

DIFFERENTIAL UPLIFT OF MIDDLE AND LATE QUATERNARY SHORELINES, NORTHWEST SOUTH ISLAND, NEW ZEALAND

R.P. Suggate

DSIR Geology and Geophysics, P.O. Box 30368, Lower Hutt, New Zealand

Discontinuous Pleistocene cliff-backed shorelines up to 220 m in altitude, and Holocene shorelines up to 12 m, border much of 125 km of coast from Westport to Hokitika in northwest South Island, New Zealand. The coastal terraces are up to 10 km wide where cut on soft Tertiary sediments but are narrow or absent on gneiss. By analogy with post-glacial shoreline development, Pleistocene shorelines are accepted as having been formed at the times of attainment of high interglacial sea levels. Past intra-regional correlations assumed minimal differential uplift, but, as with glacial outwash surfaces inland, the raised shorelines are deformed by folding. Correlations are helped by the relations of shoreline deposits to glacial outwash gravels in the south, and by a few radiometric, mainly radiocarbon, dates. Correlations with high sea levels of deep-sea Oxygen Isotope Stages are made using the best fits of the altitudes of local sequences of shorelines to the altitudes expected assuming constant rates of uplift for each sequence. Uplift rates are between 0.5 and 0.2 m/kyr, and the uplift pattern substantially matches that of uplift of Miocene to lower Quaternary sediments. The shorelines correspond to high sea levels within Oxygen Isotope Stages 15, 13, 11, 9 (two), 7 (two), 5 (two) and 1.

INTRODUCTION

The northwest of the South Island, New Zealand (Fig. 1), on the Australian Plate northwest of the Alpine Fault, is a region mainly of hard rock ranges separated by depressions filled with Cenozoic sediments. The development of these major topographic elements began in the Miocene, when Paleogene and Late Cretaceous sediments began to be eroded, particularly from the areas where the ranges were to be formed. The result is widespread unconformities beneath Miocene sediments, with some variations in the timing of the beginning of Miocene sedimentation in the depressions. Regional uplift began in the Early Quaternary, accompanied principally by folding. In coastal areas, the climatic fluctuations of the last 0.5 Ma caused glacial advances which resulted in tills and outwash gravels, alternating with interglacial rises of sea level, which resulted in shore platforms and sea cliffs with their associated deposits.

In the south, physiographic and stratigraphic evidence allows the marine deposits to be placed in sequence with deposits resulting from glacial advances that reached to within a few kilometres from the coast (Suggate, 1965, 1985; Suggate and Mildenhall, 1991). In front of the glaciers, aggrading outwash gravel locally overtopped the earlier marine deposits, and as a result the coastal terrace surfaces are not all marine (Suggate, 1965). North of Greymouth the glaciers remained high in the coastal Paparoa Range and the relations of shoreline and fluvio-glacial deposits are not clear. Near Westport some Pleistocene coastal terraces are underlain by fluvial gravels that were deposited as the shoreline prograded westwards (McPherson, 1978), as in Holocene time in the Barrytown area (Suggate,

1989). Accordingly, the altitudes of the terrace surfaces are not the keys to correlation. Nor are surface weathering and soil development, since loess in the south and reworking of dune sand in the north commonly make the surfaces much younger than the underlying deposits. The glacial and marine deposits are identified in lithostratigraphic units; the terraces are morphologic features. Correlation depends greatly on the altitudes of the tops of the marine formations at the former shorelines, usually sea cliffs.

The naming and correlation of the coastal marine formations between Westport and Hokitika by Bowen (1964) relied on mapping by Suggate (1965); the discontinuous sequences were then correlated assuming little variation in altitude along the 125 km of coast. Subsequent detailed mapping led to local nomenclatures (Table 1), especially that of McPherson (1978) for the Westport area. Correlation beyond New Zealand has been based mainly on the alternation of glacial and interglacial deposits in the south, and the inference that the higher deposits in the north also represent interglacial periods (e.g. Nathan, 1975). Ward (1985), assuming a uniform rate of uplift, matched shorelines of the Westport–Charleston sequence with the deep sea Oxygen Isotope Stages. The region is one of active tectonism, as shown inland by warping and faulting of glacial outwash surfaces, with the older surfaces being the more deformed (Suggate, 1987). As discussed below, the assumption of a different uniform rate of uplift for each separate local sequence of terrace deposits is used in inferring substantial variations of rate from one sequence to another. The pattern of differential uplift is compared with that of Late Cenozoic deformation of Miocene sediments. Correlations are made with deep sea Oxygen Isotope Stages for

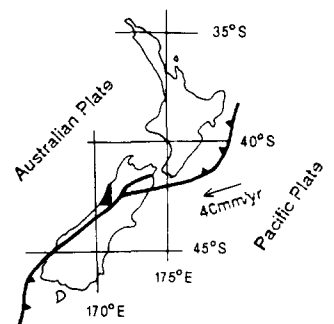
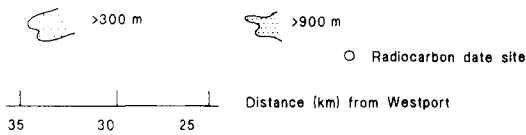
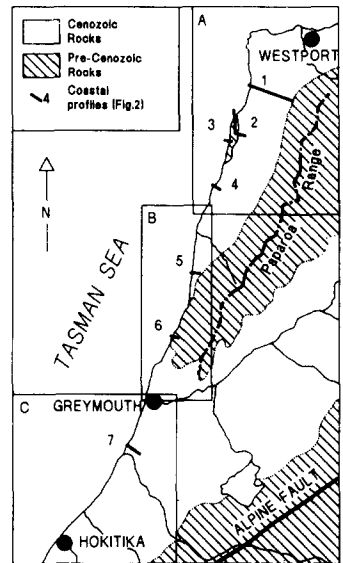
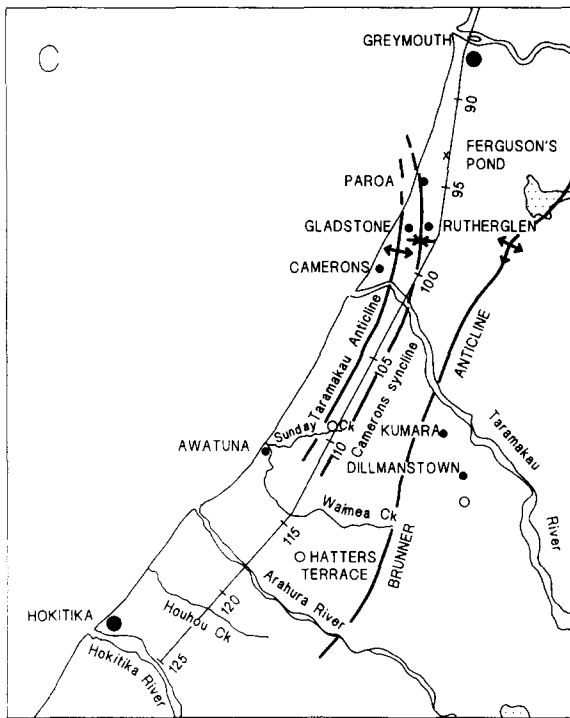
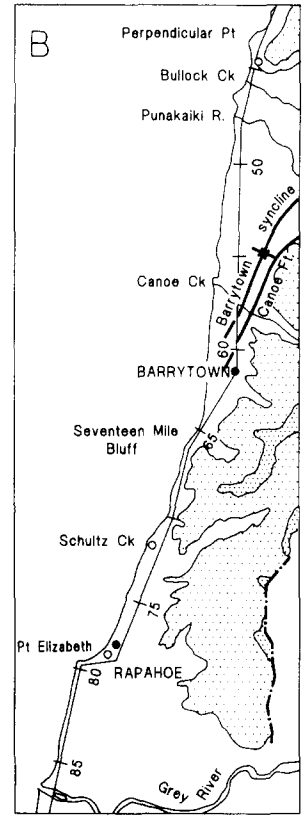
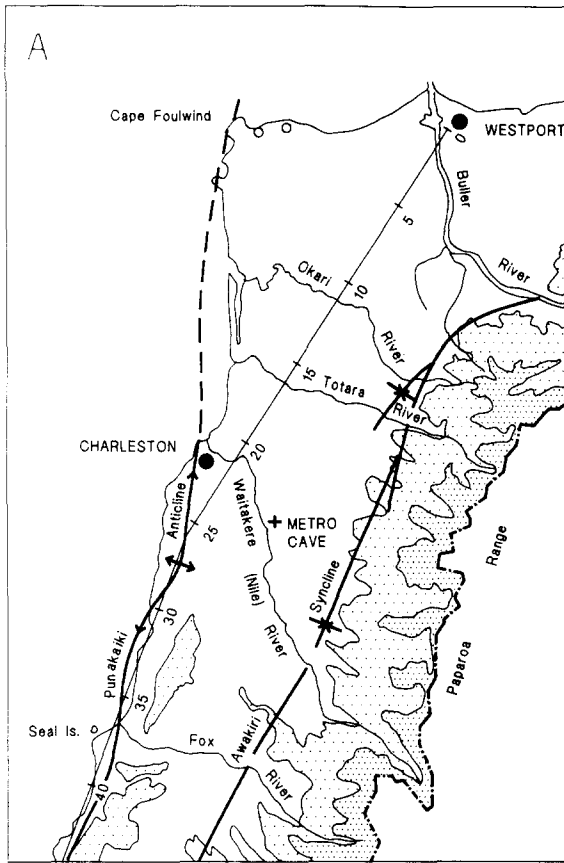


FIG. 1. Locality maps, showing principal structures affecting Late Cenozoic sediments. Positions of coastal profiles shown on Fig. 2, and N-S profile line for raised shoreline interpretation shown on Fig. 3.

TABLE 1. New correlations of sequences of Quaternary raised coastal marine formations, Westport to Hokitika

Westport- Charleston (Bowen, 1964; Suggate, 1965)	Westport (McPherson, 1967, 1978)	South Charleston (Nathan, 1976)	Westport- Charleston (Ward, 1985)	Barrytown Syncline (Laird, 1988)	Schultz CK -Rapahoe (Nathan, 1978)	South Greymouth (Nathan, 1978)	Greymouth- Hokitika (Suggate, 1965)	Greymouth- Hokitika (Suggate, 1985)	Greymouth- Hokitika Stage (This paper)	Oxygen Isotope
Albion	Caledonian*	Candlelight*	Albion-1	Caledonian						15
		Whisky*	Albion-2	Caledonian	Caledonian					13
Karoro	Addison*	Caledonian	Albion-3	Caledonian Whisky Addison	Caledonian Whisky					11
		Virgin Flat					Scandinavia		Scandinavia*	9
Awatuna	1	Virgin Flat								7
		Waites	Karoro							
	2	Virgin Flat + Waites	Awatuna-1	Waites Awatuna	Awatuna	Karoro				
			Awatuna-2							
		Nine Mile*	Nine Mile	Nine Mile	Nine Mile	Nine Mile				5
										5c
										1

*Names recommended for retention.

each main sequence of shorelines, and as a consequence, previous correlations throughout the area are revised.

COASTAL DEVELOPMENT IN THE MIDDLE AND LATE QUATERNARY

The coast from Westport south to Hokitika is substantially parallel to the Late Cenozoic structural trends, but it weaves across the unconformity between hard Paleozoic and Mesozoic basement rocks and the overlying Upper Cretaceous and Tertiary sedimentary rocks. The major contrast in resistance to marine erosion is between the basement and younger rocks, but important differences show among the latter, which vary in lithology from limestone through siltstone and sandstone to conglomerate. As a result, the coast is spectacularly varied in character. Some parts are rocky, particularly those in granite and gneiss; others have low cliffs cut in the harder sediments. Between headlands are straight beaches of sand and gravel. Along many stretches of coast, a narrow coastal lowland is backed by steep high slopes in granite and Paleozoic sediments, by bluffs of Oligocene limestone, or by low hills of Tertiary mudstone. In the north towards Westport, broad raised coastal terraces front the mountains, and in the south between Greymouth and Hokitika, comparable terraces are separated by the valleys of major rivers. Between these two areas the coastal terraces are largely reduced to remnants.

The lithological control on coastal development is illustrated in Fig. 2. Broad shore platforms, covered with marine gravel and sand and now raised to form terraces, were developed with ease across soft Tertiary rocks (Fig. 2, sections 1 and 7). Where the rocks are hard, only narrow discontinuous benches were formed (Fig. 2, section 6). The tendency to straighten coasts had led to accelerated erosion on protruding hard rock areas, but lithological control has dominated over straightening, for example south from Charleston (Fig. 2, section 3).

Along much of the coast, soft Tertiary rocks are exposed to strong wave action resulting from ocean swells driven by westerly winds. In such areas, the initial shorelines that followed the postglacial rise of sea level about 6500 BP (Gibb, 1986) were east of the present shorelines, at cliffs except where rivers reach the coast. During the rapid rise of sea level, the sea was able to continually overtop coastal deposits derived from coastal erosion and carried north from rivers by longshore drift. With stability of sea level, westward progradation and less well marked shorelines resulted from a combination of tectonic uplift and the availability of abundant gravel and sand, as at Barrytown (Suggate, 1989). Coastal erosion is continuing only at hard rock headlands and where the longshore drift bypasses a section of coast, for example in the Rapahoe area where a reef 2 km long extends north from Point Elizabeth. The post-glacial coastal development implies that, for most of the coast from Westport to

Hokitika, Pleistocene cliffs represent shorelines formed at the ends of periods of rapid interglacial rise of sea level.

Deposits on the raised shore platforms consist mainly of gravel, sandy gravel and sand, with coarse cobble gravel common in the shoreline deposits. Ilmenite and other heavy minerals including gold were concentrated close to the former cliffs, forming linear deposits termed 'leads' by the 19th century gold miners. In some places the marine deposits are overlain by lagoonal or estuarine peaty clays suitable for pollen study (Dickson, 1972; Suggate, 1965). No accumulations of drifted tree debris, as on modern storm beaches, have, however, been found, even where shoreline deposits are close to their associated cliffs. Nor are there shells, but these are extremely rare on modern beaches.

PREVIOUS PUBLISHED SEQUENCES AND INTRA-REGIONAL CORRELATIONS

Reconnaissance mapping in the 1960s adopted formation names for the younger marine deposits (excluding those of post-glacial age) in the Hokitika–Greymouth area, and lumped the deposits underlying all the older terraces, known north from Barrytown, in a single formation (Suggate, 1965). In the Westport area, detailed mapping by McPherson (1967, 1978) used local names for the extensive sequence of raised marine and associated dune and fluvial deposits. In regional mapping in the adjoining Charleston area, Nathan (1975) adopted McPherson's formation names, adding two more for high terrace deposits, and his usages were followed by Laird (1988) in the Barrytown area to the south.

For the Greymouth area, Nathan (1978) used names from Suggate (1965) for the younger deposits and his own Charleston names for the older. Ward (1985), in generalising the Westport–Charleston sequence, reverted to the nomenclature of Suggate (1965), despite the work of the intervening years. Suggate (1985) recognised one additional marine formation in the Greymouth–Hokitika area. Table 1 lists the names that have been used for the sequences in the different parts of the region, together with the new age assignments and correlations obtained from the present study. Past intra-regional correlations can largely be inferred from the names themselves. Past age assignments of named formations are principally those shown for the south Charleston area (Nathan, 1976), and for the Greymouth–Hokitika area (Suggate, 1985).

DATA RELEVANT TO CORRELATIONS

Although correlations need to make primary use of the altitudes of the marine formations, and in particular of their shoreline deposits, other direct and indirect evidence are also used. This consists principally of the relations of the marine and glacial deposits, and the independent dating of some deposits.

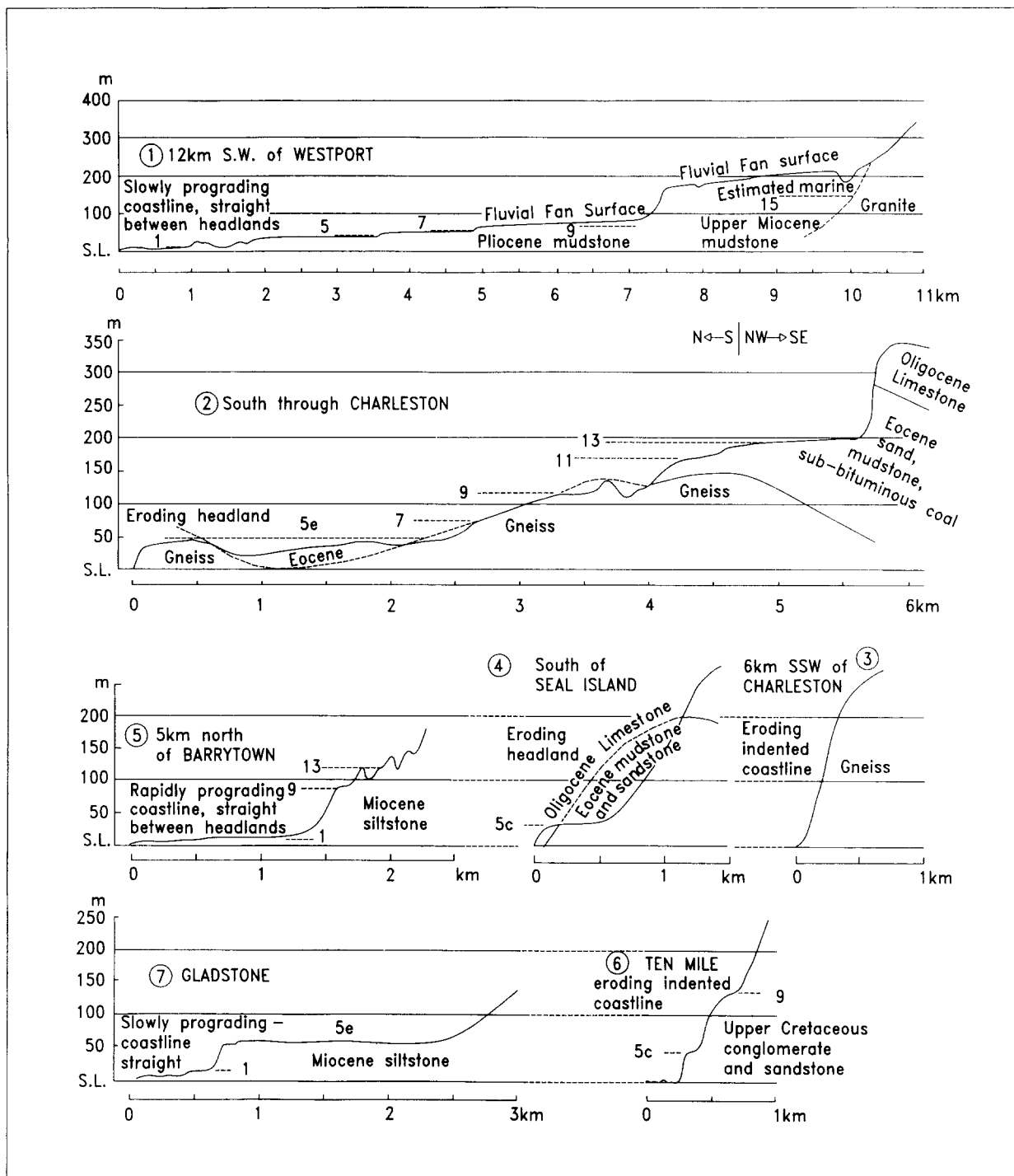


FIG. 2. Coastal profiles (for locations, see Fig. 1), showing that the harder the rock, the steeper is the coastline and the narrower are the Pleistocene terraces. Numbers indicate correlations with interglacial Oxygen Isotope Stages.

Altitudes of Raised Shorelines

Altitude data are of varying quality: from surveys, from aneroid observations and from spot heights and contours on 1 : 25,000 NZMS 270 photogrammetric plots. Especially in the south, some exposures left after gold mining show shoreline deposits close to the bases of former cliffs, where the highest marine deposits are likely to closely record maxima of high sea level episodes. Because of local dense vegetation and a general paucity of exposures at the cliffs themselves, some altitudes were estimated from observations taken

well to the seaward, this being done where gently-sloping shore platforms have been cut across soft Neogene sediments. The data, including some discussion of uncertainties, are incorporated in an unpublished DSIR Geology and Geophysics file, report LD7/834/8.

Evidence of Glaciations in Sequence with Marine Deposits

Between Hokitika and Greymouth, numerous glacial advances reached nearly to the coastlines represented

by the raised marine deposits (Suggate, 1965). The ice volumes of each major advance were broadly similar, and from physiographic and stratigraphic evidence, high sea levels intervened between most glacial advances. Modifications of the sequence were made by Suggate (1985) and by Suggate and Mildenhall (1991). Table 3 shows the presently accepted sequence.

The intervention of episodes of high sea level between major glacial advances has been accepted, since Suggate (1965), as justifying the status of full glaciation for the advances preceding and succeeding the high sea levels. More recently, however, the possibility of the assignment of the Waimea Glaciation to the low sea level episode of Oxygen Isotope Substage 5d (Chappell and Shackleton, 1986) has warranted consideration. Nelson *et al.* (1985) interpreted core from DSDP drillhole 594, Bounty Basin, 300 km east of the South Island, as providing a record of South Island glacial and interglacial episodes back to the Brunhes/Matuyama boundary. Judged by alternations of dark-coloured hemipelagic sediment and light-coloured pelagic ooze, together with mineralogical and Oxygen Isotope changes, an excellent correlation with the Oxygen Isotope Stages was established. The core lacked evidence of glaciation within Stage 5, although core representing part of Substage 5d was not recovered. Core from the adjacent site 594B, however, covered Stage 5d, and neither high resolution carbonate (Cooke, 1988) nor Oxygen Isotope (Cuthbertson, 1988) studies indicated conditions in the cool Substages 5d and 5b comparable to the glacial severity of Stages 6, 4 and 2. Accordingly glaciation in Substage 5d is discounted, and the assignment of the Waimea Glaciation to Stage 6, seem most probable. The maximum advance of the Late Otira (last) Glaciation culminated with the depositional surfaces on the Larrikins Formation ca. 18 ka BP or a little later (Suggate and Moar,

1970; Burrows, 1988). An age of > 32 ka BP (N.Z. 6497) (J.M. Soons, *pers. commun.*) from Hatters Terrace (Fig. 1C) is from 3.8 m below the aggradation surface of Loopline Formation outwash gravel, and the culmination of this glacial aggradation was probably also older than 32 ka BP. No evidence of high sea level is known between the Loopline and Larrikins Formations. These, together with the Moana Formation which represents an important re-advance of the glaciers in the early stages of retreat, are assigned to the Otira Glaciation.

Radiocarbon Ages Associated with Marine Deposits

Problems of contamination of samples with modern carbon, presumably caused by the high rainfalls of the region, are common. Duplicate samples showed widely different dates (Dickson, 1972). Special samples were collected and split, some splits being pre-treated before dating (Grant-Taylor and Rafter, 1971); severe contamination was confirmed. Later, some pollen floras proved irreconcilable if the reported dates had been all accepted (Moar and Suggate, 1979). Recently, Hammond *et al.* (1991) have indicated the need for pre-treatment of samples as young as 10 ka BP in the high rainfall Westland region.

Only determinations of '> . . . BP' can be accepted without the most careful consideration, although young post-glacial samples are likely to be little affected. Acceptable ages of samples closely associated with, usually resting on, marine deposits are listed in Table 2. It seems clear that none of the raised Pleistocene shorelines is within the range of radiocarbon dating.

Dating by Amino-acid Racemization

Two wood samples from the Ferguson's Pond (Fig. 1C) site of Soons and Lee (1984), 6 km south of Greymouth, were assigned ages of 120 ka and 140 ka

TABLE 2. Critical radiocarbon ages associated with marine deposits

Locality	Reference	Date (BP)	Stratigraphic position
Rapahoe	Suggate, 1968	4720 ± 70	Log in estuarine deposits 2 m below top of Nine Mile Formation terrace
3 km east of Cape Foulwind	Nathan, 1976	6330 ± 80	Wood on a one-boulder-thick layer on 3-m shore platform close to post-glacial cliff; Nine Mile Formation
1 km ESE of Cape Foulwind	Grant-Taylor and Rafter, 1971; Moar and Suggate, 1979	>49,400	Wood from peat resting on a one-boulder-thick layer resting on shore platform; Waites Formation
Bullock Creek	Grant-Taylor and Rafter, 1971	>48,600	Peat } From same band on marine gravel;
		>50,900	Wood } Awatuna Formation
Schultz Creek	Suggate, 1965	>42,000	Wood in silt on marine gravel; Awatuna Formation
Sunday Creek	Dickson, 1972	>40,400	Near top } silty peat over Awatuna
		>50,900	Near base } Formation

TABLE 3. Sequence of glaciations and interglacials, Greymouth-Hokitika

Glacial Formation	Glaciation	Interglacial	Marine Formation	Oxygen Isotope Stage
Cockeye	Nemona			10
Tansey	Waimaunga			8
		Karoro	} Scandinavia } } Karoro }	7
Waimea	Waimea			
		Kaihinu	} Rutherglen } } Awatuna }	5
Loopline } Larrikins } Moana }	Otira			
		Aranui (post-glacial)	Nine Mile	1

(with $\pm 30\%$ uncertainty) by Pillans (1990a). The site is closely associated with the maximum sea level represented by the Rutherglen Formation, although it had previously been correlated with the Karoro Formation by Nathan (1978) and Soons and Lee (1984).

Speleothem Dating

Williams (1982) dated 8 speleothems from the Metro Cave, in Ananui Creek, tributary of Waitakere River (Fig. 1A), using $^{230}\text{Th}/^{234}\text{U}$ and, for some, also radiocarbon methods. Although the results were not conclusive, Williams inferred a rate of river downcutting, which he accepted as equivalent to a rate of uplift, of $0.27^{+0.28}_{-0.09}$ m/kyr, over the last ca. 130 ka. Although not well constrained, this rate can be compared with those estimated below.

Pollen Sequences

Several pollen diagrams for organic sediments associated with raised coastal deposits have been published (Dickson, 1972; Moar and Suggate, 1979). Other such sequences have since been collected, and these, as well as sequences in pollen-bearing loessic cover on glacial outwash terraces, are the subject of a study in progress by N.T. Moar. Initial appraisal of the new data by N.T. Moar and R.P. Suggate indicates that the revised shoreline correlations presented in this paper have substantial support, but that some uncertainties remain.

BACKGROUND TO CORRELATION OF PLEISTOCENE SHORELINES

Published Evidence of Middle and Late Quaternary Deformation

General uplift of the region is clear from the preservation of flights of raised marine terraces. McPherson (1978) was the first to clearly document differential uplift within part of the region, citing evidence that several terraces in the Westport-Charleston area are tilted down to the north. Suggate (1987) demonstrated

progressive warping of Larrikins, Loopline, Waimea and Tansey glacial outwash surfaces close to the present coast in the Kumara area, south of Greymouth. The warping is most clearly marked at the Brunner Anticline, the principal fold of the area (Fig. 1C), and was also inferred on subsidiary axes to the east; because of paucity of data points, warping on subsidiary axes to the west was not seen, although it is equally likely. From the altitudes of post-glacial coastal deposits in the Barrytown area (Fig. 1B), Suggate (1989) inferred both general post-glacial uplift and local displacement at the Canoe Fault.

Post-glacial Uplift

From Westport to Hokitika, the altitudes of the highest post-glacial shoreline deposits vary widely. At Cape Foulwind, wood at the shoreline at an altitude of ca. 3 m was radiocarbon dated at 6330 ± 80 BP (Nathan, 1976). In the Barrytown area, Suggate (1989) inferred ca. 8.5 m post-glacial uplift north of Canoe Fault and ca. 11 m south of the fault. At Rapahoe, estuarine deposits at 9 m above m.s.l. are dated at 4720 ± 70 BP (Suggate, 1968). Two closely-spaced post-glacial shorelines south of Saltwater Creek at Paroa are at ca. 12 m and ca. 9.5 m (J.M. Soons, *pers. commun.*), but a short distance to the north and south only the younger one is preserved. The altitudes indicate differential uplift since Mid-Holocene time over the whole region, and particularly high rates of uplift in the south. Uplift of 10 m in 6500 BP gives a rate of 1.5 m/kyr, and if this rate is used back to early Stage 5e, 124 ka ago, the altitude of the interglacial shoreline, when sea level was 6 m above that of the present, would be 190 m. This is 40 m higher than the Tansey glacial outwash aggradation surface north of the Taramakau River (Suggate, 1987), and would place the Otira, Waimea and Waimaunga Glaciations (Table 3) all in the last glaciation (Stages 2 and 4). This is improbable, even if judged only by the need to accommodate 4 or 5 clearly separated major glacial advances within that period, and by the extent and depth of erosion since the Waimaunga Glaciation. Accordingly, the post-glacial rate of uplift is exceptionally high in relation to long-term rates. It may not correspond to the long-term average rate because the time period is short and the interval before the next uplift episode may be long. Thus the apparent post-glacial rate cannot be used for extrapolation back into the Pleistocene.

Did Rapid Tectonic Uplift during Episodes of High Sea Level Produce some of the Pleistocene Shorelines?

Along those parts of the coast that are not subject to net erosion, post-glacial uplift, up to at least 12 m within the last 6500 BP, has resulted in the stranding of the initial shoreline formed on completion of the rise of sea level. In areas favourable to progradation, for example the Barrytown lowland, several shorelines have been stranded at decreasing altitudes from the initial shoreline to the present coast (Suggate, 1989). Where there is a near-balance between erosion and

progradation, the initial post-glacial shoreline may be preserved, but the modern shoreline can be very close; in such places, for example from south Greymouth to Gladstone, a cliff up to ca. 6 m high has been cut in post-glacial marine gravel and sand.

The post-glacial high sea level has already lasted as long as past episodes of high sea level, judged, for example, by Fig. 1 of Chappell and Shackleton (1986). The recorded post-glacial uplifts, known to be substantially greater than are to be expected from the long-term rate of uplift, may be as large as during any single high sea level episode. The altitude differences between successive Pleistocene shorelines are rarely less than 20 m, and accordingly are not likely to have resulted from tectonic uplift during individual high sea level episodes. Accordingly the formation of successive Pleistocene shorelines is attributed to high sea level episodes and not to uplift, consistent with the record of glaciations between the formation of some shorelines between Greymouth and Hokitika.

If the post-glacial uplift is episodic, the timing of an episode of, say, 10 m uplift within a period of 5 kyr could critically affect the match between the altitude of a shoreline and that to be expected from a uniform long-term rate of uplift, making the shoreline altitudes somewhat higher or lower than anticipated.

Calculation of Present Altitudes of Paleoshorelines at Different Average Uplift Rates

Allowance is needed for the exceptionally large post-glacial uplifts when estimating the present altitude of a paleoshoreline. Accordingly, the present local altitude of the post-glacial shoreline is added to the altitude calculated from average long-term uplift rates used for the period prior to the formation of that shoreline.

The calculation of the expected present-day altitudes of paleoshorelines at different average uplift rates is made thus:

$$ALT_p = R \times (A - 5000) + H_p + ALT_{pg}$$

where: ALT_p = present altitude (m) of paleoshoreline; R = uplift rate (m/yr); A = age (yr) of paleosea-level; H_p = height (m) of paleosea-level with respect to present sea level; and ALT_{pg} = present altitude (m) of highest local post-glacial shoreline.

At some places (e.g. Rapahoe) the highest recorded post-glacial sea level is not as old as the attainment of near-stability of sea level, perhaps 6.5 ka, and an age of 5 ka is chosen for use in all paleosea-level calculations; the exact age, were it known, would make little difference.

The adopted heights and ages of paleosea-levels back to 238 ka are adopted from the HP2 curve of Chappell and Shackleton (1986, Fig. 1*). Earlier levels have been assumed from $\delta^{18}O$ minima in the deep sea

record (Imbrie *et al.*, 1984) in comparison with the values for Stage 5. The adopted values are given in Table 4. The older the sea level, the less critical is its height in estimating average uplift rates.

DIFFERENTIAL UPLIFT AND CORRELATION OF SHORELINES FROM WESTPORT TO HOKITIKA

Raised shoreline data are plotted on Fig. 3A–C, which show the substantial breaks between sections of coast with good preserved sequences of terraces. Even within these sections — Westport–Charleston, Razorback Point–Barrytown and Greymouth–Hokitika — terraces are not continuous, either older ones being removed during formation of younger ones or whole sequences being cut out at the main rivers. Accepting that differential uplift may be substantial, the best fits are made between individual local sequences and the calculated altitudes of past high sea levels at inferred individual average uplift rates. The sparse available dating and the relations of shorelines to glacial deposits in the Greymouth–Hokitika area put some constraints on the correlations that result. The adopted rates of uplift, between 0.5 and 0.2 m/kyr, are shown on Fig. 3.

Westport to Perpendicular Point: Fig. 3A

The main coastal terraces and shorelines are preserved from Westport to 4 km south of Charleston (Fig. 2, sections 1 and 2). Uplift to the south, documented by McPherson (1978) south nearly to Waitakere River, is interpreted as continuing south of Charleston where Nathan (1975) mapped the deposits of a single main terrace as representing both Waites and Virgin Flat formations of the Westport sequence. The re-interpretation (Fig. 3A) indicates that both of these formations are present and that Nathan's correlations of higher terrace deposits to the Westport area also need to be changed. At Charleston, the correlations with the deep-sea Oxygen Isotope Stages are the same

TABLE 4. Assumed paleosea-levels and their ages

Oxygen Isotope Stage	Age (ka)	Sea level (m)
Early 15	615	-10
Mid 15	595	-10
Late 15	570	-10
Early 13	500	-10
Late 13	485	-10
11	400	0
Early 9	335	0
Late 9	310	-5
Early 7	238	-15
Mid 7	212	-10
Late 7	198	-10
Mid 6	170	-24
	124	+6
5c	118	0
5c	100	-9
5a	81	-19
Early 3	59	-28
Late 3	53	-30

*Sea levels and ages for reefs VIa and VIa/VIIb are incorrect in Chappell and Shackleton's Table 2. The correct values of -9 m (100 ka) and -52 m (109 ka) were used in their Fig. 1 (J. Chappell, *pers. commun.*).

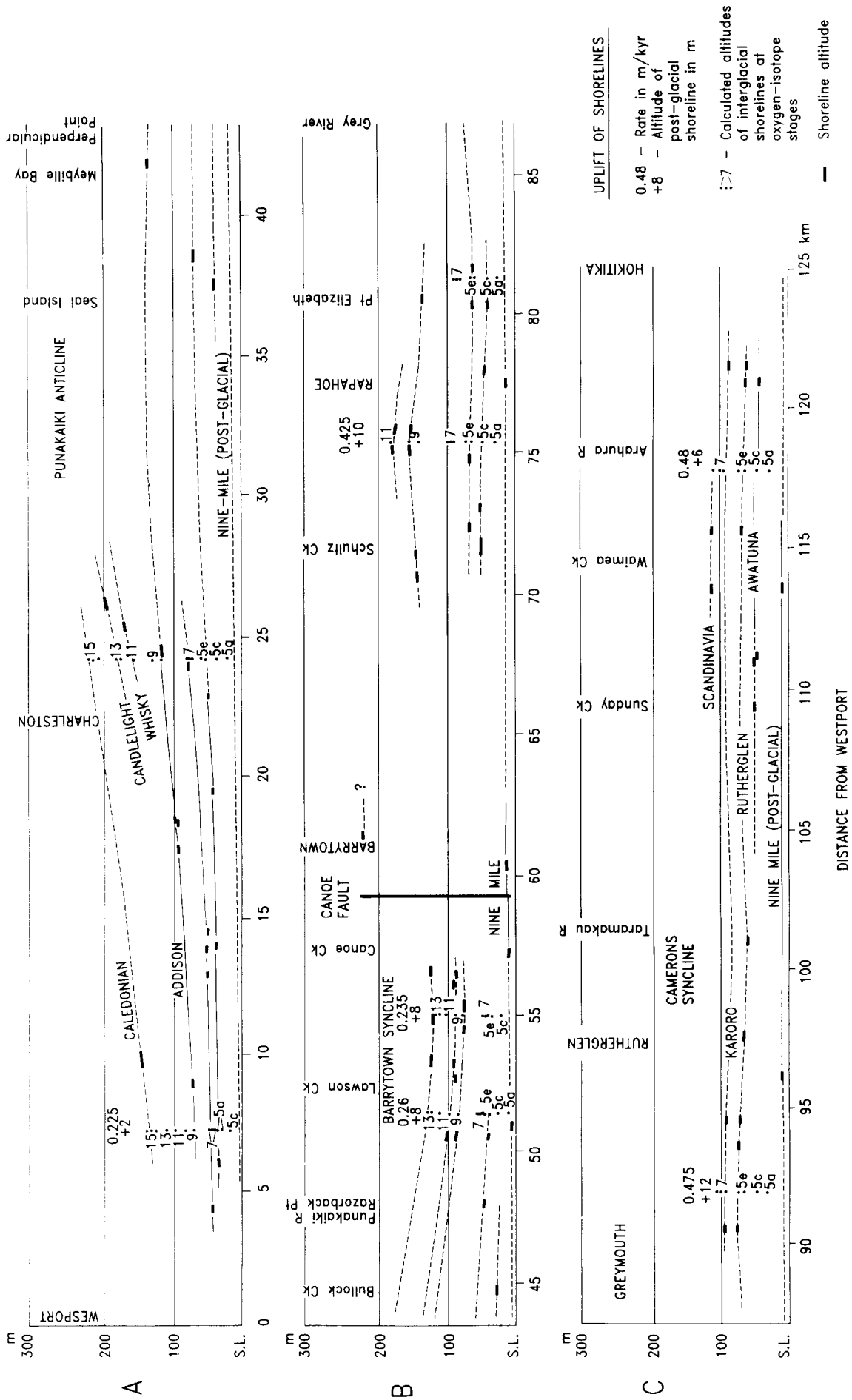


FIG. 3. Altitudes and correlations of raised shorelines, Westport to Hokitika. For profile line see Fig. 1. The revision of correlations leads to the recommendation for the use of the names Nine Mile, Addison, Whisky, Candlelight and Caledonian from the Westport-Charleston area, and Awatuna, Rutherglen, Karoro and Scandinavia from the Grey-mouth-Hokitika area.

as those deduced by Ward (1985), but in his choice of altitude for the terrace he attributed to Substage 5c, Ward ignored the tilt recorded by McPherson (1978), implicitly making correlations between Westport and Charleston that are different from those adopted here. The inferred uplift rate in the Charleston area is ca. 0.35 m/kyr; this compares reasonably well with the rate of $0.27^{+0.28}_{-0.09}$ m/kyr inferred from speleothem dating by Williams (1982).

For nearly 20 km south of the Charleston shoreline sequence, few data are available along a coast that is either rocky and steep, or has been prone to slumping across the terraces. No inferences of uplift rates can be made, and correlations depend on consideration of regional deformation, discussed below.

Perpendicular Point to Seventeen Mile Bluff: Fig. 3B

Rock debris at the foot of steep limestone bluffs masks the inner margin of the coastal terrace at Perpendicular Point. The altitude of the highest marine deposits at this terrace's shoreline must, however, be markedly higher than that of shoreline gravel at the mouth of Bullock Creek. There the marine gravel rests on > 10 m of fluvial gravel and is overlain by non-marine peat, sand and silt; the sequence appears to have resulted from rising sea level followed by regression caused by either falling sea level or uplift. The shoreline altitude is more than 10 m lower than that of the well-displayed deposits of the Razorback Point terrace, resting on a shore platform cut across sandy limestone, only 2.5 km to the south. In between, the Punakaiki terrace, cut across limestone, has its inner margin obscured by dense forest, but is probably the equivalent of the Razorback Point terrace.

The Razorback Point terrace extends only a short distance to the south before being cut out by the post-glacial cliff (Laird, 1988), where soft calcareous mudstone succeeds the sandy limestone of the point. Neither the Razorback Point shoreline nor the Bullock Creek shoreline is represented for 10 km south to Barrytown. Remnants of higher terraces are, however, preserved, correlations being shown on Fig. 2 (section 5) and Fig. 3B. Stage 7 high sea levels appear to be unrepresented, except perhaps by a fluvial terrace on the south side of Canoe Creek. Like the Razorback Point (5e) and Bullock Creek (5c) shorelines, Stage 7 shorelines may have been cut away by post-glacial cliffing. Comparable shoreline changes could account for the absence of a representative of Stage 11.

South of Canoe Fault, the southeast side of which is upthrown by post-glacial faulting (Suggate, 1989), remnants of a terrace of Barrytown are higher than any others in the region.

Seventeen Mile Bluff to Greymouth: Fig. 3B

No terraces are preserved on the steep slopes for 7 km south of Seventeen Mile Bluff, but for 5 km further south there are terrace remnants widely separated in altitude. They are, however, too few to provide a good sequence. Two narrow low benches with marine gravels

up to 46 m and 61 m probably represent substages of Stage 5, and much higher, wider terrace remnants, at ca. 145 m and 170 m, are inferred to represent Stages 9 and 11.

The only considerable step in the coastline normal to its main direction and to that of the regional structural trend is from Rapahoe west for ca. 2 km to Point Elizabeth. At the Point, the main terrace is up to 37 m, and a terrace remnant at 55 m, with marine gravel worked for gold, extends to 1 km south of the Point. These two terraces are correlated with the two low marine benches north of Rapahoe and indicate a westward decline in altitudes, in the direction of dip of the Cenozoic sediments.

Greymouth to Hokitika: Fig. 3C

This section is important for the stratigraphic and physiographic relations of shoreline deposits to glacial outwash gravels. Glacial outwash gravels overlies marine deposits in many areas south of the Taramakau River. In many places some older cliffs and shoreline deposits were removed by the cutting of younger shore platforms. Terrace correlation is further complicated by active folding (Suggate, 1987), with shorelines crossing fold axes in the north of the area. Nevertheless, the sequence of glacial and interglacial formations can be pieced together (Table 3).

Only the Karoro and Rutherglen shorelines are known in the northern part of this section, between Greymouth and the Taramakau River. At the south end of Greymouth, a small step at the seaward edge of the Karoro terrace is interpreted as the Rutherglen shoreline. Close to the Ferguson's Pond site of Soons and Lee (1984) 3 km to the south, marine shoreline deposits ca. 20 m lower than the highest Karoro Formation are correlated with the Rutherglen Formation. At this site, a rich pollen flora indicates interglacial conditions (N.T. Moar *in* Soons and Lee, 1984), and amino-acid racemization ages of 120 ka and 140 ka were reported by Pillans (1990a). The Rutherglen type locality (Suggate, 1985) is ca. 2 km inland from the top of the post-glacial cliff, to the top of which the Rutherglen Formation extends with little change in altitude (Fig. 2, section 7); the lack of seaward slope probably results from the influence of the Camerons Syncline and Taramakau Anticline (Fig. 1C). The Rutherglen Formation is correlated with the higher of the two Substage 5e high sea levels, the lower of these being probably represented by a clear but small step at the seaward edge of the Rutherglen terrace at the top of the post-glacial cliff at Gladstone (Fig. 2, section 7); this step was previously attributed to Awatuna cliffing by Suggate (1965, 1985).

A better sequence is in the south where the shorelines are close enough together to minimise the effects of any possible shore-normal tilting. The sequence is obtained by combining data from marine deposits at or close to old cliffs north and south of the Arahura River. To the north, the Scandinavia, Rutherglen and Awatuna shorelines are present, and

possibly also the Karoro shoreline close to old beach lead workings of unknown altitude, 300 m west of the Scandinavia shoreline north and south of Waimea Creek (Suggate and Mildenhall, 1991). To the south, in the Hou Hou Creek area, the Karoro, Rutherglen and Awatuna cliffs and marine deposits are preserved. The correlations adopted on Fig. 3C — Scandinavia and Karoro formations as early and late Stage 7 and Rutherglen and Awatuna formations as Substages 5e and 5c — are consistent with (a) Awatuna Formation being > 50 ka at Sunday Creek, (b) the intervention of the Waimea Glaciation between the Karoro and Rutherglen Formations, and (c) the lack of known glaciation between the Scandinavia and Karoro high sea levels (Suggate and Mildenhall, 1991).

UPLIFT PATTERN IN RELATION TO REGIONAL LATE CENOZOIC DEFORMATION

In the coastal area from Westport to Hokitika, substantially unbroken sedimentary sequences of Late Miocene to Late Pliocene or earliest Quaternary age are deformed principally by folding, and also by faulting at Canoe Fault. These sequences varied greatly in thickness, and differential uplift has resulted in varying amounts of erosion of the upper sediments. Accurate estimation of long term average rates of uplift is not possible because of this erosion, because the timing of uplift is not accurately known and because the rates may not have been constant over the long term.

Regionally, uplift began after deposition of the Late Pliocene/Early Pleistocene Old Man Group, probably about 2 Ma, but it will have been somewhat earlier or later locally, being influenced by the local structural setting.

The long-term rate of uplift can be approximately estimated at Charleston where Mid-Miocene (Waiauan) rests on Paleogene that includes Eocene coal measures. The depth of burial of Eocene sub-bituminous coal is estimated at 1200 m from Fig. 8 of Suggate (1974), and Nathan *et al.* (1986, column K29/c5) show 350 m for the Paleogene sediments between the coal and the Waiauan. Accordingly, the sub-Waiauan unconformity has been buried ca. 850 m. If uplift began ca. 2 Ma (although it may have been rather earlier at Charleston's position on a principal anticline) a rate of 0.425 m/kyr is indicated, not greatly different from ca. 0.35 m/kyr inferred there from coastal terrace uplift.

In Fig. 4, the altitude of the Stage 5e shoreline is compared with that of the unconformity beneath Mid-Miocene sediments. This unconformity is sub-Waiauan (ca. 12 Ma) north from Barrytown, and somewhat older, sub-Clifdenian (ca. 16 Ma) south from Greymouth; Miocene and Pliocene sediments are not preserved in the intervening 20 km. The general correspondence in the patterns of deformation is striking, indicating progressive and systematic deformation in this region of New Zealand during Quaternary time. The pattern of folding is used to infer

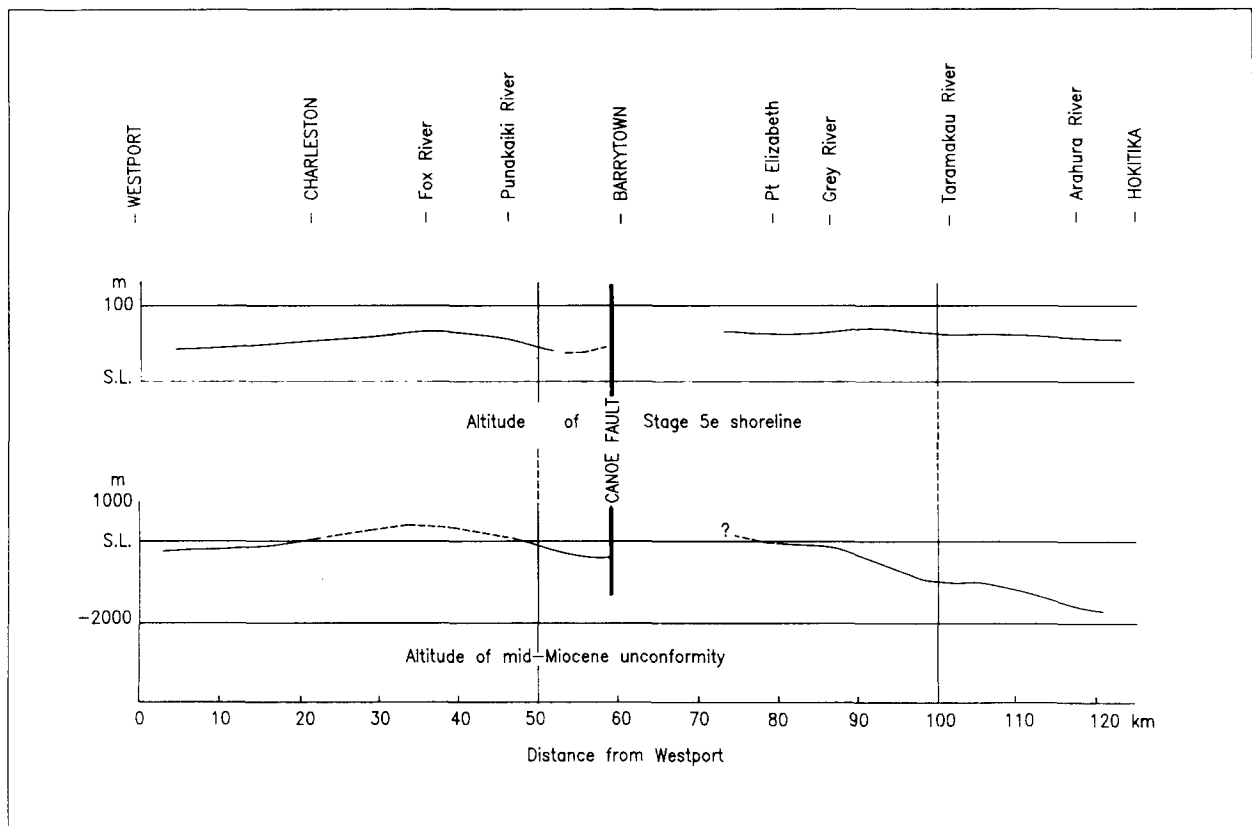


FIG. 4. Comparison of deformation patterns of the Stage 5e shoreline and the sub-Miocene unconformity.

correlations of isolated shoreline deposits, particularly in the Seal Island area and high on the spur south of Meybille Bay (Fig. 3A).

CORRELATIONS

The gaps in continuity of the coastal marine formations from Westport to Hokitika have made uncertain the intra-regional correlations of local sequences. The recognition of differential long-term rates of uplift leads to many changes from past correlations, and with these changes there is an opportunity to use a single set of formation names for the marine deposits, as indicated in Table 1. The higher rate of uplift in the south results in the recognition of formations there that have not been separately distinguished in the north. In contrast, in the north the lower uplift rate and lack of glacial erosion and deposition allow the preservation of older formations. Thus the single set of recommended formation names is drawn from the south for the younger formations and from the north for the older formations.

The inferred correlations with the deep-sea Oxygen Isotope Stages extend back to Stage 15, whereas the well-documented South Taranaki–Wanganui coastal terrace sequence in the North Island, with uplift rates between 0.2 and 0.7 m/kyr, is inferred to extend back to Stage 17 (Pillans, 1990b). Stages 5e and 5c are recognised in both areas, but 5a only in South Taranaki–Wanganui. In place of two Stage 7 shorelines in the Hokitika area, only one — apparently mid or late Stage 7 — is mapped in South Taranaki–Wanganui. At Wanganui, however, Pillans *et al.* (1988) recorded two Stage 7 high sea levels from sedimentation unrelated to the shoreline, inferring them to be early and mid Stage 7; they interpreted the single shoreline as resulting from an early one being cut away by a younger one. In both regions, two Stage 9 high sea levels are accepted, and Stages 11, 13 and 15 are represented by single terraces. In South Taranaki–Wanganui, however, an extra terrace is recorded between Stages 11 and 13. The general similarities between the sequences are to be expected in regions with generally similar inferred rates of uplift.

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