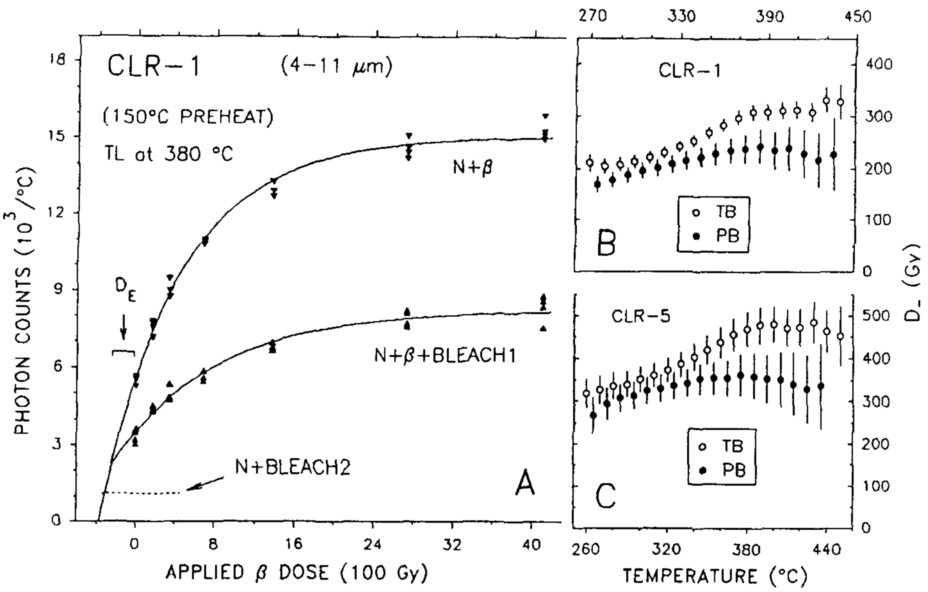
and calibrated to Wanganui Basin (Hauriri Terrace, age = 80 ka, Pillans 1983), assuming long-term temperature differences between Marlborough and Wanganui Basin have been similar to present. Temperature corrections are calculated using the Arrhenius equation:

$$\log_e K_L = A.\exp(-E/RT)$$

where A = Constant
E = Activation energy
R = Universal Gas Constant
T = Temperature in °K

Stated age uncertainties represent the combined analytical uncertainties (±1σ) in both Marlborough and Wanganui samples, plus allowance for variations (±0.5°C) in long-term temperature differences between Marlborough and Wanganui.

Fig. 12 Dose-response curves for loess sample CLR-1, showing determination of an equivalent-dose (D_E) value at a readout temperature of 380°C (**A**), and corresponding D-T plots for the two samples (**B**, **C**). The partial-bleach (PB) method uses intersection of the upper two curves to obtain D_E, whereas the total-bleach (TB) procedure uses subtraction from the upper curve of a light-insensitive residual signal in unirradiated (N) subsamples (N+BLEACH2) to obtain D_E. In B and C, the PB data have been shifted +5°C for clarity. BLEACH1 corresponds to PB and BLEACH2 to TB in Table 3.



known-age loess younger than 150 ka from North Island and other parts of South Island (Berger et al. 1992, 1994), we interpret the PB plateaus as yielding the most accurate D_E values. We do not yet understand the cause(s) of the larger D_E values at the highest readout temperatures of the TB experiments in Fig. 12B, C, though we have speculated on possible causes elsewhere (Pillans et al. 1993; Berger et al. 1994; Berger & Péwé 1994).

We used the PB plateaus, therefore, to calculate TL ages of 66.4 ± 9.7 ka and 108 ± 14 ka for the two loess samples. These age estimates for periods of increased local loess deposition correspond well to the relatively cold oxygen isotope stages 4 (55–75 ka) and 5d (105–115 ka) (Fig. 13). These TL ages also imply that the paleosol at 5 m depth at Loc. 11 (Fig. 5) developed during the relatively warm oxygen isotope stage 5a (75–90 ka), and that the basal fluvial gravels (below 7 m) were deposited just before the older loess, in stage 5d or earlier. Increased loess deposition during stage 5d has been documented elsewhere in New Zealand, in central and western North Island (Alloway et al. 1992; Pillans 1994), and in the Awatere valley in northern South Island (Berger & Pillans 1994).

Table 3 TL dosimetry and ages.

	Samples			
Item	CLR-1		CLR-5	
H_2O[a]	0.175 ± 0.030		0.190 ± 0.030	
K_2O[b]	2.061 ± 0.030	2.079 ± 0.050	2.120 ± 0.030	
C_t[c]	0.635 ± 0.013	0.602 ± 0.013	0.717 ± 0.020	
C_{Th}[c]	0.315 ± 0.44	0.255 ± 0.040	0.287 ± 0.040	
b value[d]	1.15 ± 0.16		0.85 ± 0.13	
Dose rate[e]	3.47 ± 0.17		3.24 ± 0.14	
Bleach[f]	PB(345)	TB(933)	PB(345)	TB(933)
Plateau[g]	330–420°C	370–440°C	310–400°C	370–450°C
D_E (Gy)[h]	230 ± 32	313 ± 20	349 ± 44	472 ± 47
TL age (ka)	66.4 ± 9.7	90.2 ± 7.2	108 ± 14	146 ± 15

[a]Ratio of weight water/weight dry sample, average of collected and saturation values. Here and below errors are ±1σ.

[b](wt%). A second column of K_2O and C data is given for sample CLR-1 to show that the surrounding sediment differs somewhat from the TL sample. These data yield the gamma dose-rate component.

[c](ks^{-1} . cm^{-2}). Total (C_t) and thorium (C_{Th}) alpha-particle count rates from finely powdered samples (Huntley & Wintle 1981). Uranium count rate $C_U = C_t - C_{Th}$.

[d](pGy . m^2). Alpha effectiveness factor (Huntley et al. 1988; Berger 1988).

[e](Gy . ka^{-1}). Calculated with the equations and conversion factors given by Berger (1988), and includes a cosmic-ray component 0.102 ± 0.010 Gy/ka.

[f](J . cm^{-2}). Optical energy fluence for partial-bleach (PB) (wavelengths 435–750 nm passed) and total-bleach (TB) (unfiltered Hg lamp). A heating rate of 5°C/s was used for TL readout under a positive-pressure flow of high purity He in an automated Daybreak Nuclear model 1150 high-capacity reader. TL was recorded with an EMI 9235QA photomultiplier tube behind a 5 mm thick Kopp CS-560 glass filter, which passed wavelengths 360–490 nm (at 10% cut).

[g]Temperature range spanned by recognised plateau in D_E values, including low-end range of 10°C interval of each data point.

[h]Weighted mean ± average error (1σ) over temperature interval in plateau.

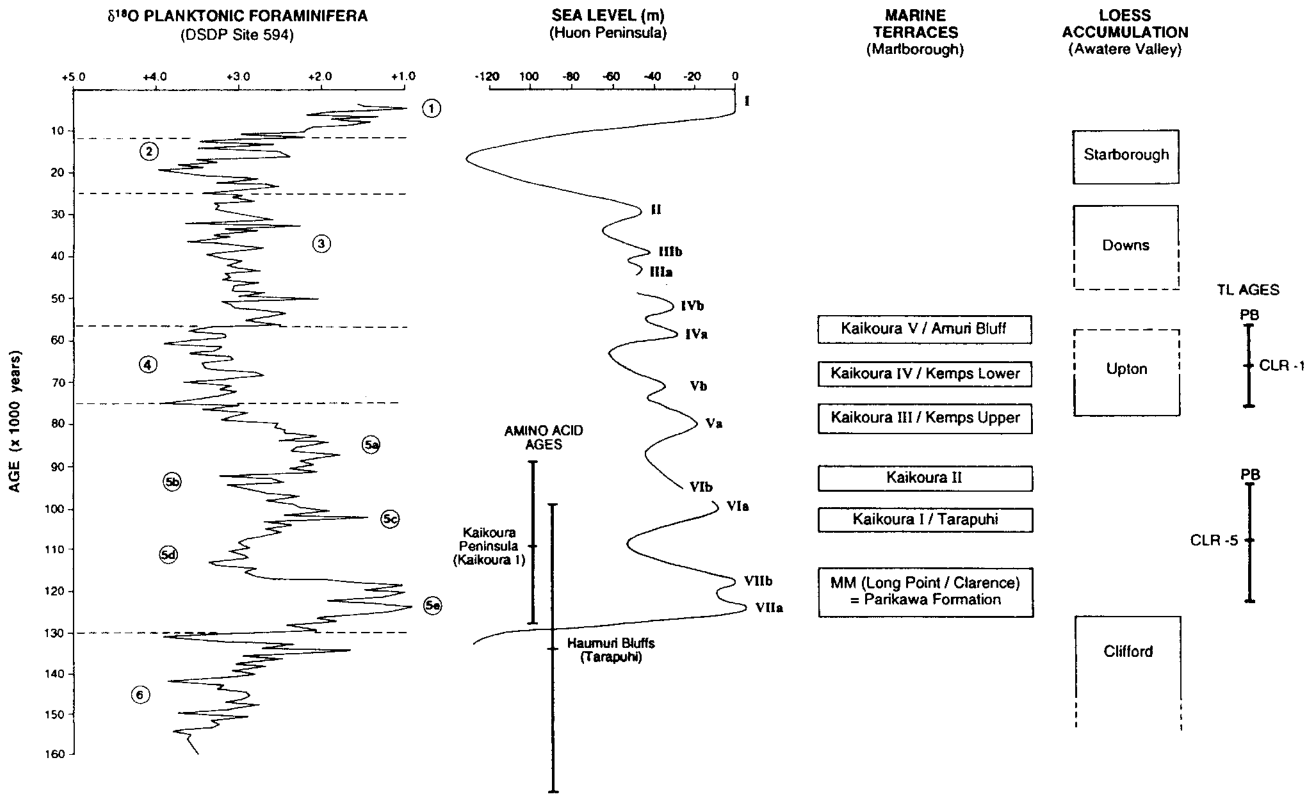


Fig 13 Oxygen isotope variations in planktonic foraminifera at DSDP Site 594 (Nelson et al. 1993). Eustatic sea-level curve from Huon Peninsula, Papua New Guinea (Chappell & Shackleton 1986). Terrace and loess chronology for Marlborough (this work; Eden 1987).

AGE AND CORRELATION OF MARINE TERRACES

Long Point to Clarence River

The main terrace in the Long Point area (MM) and that of the Kekerengu–Clarence area (MM), have the following similar characteristics: (1) they are the major marine terrace in each area, and no younger marine terraces occur below them except for the Holocene terrace; (2) these major terraces are underlain by well-defined beach deposits, which are locally thick (up to 5 m in the Long Point area, and >15 m thick, infilling valleys in the Kekerengu–Clarence area), suggesting that these terraces were formed in association with a sea-level rise; (3) they are covered by similar loess deposits with at least three paleosols at most localities. Therefore, we correlate the MM terraces in both areas, despite different elevations and degree of dissection of the terraces. Because they are the principal marine terraces above the Holocene terrace, they are considered to represent the major sea-level rise of the last interglacial, and are correlated to oxygen isotope substage 5e. MF1 on the north bank of the Clarence River merges downstream with the MM terrace, and thus MF1 probably represents the fluvial terrace that graded to the high sea-level of isotope substage 5e. TL dates in loess overlying the gravel at Loc. 11 support this age. Also the number of loess layers (typically three or four) associated with the MM terrace is consistent with regional stratigraphies of loess overlying last interglacial deposits in the northern South Island and southern North Island.

Judged by elevations within terrace sequences at each locality, we correlate the upper terrace in the Long Point area with UM in the Clarence–Kekerengu River area, and with the penultimate interglacial of oxygen isotope stage 7. The extensive fluvial terrace in the Kekerengu area (the Winterholme Formation of Suggate 1965) does not correlate with marine terraces at any other locality, and is interpreted as a fill terrace related to aggradation during the Otira Glaciation. Correlation of Parikawa Formation with the penultimate interglacial, and of Winterholme Formation with the last interglacial (Suggate 1965), is abandoned.

Kaikoura Peninsula and Haumuri Bluffs

Age estimation of the five marine terraces on Kaikoura Peninsula is particularly difficult from a morphostratigraphic point of view. However, an amino acid age of 110 ± 20 ka for *Tawera* shells from the highest terrace (Terrace I) indicates that it was formed during either isotope substage 5c or 5e (Fig. 13). Based on the dominance of cold-water species in the faunal assemblage, correlation with oxygen isotope substage 5c is preferred.

At Haumuri Bluffs, the Tarapuhi Terrace at c. 160 m a.s.l. was tentatively assigned to the antepenultimate interglacial by Fleming & Suggate (1964). Ota et al. (1984) accepted this correlation, but noted that if the average rate of Holocene uplift (c. 2 m/ka) was extrapolated back in time, then the Tarapuhi Terrace could be as young as the last interglacial (isotope substage 5e). We have calculated an amino acid age of 135 ± 35 ka for *Tawera* shells from

Tarapuhi Terrace, which indicates possible correlation with either substages 5c or 5e (Fig. 13). Based on the similarities between the Haumuri Bluffs and Kaikoura faunas, correlation with substage 5c is preferred. The substage 5e terrace would therefore be expected at higher elevation. We found no remnants of such a higher terrace in the vicinity of Haumuri Bluffs, and we assume that it has been completely removed by erosion.

To illustrate how our data correlate with global records of climate and sea-level fluctuations, we plot, in Fig. 13, oxygen isotope analyses on the planktonic foram *G. bulloides* at DSDP Site 594, 300 km southeast of Kaikoura (Fig. 1), as well as a eustatic sea-level curve from Huon Peninsula, Papua New Guinea, for the past 160 000 years. Isotopic variations in the forams are largely caused by a combination of ice volume (sea level) and sea-surface temperature changes. Accepting that 10 m sea-level lowering equates with 0.1‰ enrichment in ocean water $\delta^{18}O$ (Shackleton & Opdyke 1973), and accepting a sea-level fall of 9 m at substage 5c compared with the present day (equivalent to 0.09‰ enrichment), and a mean isotopic enrichment of c. 1‰ for isotope substage 5c relative to Holocene values (Fig. 13), then the c. 0.9‰ must represent sea-surface temperature lowering in substage 5c. Thus, sea-surface temperatures of c. 4°C cooler (0.24‰ is approximately equivalent to a 1°C shift in temperature) are predicted for substage 5c. Such cooling is consistent with the presence of cold-water, Foveaux Strait faunas at Kaikoura and Haumuri Bluffs, and consistent with the surface-water temperature differences between the two areas today. Since substage 5e sea level and sea-surface temperatures were probably similar to or slightly higher than present ones (Fig. 13, and see discussion in Nelson et al. 1993), correlation of the Kaikoura and Haumuri Bluffs faunas with substage 5e is considered unlikely. Collections of fossil Mollusca from interglacial terraces elsewhere along the north Canterbury coast do not contain the diversity or micromollusc fauna found at Kaikoura and Haumuri Bluffs, and do not provide a basis for paleotemperature interpretation similar to that presented here. The Holocene fauna obtained from Kaikoura and elsewhere along the Marlborough coast (Miyauchi et al. in prep.) do not indicate cold conditions as observed in the Kaikoura I and Tarapuhi Terrace faunas, although there was little diversity in the Holocene-age samples, which have been collected primarily for radiocarbon dating.

Considering all the evidence, a substage 5c correlation, with an age of 100 ka (Chappell & Shackleton 1986), is adopted for the Kaikoura I and Tarapuhi Terraces.

Age estimations for lower (younger) terraces can be made by assuming constant, or near-constant uplift since 100 ka, and using heights and ages of younger high sea-level events given by Chappell & Shackleton (1986) (Table 4). These terrace ages are shown in Fig. 13, which also shows the major periods of loess accumulation identified by Eden (1987) in the Awatere valley, northern Marlborough. If the Awatere loess chronology is accurate, and representative of the region, then the number of loess layers on the terraces is broadly consistent with their inferred ages.

TECTONIC DEFORMATION OF TERRACES AND ITS IMPLICATIONS

Long Point to Boo Boo Stream

The shoreline height of the main terrace (MM) varies by >20 m over the c. 3 km distance between Boo Boo Stream and Long Point, with maximum elevations at either end of the area (Fig. 2). Although there is poor control on the deformation in an east–west direction, the minimum elevation of the main terrace is in the central part of this area, roughly corresponding to a synclinal axis mapped by Lensen (1962) and Browne (1992), in middle Miocene bedrock (Fig. 1). This suggests deformation of the marine terrace (MM) was probably caused by deformation similar to what has folded the Miocene bedrock, perhaps movement along the north-striking London Hill Fault (Browne 1992) located c. 3 km to the west, or a west-dipping fault located offshore to the east.

Clarence River to Kekerengu River

Elevations of the abrasion platform at the shoreline angle beneath the main terrace (MM) range from 140 m in the south to 105 m in the north. The gradient of northward down-tilting is 3.3 m/km. The gradient of the upper marine terrace (UM), which also decreases in height to the north from 220 to 180 m, is 8.1 m/km (Fig. 14), more than double that of the MM terrace. We consider the upper terrace to be of stage 7 age, somewhat less than twice the inferred c. 125 ka age of the stage 5 main terrace, so there is some suggestion that the deformation rate may have been slower in the past 125 000 years than the preceeding c. 100 000 years. The

Table 4 Best-fit ages for marine terraces at Kaikoura and Haumuri Bluffs.

Terrace		Height (m)	Age* (ka)	Sea level* (m)	Uplift rate (m/ka)	Loess units
Kaikoura	I	105 ± 2	100 ± 5	−9 ± 3	1.1 ± 0.1	3
	II	80 ± 2	96 ± 5	−24 ± 5	1.1 ± 0.1	3
	III	60 ± 2	81 ± 5	−19 ± 5	0.9 ± 0.2	2
	IV	50 ± 2	72 ± 3	−36 ± 5	1.2 ± 0.1	2
	V	40 ± 2	59 ± 3	−28 ± 3	1.2 ± 0.1	2
Tarapuhi		165 ± 2	100 ± 3	−9 ± 3	1.7 ± 0.1	?
Kemps Upper†		110 ± 2	81 ± 3	−19 ± 5	1.6 ± 0.1	?
Kemps Lower†		90 ± 2	72 ± 3	−36 ± 5	1.8 ± 0.1	?
Amuri Bluff		37 ± 2	59 ± 3	−28 ± 3	1.1 ± 0.3	2?

*Ages and sea-level heights from Chappell & Shackleton (1986).
†These terraces do not occur at Haumuri Bluffs itself, but are increasingly prominent from c. 2 km to the southwest.

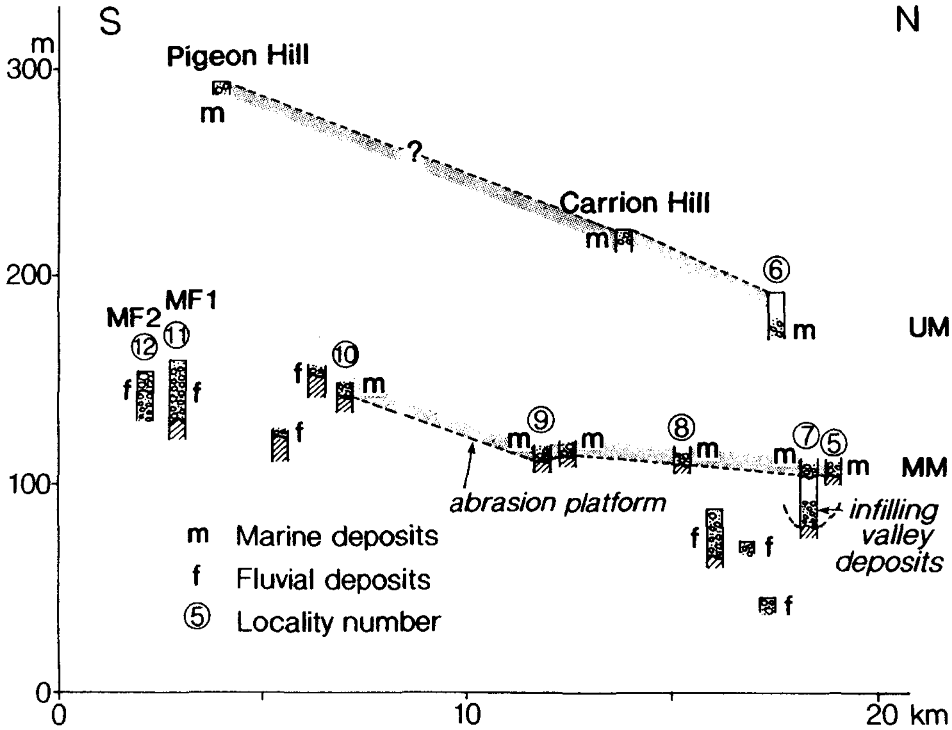


Fig. 14 Shore-parallel profile of marine and fluvial terraces from the Clarence River to Woodbank Stream.

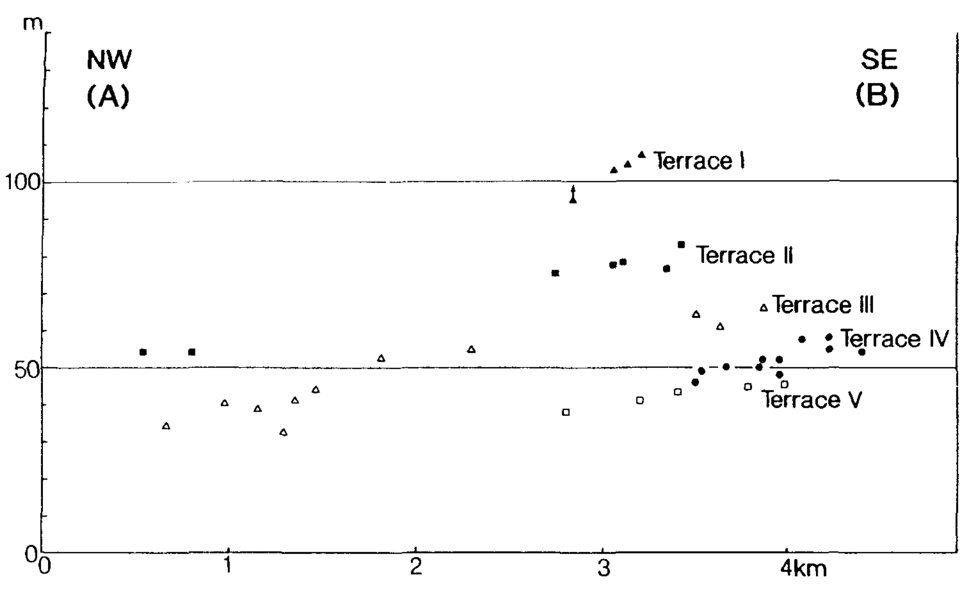


Fig. 15 Projected profile of marine terrace elevations on Kaikoura Peninsula, illustrating northwestward down-tilting. See Fig. 9 for location of cross-section.

observed tilt is only a component of the deformation because the coastline provides only a one-dimensional profile. The apparent down-tilt is towards, but oblique to, the Kekerengu Fault, but limited preservation of terraces south of the Clarence River, and the one-dimensionality of the profile, precludes differentiating between deformation caused by block tilt between the Hope and Kekerengu Faults or faulting and folding on other structures between the major strike-slip faults (Fig. 1).

Kaikoura Peninsula

The shape of Kaikoura Peninsula, and the preservation of marine terraces over a large part, allow an estimation of the total deformation pattern, not just a component of the deformation that is possible on linear sections of coastline. Estimation of the tilt direction from shoreline angle heights of each of the terraces suggests down-tilt in a direction of 315 ± 10°. This direction is parallel to the long axis of the peninsula, and the progressive nature of the tilt is illustrated in Fig. 15, which shows terrace surface elevations projected to this section line. The tilt of Terrace I is 20 m/km, although this is estimated from a section length of only c. 0.3 km. The tilts of Terraces II, III, and IV are approximately constant at 9 m/km. Our findings are in part consistent with the interpretation by Suggate (1965), who concluded that only the two higher terraces were tilted, and that there was a

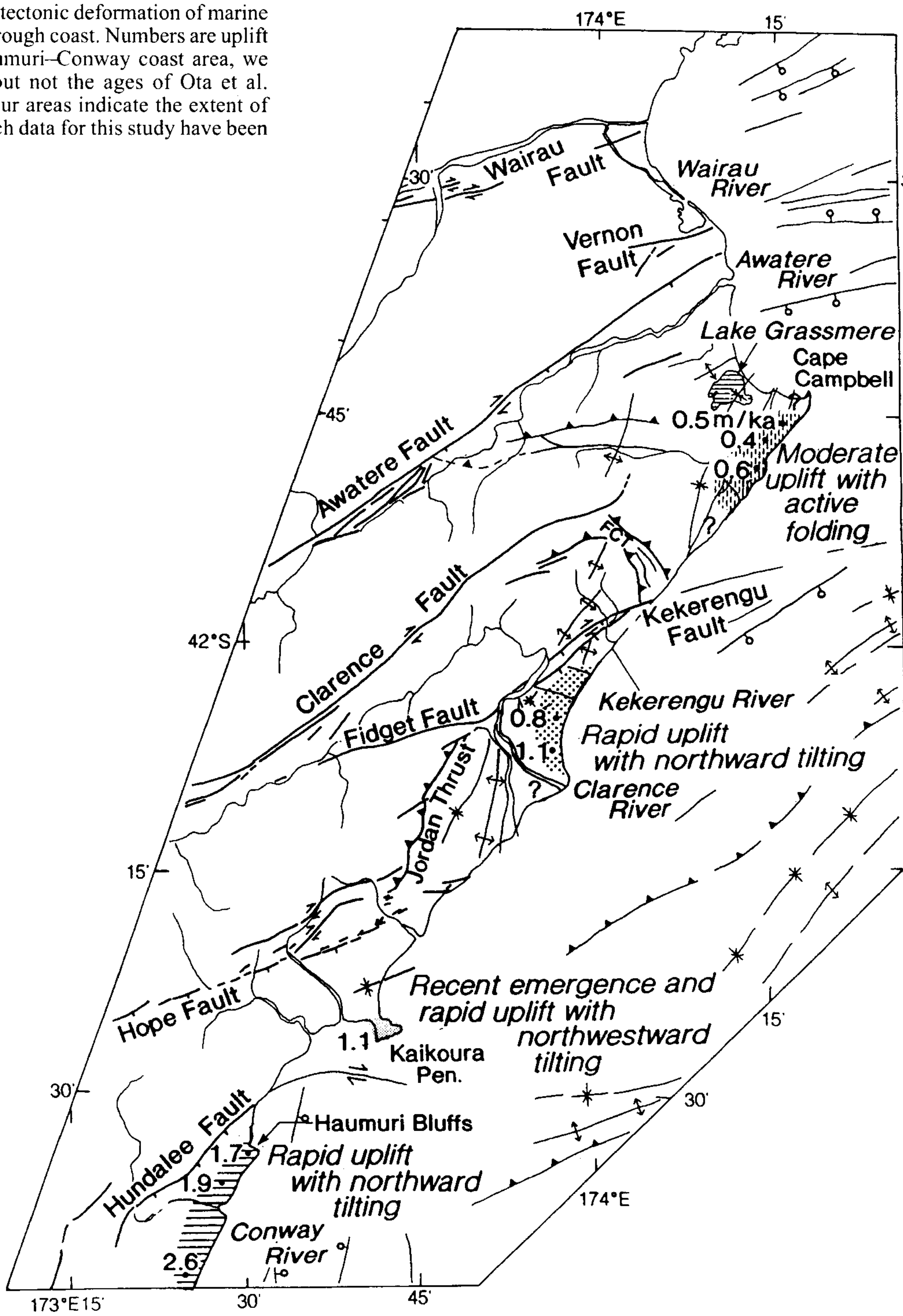


Fig. 16 Summary of the tectonic deformation of marine terraces along the Marlborough coast. Numbers are uplift rates in m/ka. In the Haumuri–Conway coast area, we accept the correlations but not the ages of Ota et al. (1984). Fill patterns in four areas indicate the extent of marine terraces from which data for this study have been obtained.

change in the position of axes of warping. Suggate tentatively correlated what we refer to as Terrace I to the penultimate interglacial, and suggested there had been little net uplift in the late Quaternary. Our data indicate much younger ages for the terraces (and thus more rapid uplift rates), and northwest down-tilt of all the terraces, suggesting no change through time in the mechanism or locus of deformation. Near Avoca Point (Fig. 10), McFadgen (1987) estimated a Holocene uplift rate of 1.5 m/ka based on heights and radiocarbon ages of beach ridges—slightly higher, but in broad agreement with our Pleistocene terrace uplift rates (Table 4). A more extensive study of the Holocene marine features along the Marlborough coast (Miyauchi et al. in prep.) also obtained data to indicate Holocene uplift rates of 1 m/ka or possibly more, on Kaikoura Peninsula.

The northwest down-tilt of Kaikoura Peninsula is almost orthogonal to the Mt Fyffe segment of the Hope Fault (Van Dissen & Yeats 1991), located c. 9 km to the northwest. Kaikoura Peninsula is also located inboard of a west-dipping reverse fault c. 5 km southeast of the peninsula (Fig. 1), and movement on this fault is inferred to be responsible for uplift and tilting of the peninsula. In contrast to the coincidence in deformation pattern of the interglacial terraces and underlying Tertiary folds near Cape Campbell described above, and the Waipara area (Nicol et al. 1994), there is no such correlation at Kaikoura Peninsula (Fig. 9), where a series of northeast-striking, short wavelength (1–2 km) folds disrupt the Upper Cretaceous – middle Miocene bedrock sequence.

Haumuri Bluffs

Ota et al. (1984) established a northward component of down-tilting along the section of coast from the Conway River to Haumuri Bluffs. Although this study has revised the age estimates of the terraces at Haumuri Bluffs, the terrace distribution and amount of tilt remain the same, but uplift rates have been increased by a factor of three so that late Pleistocene uplift rates are now in close agreement with the Holocene uplift rate. The approximately northward, shore-parallel component of down-tilt of the Tarapuhi Terrace is 8.3 m/km, while that for the Amuri Bluff Terrace is 5.8 m/km. The steeper tilt of the older terrace indicates progressive deformation, perhaps related to rupture of the northeast-striking, southeast-dipping Hundalee Fault (Fig. 1), or of an unnamed fault located c. 4 km offshore of Haumuri Bluffs.

UPLIFT RATES AND REGIONAL CHARACTERISTICS OF MARINE TERRACE DEFORMATION

The general geomorphology of the Marlborough coast from Cape Campbell to south of Kaikoura, and the elevation and distribution of remnants of interglacial marine terraces, shows that the region is uplifted. Deformation of the four areas of interglacial terrace remnants indicates they are on separate structural blocks, although there may well be an unrecognised component of regional uplift common to all areas, driven by shallow subduction beneath Marlborough.

Maximum average uplift rates of presumed isotope substage 5e terraces are 0.6 m/ka in the north near Long Point, and 1.1 m/ka on the north side of the Clarence River. At Kaikoura Peninsula and Haumuri Bluffs, the maximum average uplift rates of the substage 5c terrace are 1.1 m/ka, and 1.7 m/ka, respectively, increasing to >2 m/ka on the south side of the Conway River (Fig. 16). In general, the uplift rates are lower in the north than the south, perhaps consistent with what one might expect from regional uplift related to subduction where the distance from the coast to the trench is larger in the north than in the south. However, the deformation pattern is also suggestive (because of the 5–10 km wavelength of the deformation) of activity on local faults and folds in the upper plate. Nicol et al. (1994) have interpreted the deformation of marine terraces in the Waipara area in the same way. In three of the four areas in our study where the preservation of marine terraces is sufficient to determine a deformation pattern (Long Point, Kaikoura, and Haumuri Bluffs – Conway River), the causative structures appear to be reverse faults either between or to the south of the major strike-slip faults of the Marlborough fault system (Fig. 16). We cannot relate the apparently northward down-tilted Clarence River area sequence of terraces to a particular fault. That area is between the seaward segment of the Hope Fault and the Kekerengu Fault (Fig. 1), but there are also several reverse faults and associated folds within the Cenozoic cover rocks in this area (Fig. 1) that may be still active. Movement on non-emergent reverse faults with growing folds at the surface also need to be considered.

CONCLUSIONS

Remnants of marine terraces that range in age from c. 220 ka (oxygen isotope stage 7) to c. 60 ka (oxygen isotope stage 3) occur in four areas of the Marlborough coast from Cape Campbell to Haumuri Bluffs – Conway River; at Kaikoura Peninsula, five marine terraces are preserved. Using a combination of amino acid dating, recognition of cold-water marine fauna in beach deposits, and loess stratigraphy, we correlate the Kaikoura I (highest) terrace to oxygen isotope substage 5c, with an age of 100 ka. Closely similar marine fauna in beach deposits from the highest terrace at Haumuri Bluffs (the Tarapuhi Terrace of Ota et al. 1984), and amino acid dating of *Tawera* sp. from these beach deposits, also indicate an oxygen isotope substage 5c correlation. The molluscan fauna obtained from the Kaikoura I and Tarapuhi Terraces inhabited the coldest water of any reported New Zealand Cenozoic fossil fauna.

Marine terrace remnants to the north of the Clarence River, named Parikawa Formation by Suggate (1965), are here correlated to oxygen isotope substage 5e of the last interglacial, rather than the penultimate interglacial as Suggate proposed. TL dating of loess supports this interpretation. The extensive terrace named Winterholme Formation at Kekerengu and correlated to the last interglacial by Suggate (1965) is reinterpreted as a last glaciation fluvioglacial terrace graded to a low-stand of the sea. Thus, we abandon the Winterholme and Parikawa Formations and prefer to correlate terraces to the geochronometrically and astronomically tuned oxygen isotope chronology (Fig. 13).

Uplift rates vary from c. 2 m/ka at Conway River to c. 0.5 m/ka in the Long Point area c. 10 km south of Cape Campbell, but individual sections along the coast have been tilted at different rates. The nature of the marine terrace deformation identified in this study indicates that local structures are primarily responsible for uplift, and that in at least three of the four areas, the causative faults are contractional fault/fold structures between, or south of, the major strike-slip faults of the Marlborough fault system. This conclusion is unexpected, considering the high proportion of plate boundary strain that is associated with the Marlborough fault system (Lamb & Bibby 1989), and is different from the Wellington region where Ota et al. (1981) found the strike-slip faults of southern North Island formed the boundaries to blocks on which the marine terraces were tilted and deformed. This conclusion, however, is similar to that of Nicol et al. (1994) for the Waipara region of north Canterbury.

Presuming that the middle and late Pleistocene marine terraces are uplifted in discrete steps associated with large earthquakes on active faults, in the same way that Holocene marine terraces have been uplifted along the Marlborough coast, the subsidiary faults and folds between the major strike-slip elements of the Marlborough fault system would be additional sources of major earthquakes. Further work on these structures is required to establish their Quaternary activity and their contribution to the earthquake hazard of the region.

ACKNOWLEDGMENTS

Research funding for this project was made available from a Grant-in-Aid for Scientific Research from the Japan International Scientific Research Program, and from New Zealand Geological Survey (now Institute of Geological and Nuclear Sciences). TL dating was supported by grant EAR–9005234 to Berger from US National Science Foundation. We thank Pat Suggate, Sarah Beanland, Jane Soons, Len Brown, and Russ Van Dissen for their interest in our work and useful discussions. We thank Canterbury University for permission to use their Kaikoura Research Station as our field base in that area. We wish to acknowledge the assistance of Bruce Marshall (Museum of New Zealand) in identifying marine molluscs and Frank Climo (Museum of New Zealand) in identifying land molluscs. Pat Suggate and Robert Yeats provided thorough and thoughtful journal reviews that have resulted in many improvements to the manuscript.

REFERENCES

Aitken, M. J. 1985: Thermoluminescence dating. New York, Academic Press.

Alloway, B. V.; Stewart, R. B.; Neall, V. E.; Vucetich, C. G. 1992: Climate of the last glaciation in New Zealand, based on aerosolic quartz influx in an andesite terrain. *Quatenary research 38*: 170–179.

Berger, G. W. 1988: Dating Quaternary events by luminescence. *In*: Easterbrook, D. J. *ed.* Dating Quaternary sediments. *Geological Society of America special paper 227*: 13–50.

Berger, G. W. 1990: Effectiveness of natural zeroing of the thermoluminescence in sediments. *Journal of geophysical research 95*: 12375–12397.

Berger, G. W. 1994: Thermoluminescence dating of sediments older than 100 ka. *Quaternary science reviews 13*: 445–455.

Berger, G. W.; Anderson, P. M. 1994: Thermoluminescence dating of an Arctic lake core from Alaska. *Quaternary science reviews 13*: 497–501.

Berger, G. W.; Péwé, X. X. 1994: Chronology of interior Alaskan loess-paleosol deposits by thermoluminescence. *In*: Lanphere, M. A.; Dalrymple, G. B.; Turrin, B. D. *ed.* Abstract of the Eighth International Conference on Geochronology, Geomorphology and Isotope Geology. *U.S. Geological Survey circular 1107*: 28.

Berger, G. W.; Pillans, B. J. 1994: Thermoluminescence dating of a loess-paleosol sequence from Awatere River area, South Island, New Zealand. *Geological Society of America abstracts with program 26 (7)*: A–257.

Berger, G. W.; Pillans, B. J.; Palmer, A. S. 1992: Dating loess up to 800 ka by thermoluminescence. *Geology 20*: 403–406.

Berger, G. W.; Pillans, B. J.; Palmer, A. S. 1994: Test of thermoluminescence dating of loess from New Zealand and Alaska. *Quaternary science reviews 13*: 309–333.

Beu, A. G.; Maxwell, P. A. 1990: Cenozoic Mollusca of New Zealand. Drawings by R. C. Brazier. *New Zealand Geological Survey paleontological bulletin 58*: 518 p., 57 pl.

Bowen, D. Q.; Sykes, G. A.; Reeves, A.; Miller, G. H.; Andrews, J. T.; Brew, J. S.; Hare, P. E. 1985: Amino acid geochronology of raised beaches in south west Britain. *Quaternary science reviews 4*: 279–318.

Browne, G. H. 1992: The northeastern portion of the Clarence Fault: tectonic implications for the late Neogene evolution of Marlborough, New Zealand. *New Zealand journal of geology and geophysics 35*: 437–446.

Bull, W. B. 1984: Tectonic geomorphology. *Journal of geological education 32*: 310–324.

Bull, W. B. 1985: Correlation of flights of marine terraces. *In*: Morisawa, M.; Hack, J. *ed.* Tectonic geomorphology. Boston, Allen & Unwin. Pp. 131–152.

Campbell, J. K. 1975: Field guide to the geology of the coastal section along the south-eastern side of Kaikoura Peninsula. Geological Society of New Zealand tour notes. 7 p., map.

Carter, R. M.; Carter, L. 1982: The Motunau Fault and other structures at the southern edge of the Australian–Pacific plate boundary, offshore Marlborough, New Zealand. *Tectonophysics 88*: 133–159.

Chappell, J.; Shackleton, N. J. 1986: Oxygen isotopes and sea-level. *Nature 324*: 137–140.

Cotton, C. A. 1914: A preliminary note on the uplifted east coast of Marlborough. *Transactions of the New Zealand Institute 46*: 286–294.

Cotton, C. A. 1916: Fault coasts in New Zealand. *Geographical review 1*: 20–47.

Eden, D. N. 1987: Stratigraphy and chronology of Seaview Formation, Awatere Valley, South Island, New Zealand. *In*: Liu, T. *ed.* Aspects of loess research. Beijing, China Ocean Press. Pp. 216–230.

Fleming, C. A.; Suggate, R. P. 1964: The 550 ft raised beach at Amuri Bluff. *New Zealand journal of geology and geophysics 7*: 353–358.

Gardner, J. P. A. 1992: *Mytilus galloprovincialis* (Lmk) (Bivalvia, Mollusca): the taxanomic status of the Mediterranean mussel. *Ophelia 35*: 219–243.

Heath, R. A. 1970: An occurrence of low water temperatures on the north Canterbury coast (note). *New Zealand journal of marine and freshwater research 4*: 223–226.

Heath, R. A. 1972a: The Southland current. *New Zealand journal of marine and freshwater research 6*: 497–533.

Heath, R. A. 1972b: Wind-driven water motion off the east coast of New Zealand. *New Zealand journal of marine and freshwater research 6*: 352–364.

Heath, R. A. 1985: A review of the physical oceanography of the seas around New Zealand—1982. *New Zealand journal of marine and freshwater research 19*: 79–124.

Hearty, P. J.; Miller, G. H.; Stearns, C. E.; Szabo, B. J. 1986: Aminostratigraphy of Quaternary shorelines in the Mediterranean Basin. *Geological Society of America bulletin 97*: 850–858.

Henderson, J. 1924: The post-Tertiary history of New Zealand. *Transactions of the New Zealand Institute 55*: 580–599.

Huntley, D. J.; Wintle, A. G. 1981: The use of alpha scintillation counting for measuring Th-230 and Pa-231 contents of ocean sediments. *Canadian journal of earth sciences 18*: 419–432.

Huntley, D. J.; Berger, G. W.; Bowman, S. G. E. 1988: Thermoluminescence responses to alpha and beta irradiations, and age determination when the high dose response is non-linear. *Radiation effects 105*: 279–284.

Jobberns, G. 1928: The raised beaches of the north-east coast of the South Island of New Zealand. *Transactions of the New Zealand Institute 59*: 508–570.

Kirker, A. I. 1989: The late Cenozoic structure of eastern Marlborough. Unpublished B.Sc. (Hons) thesis, lodged in the Library, Victoria University of Wellington, New Zealand. 75 p.

Lamb, S. H.; Bibby, H. M. 1989: The last 25 Ma of rotational deformation in part of the New Zealand plate-boundary zone. *Journal of structural geology 11*: 473–492.

Lensen, G. J. 1962: Sheet 16—Kaikoura. Geological map of New Zealand 1:250 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

Lewis, K. B.; Bennett, D. J. 1985: Structural patterns on the Hikurangi margin: an interpretation of new seismic data. *In*: Lewis, K. B. *comp*. New seismic profiles, cores, and dated rocks from the Hikurangi margin, New Zealand. *NZOI oceanographic field report 22*. DSIR, Division of Marine and Freshwater Science. Pp. 3–25.

McDonald, J. H.; Seed, R.; Koehn, R. K. 1991: Allozymes and morphometric characteristics of three species of *Mytilus* in the Northern and Southern Hemispheres. *Marine biology 111*: 323–333.

McFadgen, B. G. 1987: Beach ridges, breakers and bones: late Holocene geology and archaeology of the Fyffe site, S49/46, Kaikoura Peninsula, New Zealand. *Journal of The Royal Society of New Zealand 17*: 381–394.

McKay, A. 1877: Report on Kaikoura Peninsula and Amuri Bluff. *New Zealand Geological Survey reports of geological explorations for 1874–1876 (9)*: 172–183.

McKay, A. 1886: On the geology of the eastern part of Marlborough Provincial District. *New Zealand Geological Survey reports of geological explorations for 1885 (17)*: 27–136.

Nelson, C. S.; Cooke, P. J.; Hendy, C. H.; Cuthbertson, A. M. 1993: Oceanographic and climatic changes over the past 160,000 years at Deep Sea Drilling Project Site 594 off southeastern New Zealand, southwest Pacific Ocean. *Paleoceanography 8*: 435–458.

New Zealand Meteorological Service 1983: Temperature normals 1951 to 1980. *New Zealand Meteorological Service miscellaneous publication 183*.

Nicol, A.; Alloway, B.; Tonkin, P. 1994: Rates of deformation, uplift, and landscape development associated with active folding in the Waipara area of North Canterbury, New Zealand. *Tectonics 13*: 1327–1344.

Ota, Y.; Williams, D. N.; Berryman, K. R. 1981: Parts sheets Q27, R27, R28—Wellington. Late Quaternary tectonic map of New Zealand 1:50 000 with notes. Wellington, New Zealand. Department of Scientific and Industrial Research.

Ota, Y.; Yoshikawa, T.; Iso, N.; Okada, A.; Yonekura, N. 1984: Marine terraces of the Conway coast, South Island, New Zealand. *New Zealand journal of geology and geophysics 27*: 313–325.

Pillans, B. 1983: Upper Quaternary marine terrace chronology and deformation, South Taranaki, New Zealand. *Geology 11*: 292–297.

Pillans, B. 1994: Direct marine-terrestrial correlations, Wanganui Basin: the last million years. *Quaternary science reviews 13*: 189–200.

Pillans, B. J.; McGlone, M.; Palmer, A. S.; Mildenhall, D.; Alloway, B.; Berger, G. W. 1993: The Last Glacial maximum in central and southern North Island, New Zealand: a paleoenvironmental reconstruction using the Kawakawa Tephra Formation as a chronostratigraphic marker. *Palaeogeography palaeoclimatology palaeoecology 101*: 283–304.

Powell, A. W. B. 1979: New Zealand Mollusca. Marine, land and freshwater shells. Auckland, Collins. 500 p., 82 pl.

Prebble, W. M. 1980: Late Cainozoic sedimentation and tectonics of the east coast deformed belt in Marlborough, New Zealand. *In*: Ballance, P. F.; Reading, H. G. *ed*. Sedimentation in oblique-slip mobile zones. *International Association of Sedimentologists special publication 4*: 217–228.

Rait, G.; Chanier, F.; Waters, D. W. 1991: Landward- and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand. *Geology 19*: 230–233.

Reay, M. B. 1993: Geology of the middle Clarence valley. Scale 1:50 000. *Institute of Geological and Nuclear Sciences geological map 10*. 1 sheet + 144 p. Lower Hutt, New Zealand. Institute of Geological and Nuclear Sciences Ltd.

Ridgeway, N. M. 1969: Temperature and salinity of sea water at the ocean floor in the New Zealand region. *New Zealand journal of marine and freshwater research 3*: 57–72.

Shackleton, N. J.; Opdyke, N. D. 1973: Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28–238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. *Quaternary research 3*: 39–55.

Suggate, R. P. 1965: Late Pleistocene geology of the northern part of the South Island, New Zealand. *New Zealand Geological Survey bulletin 77*: 91 p.

Van Dissen, R. J.; Yeats, R. S. 1991: Hope fault, Jordan thrust, and uplift of the Seaward Kaikoura Range, New Zealand. *Geology 19*: 393–396.

Warren, G.; Speden, I. 1978: The Piripauan and Haumurian stratotypes (Mata series, upper Cretaceous) and correlative sequences in the Haumuri Bluff district, south Marlborough (S56). *New Zealand Geological Survey bulletin 92*.

Wellman, H. W. 1979: An uplift map for the South Island of New Zealand, and a model for uplift of the Southern Alps. *In*: Walcott, R. I.; Cresswell, M. M. *ed*. Origin of the Southern Alps. *The Royal Society of New Zealand bulletin 18*: 13–20.

Appendix 1

Mollusca from Parikawa locality

A. G. BEU
F. M. CLIMO

Mollusca identified by F. M. Climo from three subsamples of siltstone in P30/f430 (the type locality of Parikawa Formation of Suggate 1965) are listed in Table 5. The three subsamples each consisted of a fist-sized sample of grey sandy mud from discrete stratigraphic horizons at the site shown in the column for Loc. 7 (Fig. 4, 5). The subsamples were disaggregated with hydrogen peroxide and wet-seived, resulting in the three collections listed in Table 5. The collection has been assigned collection number GS14721: all material is now housed in the Museum of New Zealand.

The diversity and number of specimens (18 species, 158 specimens) is enormously high for a New Zealand fossil land snail fauna, other than from limestone caves. The larger taxa (*Rhytida*, *Thalassohelix*, some species of *Flammulina*) are represented by few specimens, fragments, or a juvenile specimen of *Rhytida*, whereas the small taxa are represented by large numbers of complete specimens retaining their colour. Conclusions on habitat and environment of deposition are presented in the main text.

Table 5 Mollusca identified by F. M. Climo in three subsamples of siltstone from P30/f430 (sidestream 300 m south of Trig. 4332, c. 300 m west of Highway 1 and 500 m north of Parikawa Station, grid ref. P30/879031; collected by K. R. Berryman and Y. Ota, 10 December 1989). Numbers of specimens are listed; f = fragment.

Taxa	Subsamples 167/ 1	2	3
Bivalvia			
?Austrovenus stutchburyi (Gray), fragment		1	
Gastropoda			
Hydrocenidae:			
Omphalorissa purchasi (Pfeiffer)	4	13	
Rhytidae:			
Rhytida greenwoodi (Gray), "stephenensis" form		1	
Charopidae:			
Flammulina crebriflammis (Pfeiffer)		2f	
zebra (le Guillou)	1		
Cavellia buccinella (Reeve)		18	
serpentinula (Suter)	2	4	3
subinfecta (Suter)		1	
sylvia (Hutton)		16	2
"Geminoropa" subantialba (Suter)		7	
Huonodon aorangi (Suter)		3	
Mocella eta (Pfeiffer)		7	
Pseudegestula brookesi Dell			f
Thalassohelix igniflua (Reeve)	f	f	f
Therasia zelandiae (Gray)		2+f	
Punctidae:			
Austroiotula arewa Climo, MS		18	
Paralaoma morehu Climo, MS		3	
Punctum lateumbilicata (Suter)	1	34	
Umbilaoma elevata Climo, MS		15	