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Glacial geology of the upper Wairau Valley, Marlborough, New Zealand

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Abstract Late Pleistocene glaciers in the upper Wairau Valley deposited four groups of moraines inferred to represent one Waimean ice advance, two Otiran ice advances, and an advance of early Aranuian age. The Waimean and early Otiran glaciers advanced into Tarndale Valley, deposited terminal moraines, and shed outwash down both the Alma River and Travellers Valley. The middle Otiran glacier terminated in northern Tarndale Valley and shed outwash from the southern part of its terminus down the Alma River. The north side of the terminus abutted a large ice-dammed lake in the Wairau Gorge, and fan-deltas graded to an old shore level at an elevation of 1040 m. Well-preserved moraines at the mouths of four glaciated tributaries may be middle Otiran recessional, or late Otiran terminal moraines. The latest ice advance extended 11 km down the upper Wairau Valley and deposited a subdued moraine at Island Gully. The composite chronology of the latest glacial advance based on 10 radiocarbon ages suggests it occurred between about 9.5 and 10.2 ka. This age span is similar to that of early Aranuian glacial advances dated by other workers in the Southern Alps, and may reflect Younger Dryas cooling.

Keywords glacial geology; Otira Glaciation; Aranuian glaciation; Wairau River; radiocarbon ages

INTRODUCTION

This paper describes glacial deposits on the uppermost reaches of the Wairau River affected by the Waimean, Otiran, and early Aranuian(?) glaciations. The study area encompasses the 25 km between the valley head and the Wairau River gorge (Fig. 1), and also includes the Tarndale Valley which extends 7 km south of the Wairau River. Less detailed reconnaissance mapping connects these two valley areas, particularly in the Island Pass Creek – Island Gully valleys. The glacial geology and chronology were studied to provide a Quaternary stratigraphic framework for assesssing the paleoseismicity of this part of the Awatere Fault.

METHODS

Quaternary deposits were mapped in the field on 1:25 000 and 1:50 000 scale aerial photographs. Heights of deposits above modern stream level were measured with a stadia rod and Abney level. Weathering-rind data were collected from 13 stations on moraines, outwash terraces, alluvial fans, and landslides, using the methods of Whitehouse et al. (1986). Soil profiles were described at eight locations on moraines, terraces, and landslides. Ten radiocarbon samples were collected at five sites, and eight radiocarbon ages bear directly on the glacial history. More complete field data for weathering rinds, soils, and radiocarbon ages are presented in McCalpin (in press).

GLACIAL GEOLOGY

Glacial deposits in this region were previously described by Suggate (1965), who recognised two Otiran ice limits—a younger one only a few kilometres from the valley head, and an older one in the Lake Sedgemere area (Fig. 1). My revised mapping indicates a more complex history. Otiran and pre-Otiran glaciers scoured the upper Wairau Valley and deposited four terminal moraine complexes. The three earlier advances filled much of the Tarndale Valley, where moraines escaped later erosion by the Wairau River and still are well preserved (Fig. 2). This discussion describes the distribution, morphology, weathering characteristics, and inferred ages of the four moraines.

Waimean(?) moraines (gtw)

The oldest moraines in the study area occur 1–2 km north and northeast of Tarndale Station, and consist of a pair of well-preserved lateral moraine ridges (Fig. 2, 3). These moraines are broad-topped, slightly hummocky embankments on the east, and broad, smoother timbered ridges on the west. Surface boulders are much more strongly pitted and spalled than those of Otiran moraines further upvalley. Correlation of these moraines with the Waimea Glaciation of Suggate (1965) rests mainly on their valley position, smooth morphology, and extremely weathered surface boulders.

Early Otiran moraines (gto_1)

A small moraine remnant on the western side of Tarndale Valley, between the inferred Waimean and middle Otiran moraines, is ascribed to an early(?) Otiran advance (Fig. 2). This moraine is paralleled by a tributary stream which appears to be in an old ice-marginal position downvalley of the moraine. Both the moraine and the stream crosscut the older (Waimean?) moraines previously described, whereas the eastern end of the ridge is truncated at a high angle by middle Otiran outwash channels. Correlation of this deposit with the early Otiran is tenuous, and rests mainly upon its intermediate position between subdued moraines with little original topographic detail (Waimean?), and well-preserved moraines typical of the Otiran glaciation.

The eastern extent of early Otiran ice is not clearly defined. Indistinct north–south-trending moraine ridges north of

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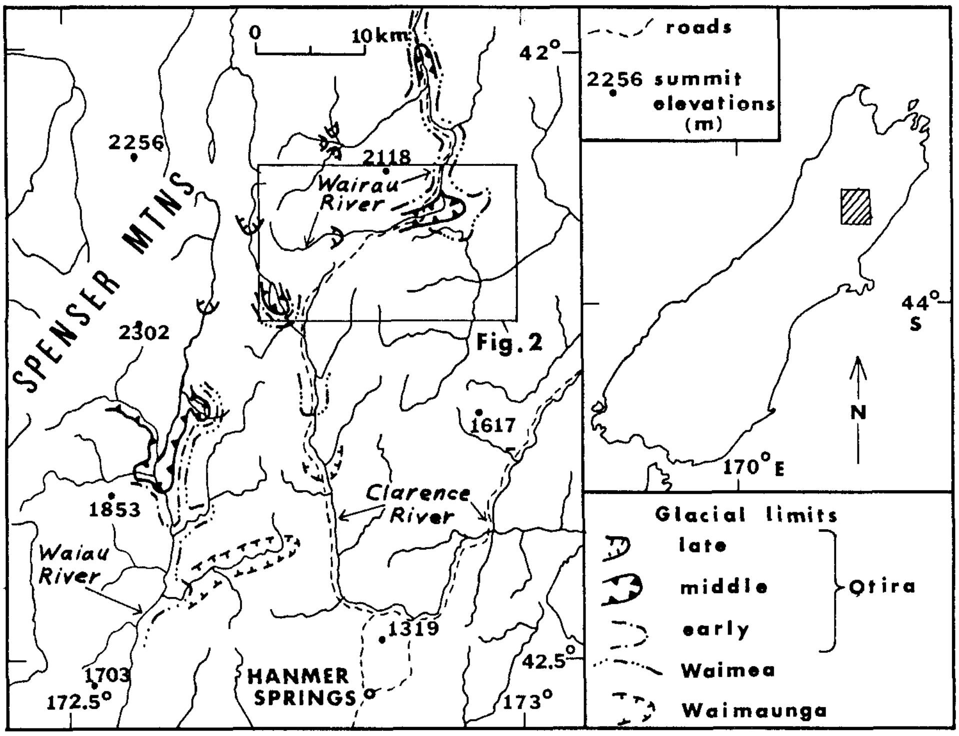

Fig. 1 Location map of the study area and glacial limits on the Wairau River and adjacent drainages as interpreted by previous workers (Suggate 1965; Clayton 1968). Ice limits identified in this study differ from those of Suggate (1965) only in the upper Wairau drainage (see Fig. 2).

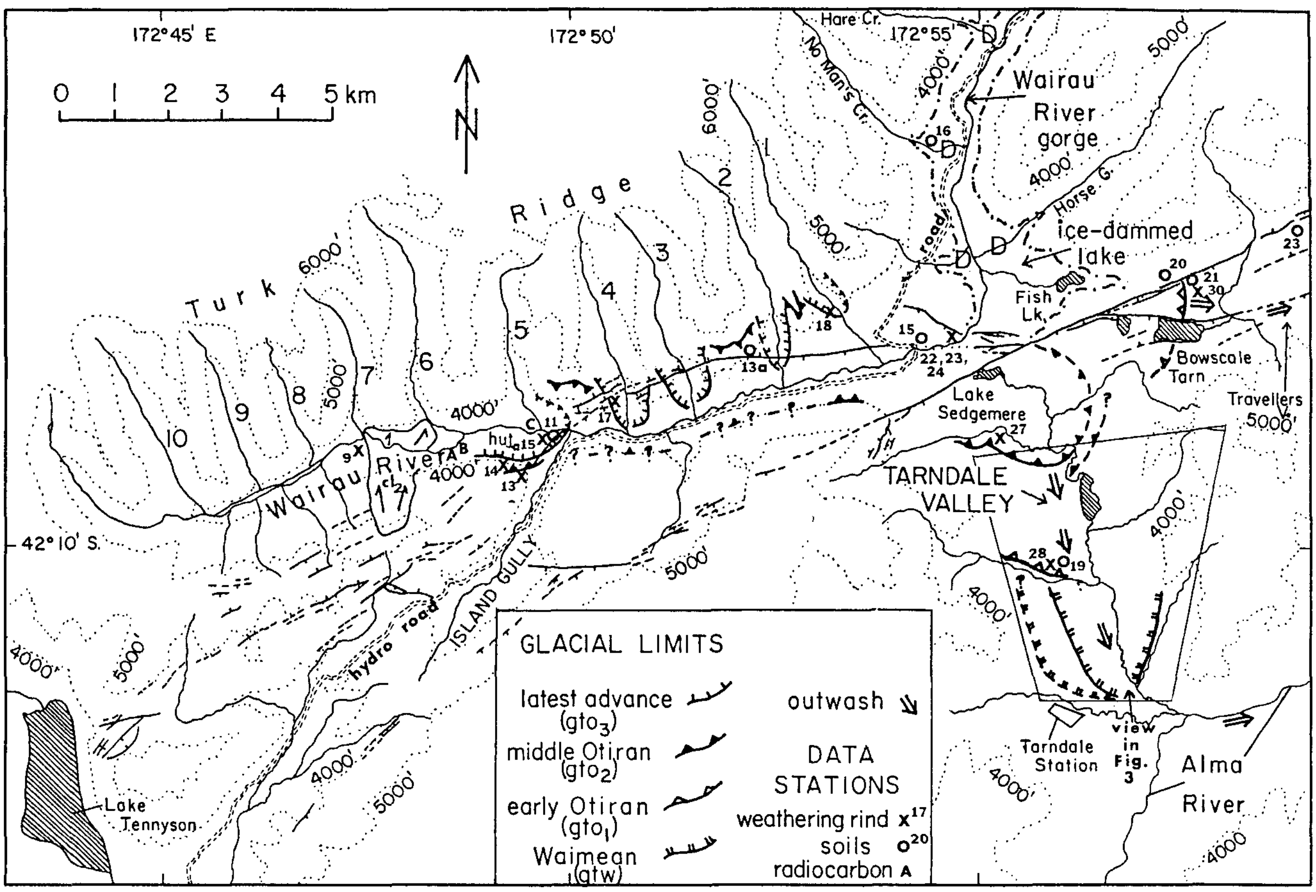

Fig. 2 Glacial advance limits in the upper Wairau and Tarndale Valleys as revised in this paper. Heavy lines show limits of four ice advances (solid where moraine is well preserved, dashed where moraine is poorly preserved, dashed and queried where glacial trimline is indistinct). Quaternary scarps of the Awatere Fault are shown by medium-weight lines with tick mark on downthrown side (solid where scarp is well preserved, dashed where poorly preserved). cl_2, late(?) Holocene landslide. Dashed-and-dotted line in Wairau Gorge shows inferred limits of ice-dammed lake; "D"s indicate fan-deltas (see text). Numbered tributaries from Turk Ridge correspond to numbered confluences shown on Fig. 5.

Fig. 3 Oblique aerial photograph of the two forested Waimean(?) moraines in Tarndale Valley. View is to the north, the area in view is marked on Fig. 2. The road at left goes from Tarndale homestead (just off photo at bottom) to Lake Sedgemere. Irregular light-and-dark-toned area between the forested moraines is the middle Otiran outwash surface, which originates from the middle Otiran terminal moraine (forested strip at top left margin of photograph).

Fig. 4 View to the east down the upper Wairau Valley, from the crest of the middle Otiran moraine (right centre) above Island Gully Hut (station 14, Fig. 2 and 5). The Island Gully moraine is at the photograph centre near the valley floor, some 100 m below the crest of the middle Otiran moraine. The three undulating ridges at lower left centre are the tops of rotated landslide blocks, derived from the unvegetated left flank of the middle Otiran moraine.

Bowscale Tarn define a broad ice margin that grades into a high-level outwash surface which today slopes gently eastward. If this surface has not been tilted by Awatere Fault movements, its slope suggests that outwash from the northern part of the early Otiran terminus drained east, down Travellers Valley (Fig. 2). Geomorphic details in this part of the moraine complex are obscured by extensive grabens and lakes formed along the Awatere Fault.

Middle Otiran moraines (gto_2)

The downvalley extent of the next younger ice advance is well defined in the Tarndale Valley by a looping, timber-covered end moraine only slightly breached by the axial drainage (Fig. 2). The poorly drained area northwest of the moraine, part of which is occupied by Lake Sedgemere, probably is the bed of a lake once dammed behind the terminal moraine. Downwarping adjacent to the Awatere Fault may explain the location and shape of Lake Sedgemere. The large moraine volume, well-preserved morphology, and association with the most extensive outwash plain support a middle Otiran age. Most of the outwash from the terminus flowed south through Tarndale Valley, forming a broad, braided outwash surface. This surface has been beheaded from its source in the Wairau Valley, partly by the formation of horsts along the Awatere Fault, partly by landsliding near the fault, and partly by post-Otiran incision of the Wairau River. The voluminous outwash in Tarndale Valley must have continued eastward down the Alma River, but no terraces are preserved in that valley.

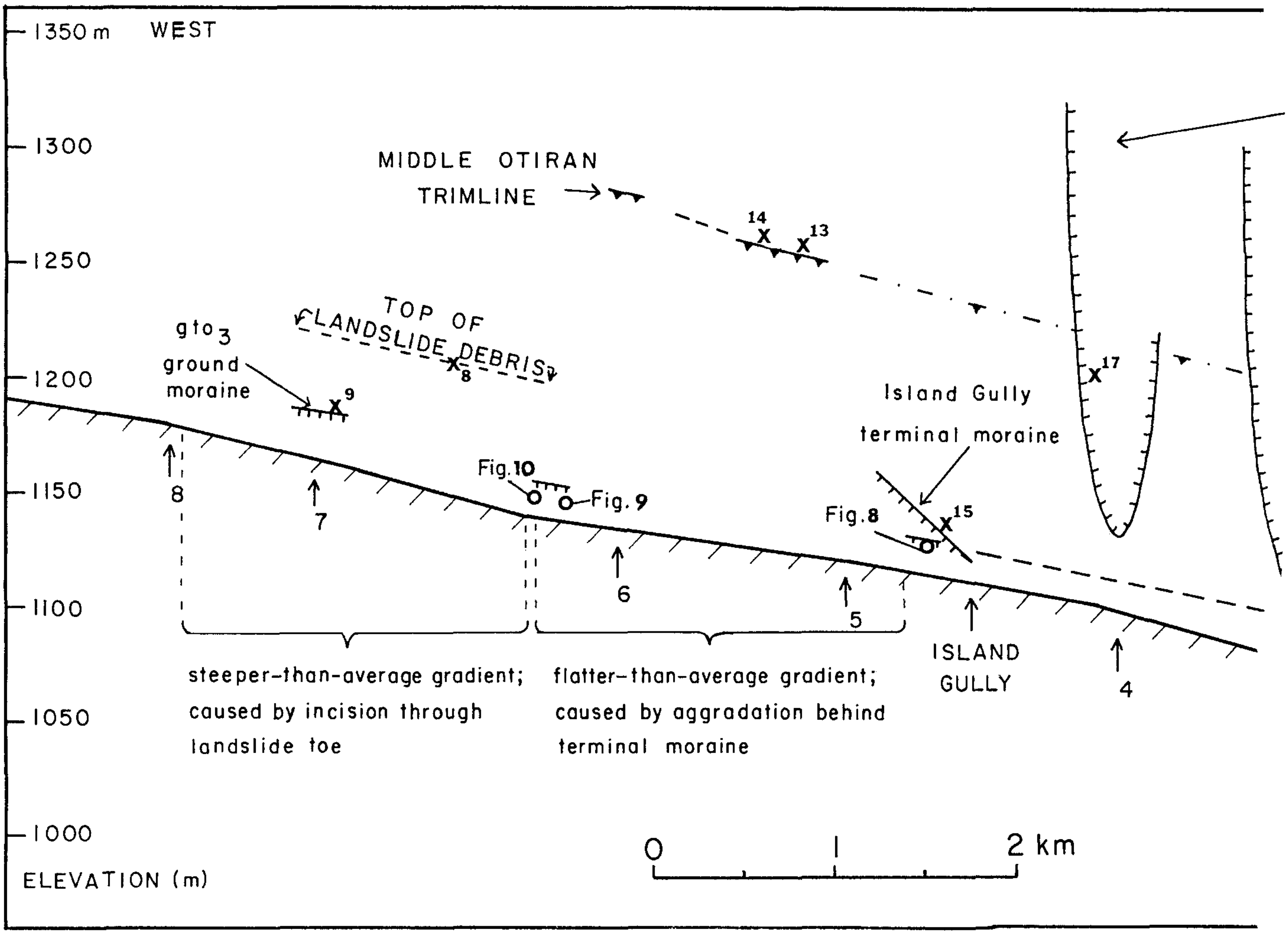

Fig. 5 Reconstructed longitudinal ice profile for the middle Otiran and latest glacial advances in the upper Wairau Valley. The middle Otiran trimline is based on lateral moraine crests; the terminal moraine is 2 km beyond the right limit of the graph. Numbered Xs show weathering-rind stations; open circles show locations of radiocarbon-dated exposures. Numbers below the bed of Wairau River indicate confluences of numbered tributaries shown in Fig. 2. The Electricorp road between Island Gully and the Wairau Gorge is on the main aggradation surface (latest glacial outwash).

The middle Otiran ice limit is not so obvious along the Wairau River north of Tarndale Valley and the Awatere Fault. The most prominent geomorphic surfaces along the Wairau River as it enters the Wairau Gorge are high-level, low-gradient alluvial surfaces at the mouths of tributary creeks (Fig. 2). These deposits, which superficially resemble alluvial fans, are probably fan-deltas that prograded into a lake which filled the Wairau Gorge in middle Otiran time. Several lines of evidence support this hypothesis: (1) the lateral moraine of the middle Otiran Rainbow River glacier (Fig.1) should have blocked the Wairau Gorge at an elevation of about 1040 m (Suggate 1965); (2) Suggate (1965) also reported lake deposits in the Wairau Gorge near the Rainbow confluence; (3) faint horizontal shorelines, which cannot be associated with any existing dam, are cut into the early Otiran moraine south of Fish Lake at roughly 1040 m; and (4) the multiple inset terraces at Horse Gully are reminiscent of delta-axis strath terraces caused by episodic drops in lake level (e.g., Gilbert 1890). If this hypothesis were correct, it would explain the absence of middle Otiran lateral or terminal moraines in the upper end of the Wairau Gorge at elevations similar to that of the contemporaneous moraine in Tarndale Valley. If glacier ice was calving into a deep narrow lake, distinct moraines probably would not have formed.

Two small remnants of lateral moraine are preserved high up on valley walls in the upper Wairau Valley, one 2.5 km west of Lake Sedgemere and another above the Island Gully confluence (Fig. 4). These remnants help define the longitudinal surface profile of middle Otiran ice (Fig. 5), and emphasise how the terminal moraines of the glaciated tributaries grade to a much lower level than the middle Otiran trimline.

The Island Gully moraine (late Otiran – early Aranuian?) (gto_3)

The latest ice to advance down the upper Wairau Valley built a subdued moraine at the confluence with Island Gully (Fig. 2), after which the moraine is informally named. Suggate (1965, p. 42) had previously identified the youngest Wairau Valley moraine as "heaps 1.5 miles above Island Gully", but field inspection reveals the large valley-floor deposit to be the toe of a landslide from the south valley wall (Fig. 2, 3).

Two lines of geomorphic evidence indicate that the latest ice advance did not go beyond the mouth of Island Gully.

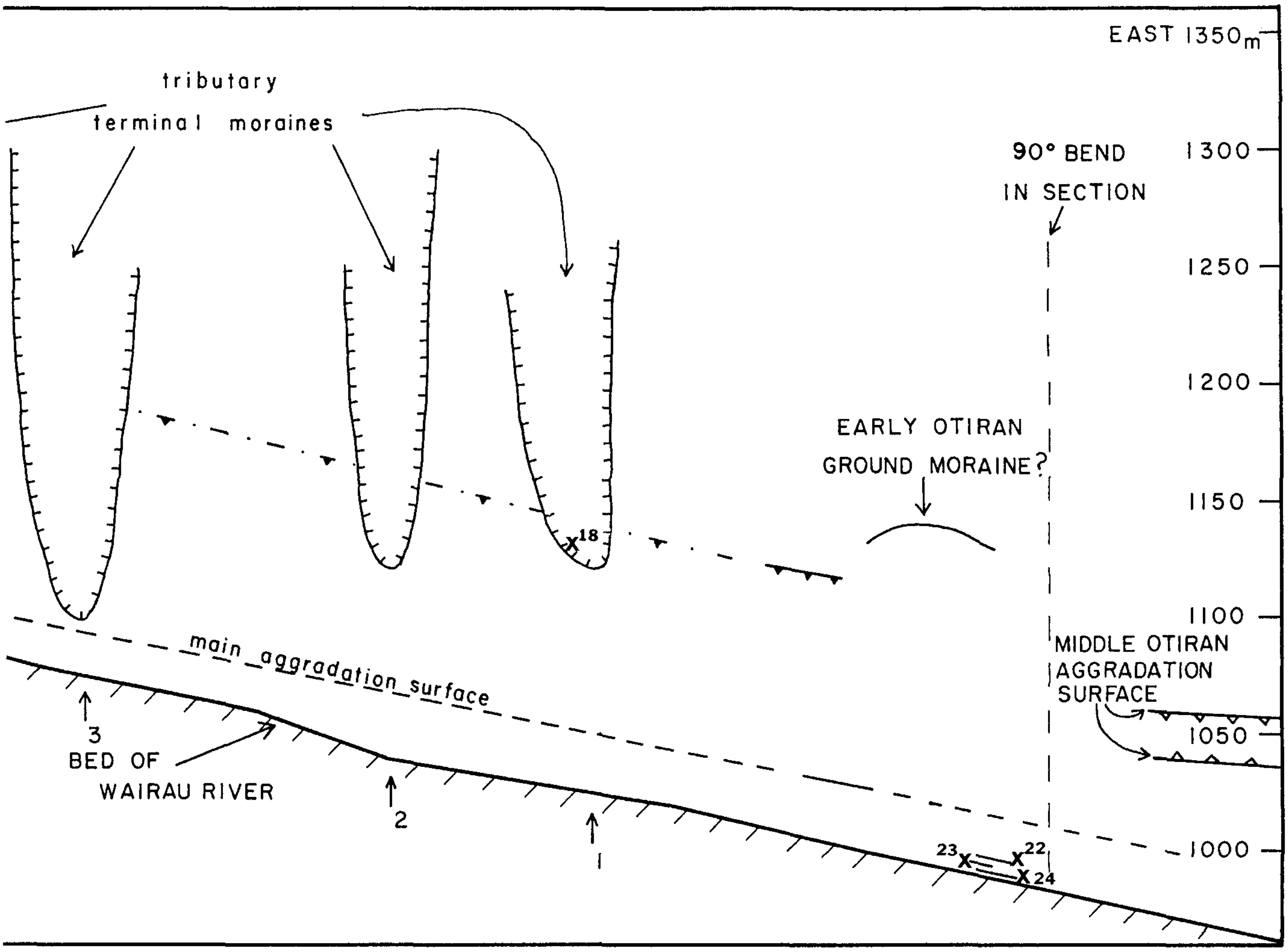

Fig. 5 *(continued)*.

1. Ten glaciated tributary canyons enter the upper Wairau Valley from Turk Ridge in the north (Fig. 2). Downvalley from the confluence with Island Gully, all tributaries contain a morphologically fresh, bouldery terminal moraine at their mouths. These moraines have well-preserved morphology and occur at elevations well below that of the middle Otiran trimline (Fig. 5); therefore they are post-middle Otiran. In contrast, identical tributary valleys upstream of the Island Gully confluence lack traces of young terminal moraines. Instead, trimlines from each tributary merge with lateral trimlines of the Wairau Valley, indicating a continuous ice mass existed as far downstream as Island Gully.

2. The main aggradation surface in the upper Wairau Valley does not extend upstream of Island Gully, but grades to the Island Gully moraine. Traced downstream toward the Wairau Gorge, this outwash surface is lower than the middle Otiran moraines or lake beds in Tarndale Valley and comprises the highest terrace level which can be traced through the right-angle bend in the Wairau River upstream of the gorge entrance. Therefore, this outwash was deposited by a through-flowing stream which postdated the diversion of upper Wairau drainage out of the Tarndale Valley, and also postdated the middle Otiran lake in the Wairau Gorge.

POST-OTIRAN HISTORY

At least three levels of discontinuous terraces occur along the upper Wairau River below the main glacial aggradation surface (Fig. 5). Basal peat from a terrace 3 m above modern stream level dates at 4090 ± 90 yr B.P. (Beta-30063), and a buried soil on a terrace 1 m above stream level dates at 1210 ± 100 yr B.P. (NZ 7657). If the age of the 15–27 m high main aggradation surface is about 9.5–11.5 ka (see Radiocarbon Chronology), the average rate of postglacial incision here has been about 1–2 m/1000 years.

SOIL PROFILES

Field descriptions were made of eight soil profiles developed on deposits ranging in age from Postglacial to Waimean(?) (Fig. 6, Table 1). Most profile development occurs within a 20–55 cm thick cap of loess which overlies till or outwash gravels. Soils on middle Otiran or younger deposits exhibit A/C or A/Bw/C profiles in a single, younger loess unit (horizon terminology after Soil Survey Staff 1975, and Birkeland 1984a). Soils on early Otiran and Waimean deposits are developed on two loess units, the upper of which is identical to the loess overlying middle Otiran and younger deposits (Fig. 6). The lower loess unit is more dense and compact than

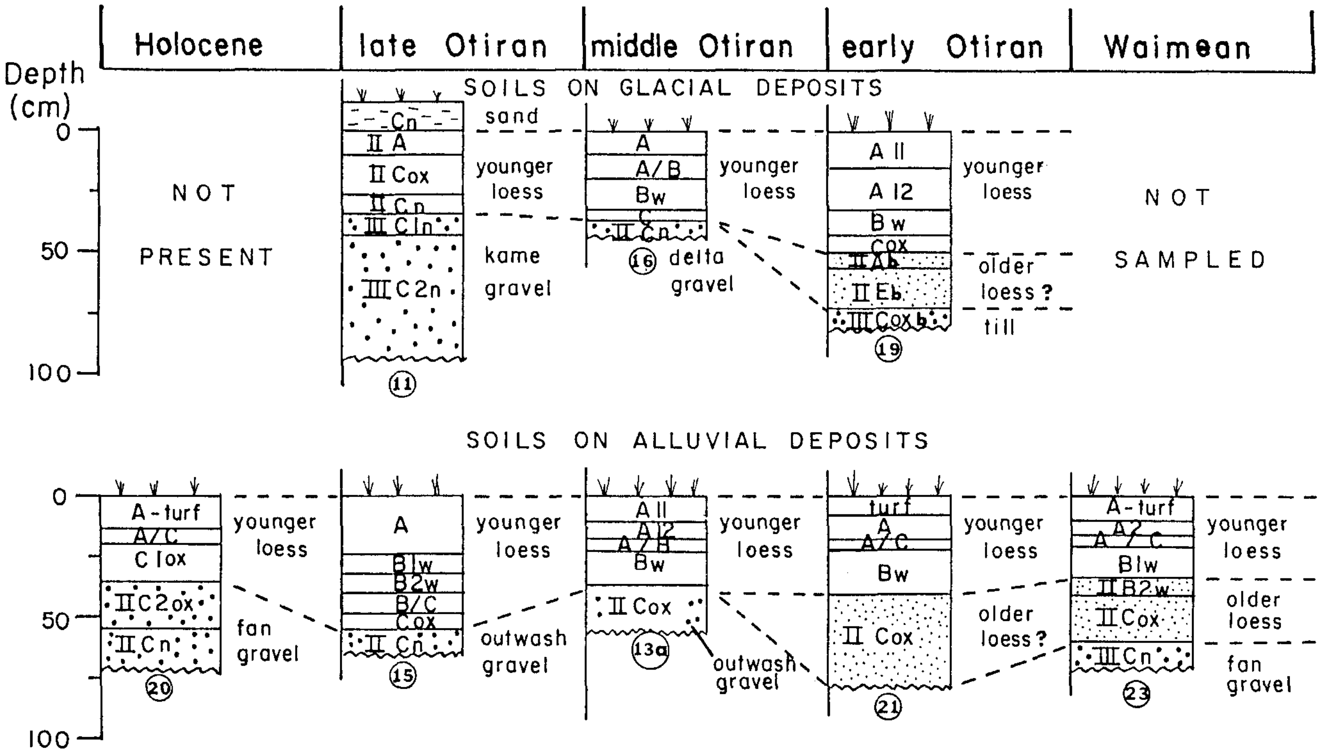

Fig. 6 Comparison of soil profile morphology on glacial and alluvial deposits of five different ages in the upper Wairau and Tarndale Valleys. Soil nomenclature is from Soil Survey Staff (1975) and Birkeland (1984a). Numbers under profiles are locations shown on Fig. 2.

the upper unit and may have rare admixed stones, suggestive of frost heaving or churning of underlying gravel clasts.

There is a weak increase in the thickness and maximum colour of the cambic B horizon with increasing soil age (Table 1). Other studies on Holocene and late-glacial soils in New Zealand have shown that soil rubification (soil redness compared to parent material redness) exhibits a high correlation with inferred deposit age (Birkeland 1984b; Rodbell 1990). Rubification values (calculated after Harden 1982) in upper Wairau soils are lowest in the youngest soils, but show no consistent trend with age in middle Otiran or older soils (Table 1). Rubification values on latest glacial soils (34.5–46.5) are comparable to values quoted from the Mt Cook area by Birkeland (1984b) (38.1–63.7) where soil age and postglacial loess thickness (25–45 cm) are similar, but are less than values from late glacial soils in the Arrowsmith Range (78.0–122.2) where loess is much thicker (78–175 cm; Rodbell 1990).

The similarity of soil profiles on deposits ranging from late Otiran to Waimean age suggests that most of the pre-Holocene soil weathering has been removed. This phenomenon has been widely observed in the South Island of New Zealand (Bruce 1973; Ives 1973; Tonkin et al. 1974; Rodbell 1990) and is ascribed to episodic "pedospheric stripping" of loess covers, and their included soils, from the landscape. The extent of loess erosion is presumably controlled by microtopography and wind direction, so that soils on a single geomorphic surface may be irregular in thickness and development. The inconsistent trend of rubification values with inferred age in Table 1 may result from such irregularities, and may indicate that soil development indices cannot be used alone as age indicators on pre-Holocene deposits.

WEATHERING-RIND DATA

Weathering-rind thickness on surface clasts increases with inferred deposit age (Fig. 7, Table 2). Both the largest significant mode (LSM; after Whitehouse et al. 1986) and the mean rind thickness are calculated, following Knuepfer's (1988) suggestion that, in rare cases, mean values reflect deposit relative ages correctly while modal values do not. Rind thicknesses are converted to apparent ages (Table 2) using the calibrated regressions of Knuepfer (1988, fig. 4).

A Holocene terrace 1 m above stream level yields modal and mean rind ages of 973 ± 70 and 1144 ± 138 yr B.P., respectively, compared to a radiocarbon age of 1210 ± 100 yr B.P. (NZ 7657; Table 3). Terraces below, and above, a terrace dated at 4090 ± 90 yr B.P., yield modal or mean rind ages of 3846 ± 473 or 3539 ± 719 yr B.P., and 6195 ± 870 or 6066 ± 1462 yr B.P., respectively. On moraines of the latest glacial advance, rind ages are slightly less than radiocarbon ages. Ground moraine in the upper Wairau Valley (station 9, Fig. 2) yields modal and mean rind ages of 8349 ± 1264 and 7780 ± 2009 yr B.P., whereas radiocarbon ages indicate that the valley 1 km downstream had been deglaciated by 9460 ± 110 yr B.P. (Beta-30057). The terminal moraine at Island Gully (station 15) yields modal and mean rind ages of 8349 ± 1264 and 8171 ± 2138 yr B.P., whereas radiocarbon ages indicate the site was ice free by 9800 ± 86 yr B.P. (NZ 7660). Weathering rinds from the young terminal moraines (gto_3) at the mouths of glaciated tributaries (stations 17, 18, Fig. 2) are much thicker than rinds on the correlative Island Gully moraine, but are similar to rinds on middle Otiran lateral moraines higher on the valley walls (Fig. 5, Table 2). Rind thicknesses thus suggest that, despite morphologic similarity, the tributary

Table 1 Selected field data for soils.

Soil no.	Parent material	Horizon*	Depth (cm)	Colour†	Texture‡
11	gto_3	Cox	0–12	2.5Y5/2	s
		2A	12–21	10YR3/4	l
LT = 39 cm		2C1ox	21–39	10YR4/6	l
Rub. = 34.5		2C2ox	39–46	10YR3/6	gsl
		3C3ox	46–55	2.5Y3/2	g
		3C4ox	55–105+	2.5Y4/2	g
13a	ao_2	A11	0–9	10YR5/3	si
		A12	9–1	10YR6/5	si
LT = 35 cm		A/B	16–21	10YR5/6	gsi
Rub. = 50.8		Bw	21–35	7.5YR5/8	si
		2Cox	35–56+	2.5Y6/4	g
15	ao_3	A	0–23	10YR3/6	si
		B1w	23–31	10YR5/8	si
LT = 55 cm		B2w	31–40	10YR6/8	si
Rub. = 46.5		B/C	40–47	2.5Y5/6	si
		C1ox	47–55	2.5Y5/4	si
		2C2ox	55–60+	2.5Y4/2	g
16	ld_2	A	0–9	10YR3/4	si
		A/B	9–18	10YR4/6	si
LT = 36 cm		Bw	18–32	10YR5/8	si
Rub. = 54.5		C1ox	32–36	10YR5/6	si
		2C2ox	36–43+	10YR5/4	g
19	gto_1	A11	0–15	10YR6/4	si
		A12	15–32	10YR5/6	si
LT = 50 cm		Bw	32–42	10YR5/8	si
Rub. = 52.0		Cox	42–50	10YR3/6	si
		2Ab	50–56	10YR4/4	gssi
		2Eb	56–73	2.5Y6/4	gl
		3Coxb	73–83+	2.5Y4/4	g
20	afy	A+turf	0–12	10YR3/4	gsi
		A/C	12–20	10YR4/4	si
LT = 35 cm		C1ox	20–35	10YR5/4	si
Rub. = 30.0		2C2ox	35–55	2.5Y4/2	g
		2C3ox	55–70+	2.5Y5/2	g
21	ao_1	turf	0–7	10YR3/3	pt
		A	7–17	10YR4/4	si,pt
LT = 40 cm		A/C	17–21	10YR4/6	si
Rub. = 42.3		Bw	21–40	10YR5/6	si
		2Cox	40–77+	10YR5/4	sg
23	aow	A+turf	0–10	10YR3/4	si,pt
		A2	10–15	10YR4/4	si
LT = 20 cm		A/B	15–20	10YR4/6	si
Rub. = 54.3		B1w	20–32	10YR5/8	si
		2B2w	32–40	10YR5/8	gsi
		2C1ox	40–60	10YR5/4	g
		2C2ox	60–65+	10YR5/3	g

*Soil horizon nomenclature follows Soil Survey Staff (1975) and Birkeland (1984a).

†Initial parent material colour is assumed to be 5Y6/1 (till) and 5Y7/1 (loess), after Birkeland (1984b).

‡si, silt; s, sand; l, loam; g, gravel; pt, peat; modifier precedes primary texture; comma indicates two distinct textures within horizon.

LT = loess thickness.

Rub. = rubification index, after Harden (1982). Values are not normalised for maximum value, but are normalised such that the lowest horizon is assumed to extend to 105 cm depth (after Birkeland 1984b, p. 121).

Abbreviations for Parent Material not used elsewhere: afy, Holocene alluvial fan; ao_3, late Otiran outwash; ao_2, middle Otiran outwash; ld_2, middle Otiran delta; ao_1, early Otiran outwash; aow, Waimean outwash.

moraines are older than the Island Gully moraine, and may represent middle Otiran recessional moraines, or possibly late Otiran terminal moraines.

Rinds from the middle Otiran moraine in Tarndale Valley (station 27) are considerably thicker than those on correlative lateral moraines above Island Gully (stations 13, 14). This discrepancy has two possible explanations. First, most rinds larger than 7 mm at stations 27, 28, and 30 were developed exclusively on an abnormally soft, "sugary"-textured sandstone that was not observed at other stations. The second possibility, assuming rinds are representative of age, is that the terminal moraine may be older than middle Otiran; Suggate (1965) mapped this moraine as Waimean. The middle Otiran correlation is based on massive moraine volume and minimal axial breaching; however, breaching may not be representative of age since the Wairau drainage was diverted soon after ice retreat began. The strongest evidence for a middle Otiran age is the intermediate position between very weathered moraines and very fresh moraines, and the absence of any other suitable moraines that might represent the maximum late Pleistocene advance.

For deposits of Otiran and even older ages, weathering rinds underestimate the inferred deposit age by progressively greater amounts (Table 2). The divergence of age estimates based on rinds from those based on radiocarbon chronologies suggests that, on older deposits, few clast surfaces have been continuously exposed to weathering since initial deposition. Whitehouse et al. (1986) stated that, for deposits older than c. 20 ka, the rate of spalling and disintegration approaches the rate of inward rind migration, and weathering rinds assume a "steady-state" modal value of roughly 8 mm. While this modal size has been reached on early Otiran and some middle Otiran deposits in this area, other middle Otiran deposits only reach a modal size of 6 mm (Fig. 7, Table 2). The thinner rinds on these latest glacial and middle Otiran deposits may result from the episodic burial of surface clasts by loess, and later exhumation, as inferred from soil profile evidence.

RADIOCARBON CHRONOLOGY

Ten samples from cuts in the upper Wairau Valley yielded radiocarbon ages (Table 3). Because these cuts are at the Island Gully terminal moraine or upstream from it, they expose mainly deposits of the youngest glaciation and of postglacial time. The roadcut near Island Gully Hut (Fig. 8) exposes the uppermost stratigraphy in the youngest terminal moraine complex. Bouldery till (not exposed in the cut but exposed about 100 m to the southeast) is overlain by 2.0 m of well-sorted, fine–medium gravel (probably a kame or kame-delta). A buried A horizon developed on kame gravels and on thin sag-pond clays is dated at 9800 ± 86 yr B.P. (NZ 7660). This age suggests that ice of the latest advance had abandoned the area by before 9800 yr B.P. Two streamcuts about 2 km upstream of Island Gully (A and B on Fig. 2) expose a more complete stratigraphic record of the latest glacial advance. In the more eastern cut (Fig. 9), reddish pre(?)-glacial stream gravels are overlain by till of the latest glacial advance. Thin peat beds between the two units date at 12 600 ± 160 yr B.P. (Beta-30056), suggesting that the latest ice advanced over a peaty valley floor some time after 12.6 ka. The till is overlain by a thin, organic-rich clay (similar to that overlying kame gravels at the Island Gully Hut terminal moraine), which dates at 9460 ± 110 yr B.P. (Beta-30057). At the western cut

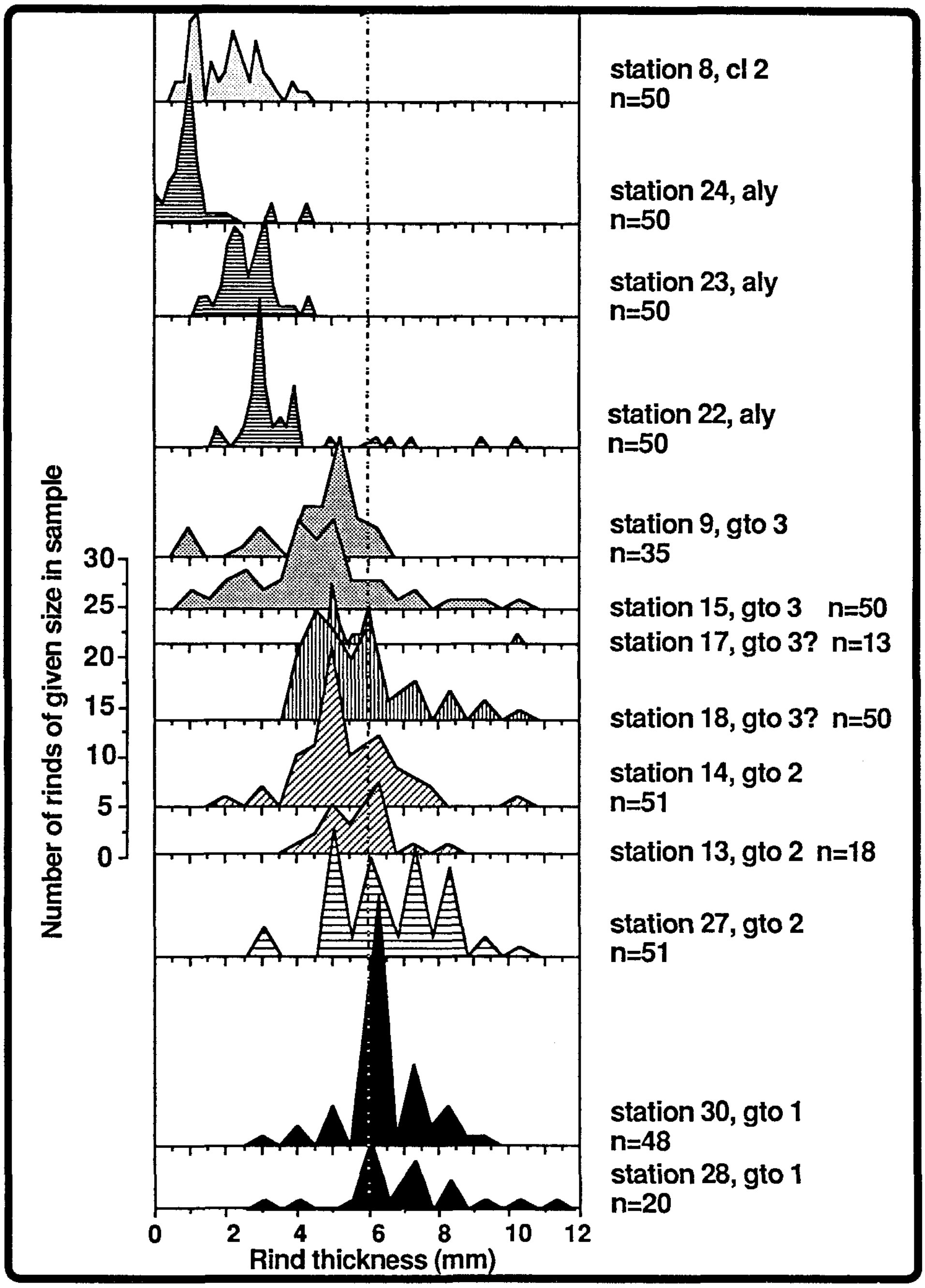

Fig. 7 Weathering-rind data from Holocene and Pleistocene deposits. Station numbers and map unit abbreviations are the same as on Fig. 2, with this addition: aly, Holocene terrace alluvium: n, number of clasts measured. Histograms represent the original, unsmoothed field data; deposits of similar age have simiar histogram shading. Modal and mean rind thicknesses and apparent rind ages are given in Table 2.

(Fig. 10), several pre-late Otiran scree deposits and soils (ages 9180 ± 110 yr B.P.; Beta-30059, to 10 070 ± 170 yr B.P.; Beta-30060) are overlain by till containing peat and wood (ages 9620 ± 80 yr B.P. to 10 200 ± 89 yr B.P.; NZ 7671).

The radiocarbon ages suggest that the latest ice advanced over a peaty, partly forested valley, incorporated pieces of peat and wood with ages as old as 12.6 ka, and built the Island Gully moraine. By 9.8 ka the Island Gully moraine had been abandoned, but ice several kilometres upvalley was still active, as indicated by wood in till dated at 9.6 and 9.7 ka. By 9.5 ka, this ice upvalley was no longer active, and thin lake sediments were covering the till. The anomalous age of 9.18 ka from underneath the latest till (Fig. 10) is not easily reconciled with ages of 9.5–9.8 ka overlying the till, and may result from sample contamination with younger carbon. Two radiocarbon ages from Serpentine Creek in the adjacent Clarence River drainage (McCalpin 1992, this issue) also can be correlated with the upper Wairau chronology. Outwash aggradation reached the Lake Tennyson area by 11.3 ka; presumably, glaciation in the headwaters of the Clarence River, 15 km upstream, had begun earlier. By 9.2 ka, alluvial fans were covering the floodplain, probably signalling the end of glacial aggradation.

CORRELATION

Correlation with other dated moraines in New Zealand

The radiocarbon ages cited in Table 3 bracket the latest glacial advance in the upper Wairau Valley between about 9.5 and 10.2 ka. This age range is significantly younger than the commonly accepted age for the late Otiran glaciation in Marlborough, Westland, and Nelson (13–14 ka; Suggate & Moar 1970). Workers in Canterbury and Westland have dated

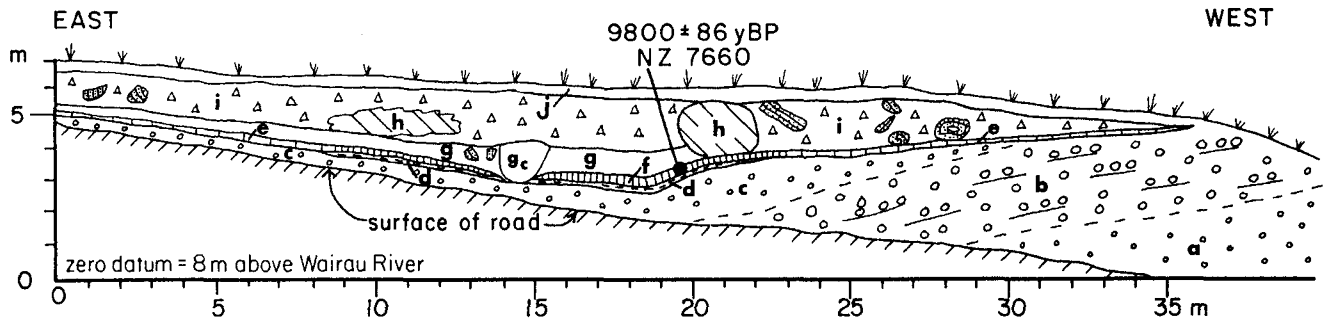

Fig. 8 Sketch of a roadcut exposure 100 m northeast of the Island Gully Hut (location C, Fig. 2) in the Island Gully terminal moraine-kame complex. a,b,c, kame gravel of the Island Gully moraine; d, grey lacustrine clay; e, soil horizons; f, twigs and peat; g, h, i, post-latest glacial debris flows?; unit i includes blocks of various bedding attitudes as shown, some sand beds are deformed into complete circles (earthquake deformation?); j, loess-rich slopewash.

several prominent moraines at between 10.2 and 12.4 ka (Burrows 1989; Basher & McSaveney 1989; McSaveney & Whitehouse 1989; Table 1). If the latest glaciation in the upper Wairau Valley is correctly dated, then it is an early Aranuian, and not a late Otiran, advance.

Possible explanations for the lack of late Otiran moraines in the upper Wairau Valley are: (1) there was no such advance in this valley; (2) late Otiran moraines existed, but were overrun by the early Aranuian advance in the uppermost Wairau Valley—the moraines at the four tributary mouths would then be late Otiran, as suggested by the weathering-rind data: (3) late Otiran moraines are buried under the main aggradation surface; or (4) the latest glacial moraine at Island Gully is indeed late Otiran, and the radiocarbon-dated deposits upvalley are postglacial diamictons (landslide deposits?) which have been mistaken for latest glacial till. Weathering-rind data, soil data, and exposed stratigraphy best support explanation 2.

Global correlation

The inferred age of the latest glacial advance (9.5–10.2 ka) is similar to, but slightly younger than, the age of the Younger Dryas Chron (Broecker & Denton 1990). Evidence for Younger Dryas cooling in the Southern Hemisphere is not abundant, but a recent analysis of marine cores in the Sulu Sea, Philippines, has identified a distinct cool period which began by 11.1 ka and had ended by 9.4 ka (Kudrass et al. 1991). The immediately preceding postglacial warm period reached its peak about 12.3 ka, which is similar to the age of valley-floor peats incorporated into the youngest upper Wairau till. By 9 ka, atmospheric circulation models suggest that July temperatures on Southern Hemisphere land masses were about 0.3°C warmer than at present, making glacial advances unlikely (Kutzbach 1983). This chronology of slow warming up to c. 12.3 ka, a brief but severe climatic reversal from 11.1 to 9.4 ka, and subsequent warming, explains the observed chronology of the latest glacial advance in the upper Wairau Valley.

CONCLUSIONS

Mapping and dating of glacial deposits in the upper Wairau Valley amend earlier work (Suggate 1965) by identifying four terminal moraine complexes. The oldest (Waimean?) ice advance spilled out of the upper Wairau Valley and constructed a massive terminal complex at the south end of Tarndale Valley. The limits of the next younger early Otiran

Table 2 Weathering-rind data.

Deposit	Station no.	LSM (mm)	Mean (mm)	Apparent age (yr B.P.) (LSM)*	Apparent age (yr B.P.) (Mean)†	Radiocarbon age‡ (yr B.P.)
aly	24	1.0	1.05	973 ± 70	1144 ± 138	1210 ± 100
cl_2	8	2.6	1.89	3483 ± 415	2521 ± 451	<9.5 ka
aly	23	2.8	2.43	3846 ± 473	3539 ± 719	<4090 ± 90
aly	22	4.0	3.62	6195 ± 870	6066 ± 1462	>4090 ± 90
gto_3	9	5.0	4.35	8349 ± 1264	7780 ± 2009	<9460 ± 110
gto_3	15	5.0	4.51	8349 ± 1264	8171 ± 2138	>9800 ± 86
gto_3	17	6.0	5.75	10 655 ± 1707	11 362 ± 3228	c. 13–14 ka
gto_3	18	6.0	5.67	10 655 ± 1707	11 148 ± 3153	c. 13–14 ka
gto_2	13	6.0	5.58	10 655 ± 1707	10 908 ± 3069	c. 20 ka
gto_2	14	6.0	5.32	10 655 ± 1707	10 224 ± 2832	c. 20 ka
gto_2	27	8.0	6.33	15 660 ± 2729	12 947 ± 3793	c. 20 ka
gto_1	28	8.0	6.85	15 660 ± 2729	14 414 ± 4326	c. 60 ka
gtol	30	8.0	6.29	15 660 ± 2729	12 836 ± 3753	c. 60 ka

For deposit and station numbers refer to Fig. 2.
LSM = largest significant mode (contains >5% of sample).
*Age (yr) = (973 ± 70) $R^{1.33 \pm 0.05}$, where R = rind thickness (mm).
†Age (yr) = (1071 ± 125) $R^{1.33 \pm 0.10}$, where R = rind thickness (mm).
‡Radiocarbon ages from Table 3 or from regional correlation.

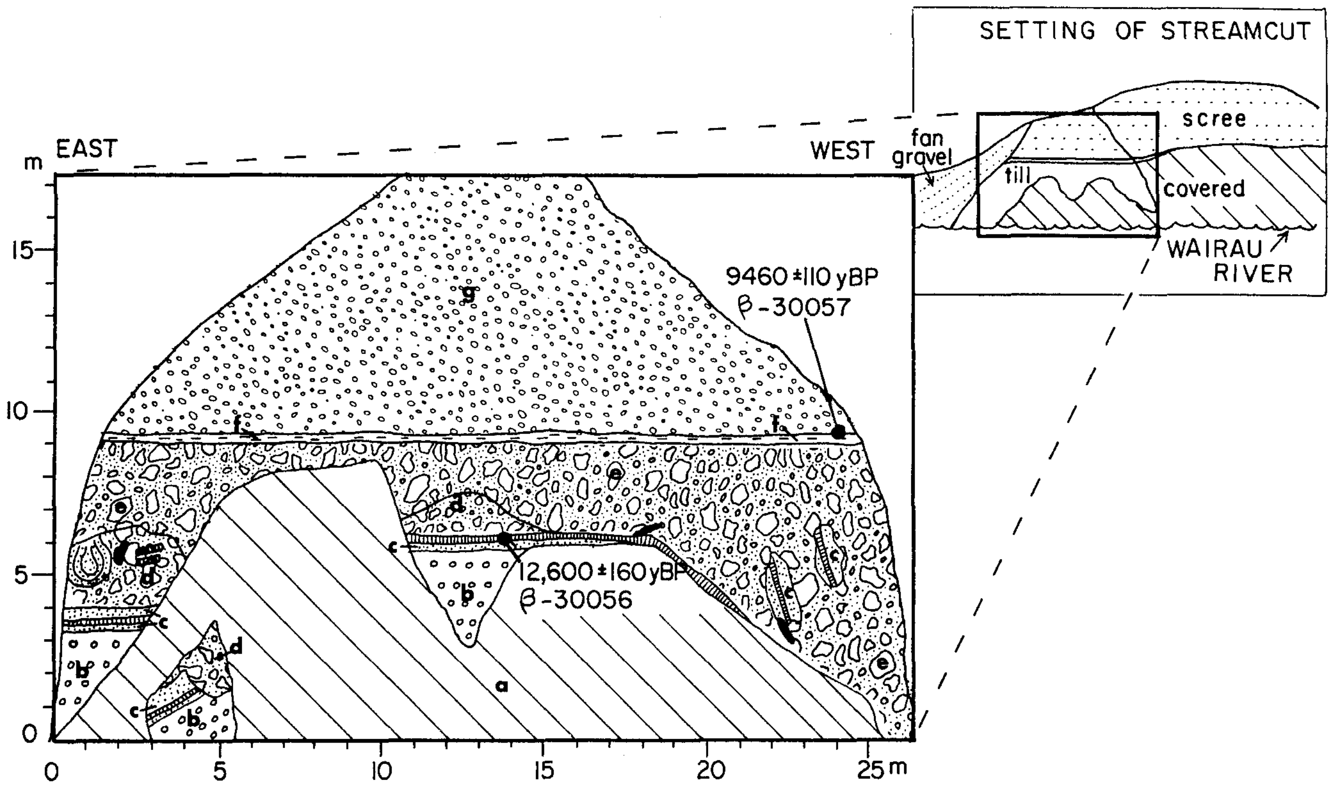

Fig. 9 Sketch of the eastern of two streamcuts in the upper Wairau Valley (location B, Fig. 2). Cut exposes postglacial scree (g) overlying a thin postglacial lake bed (f), which in turn overlies till of the latest glaciation (d, e). Till overlies a sequence of peat (vertical hachures) and thin sand beds which overlie preglacial stream alluvium (b). a, covered slope. Solid black items are tree trunks. Radiocarbon ages bracket latest till deposition between about 9.5 and 12.6 ka (see Table 3 for additional radiocarbon data).

Table 3 Radiocarbon ages from the upper Wairau Valley.

Lab. no.[1]	Radiocarbon age[2] (years B.P.)	Pretreatment	Material	Locality[3]	Stratigraphic setting
NZ 7657	1210 ± 100	Dilute NaOH, dilute H_3PO_4 extraction.	soil	N30/025975	Buried soil atop 1m terrace.
Beta-30063	4090 ± 90	Hot HCl dispersion distilled water rinse.	peat	N30/006970	Basal peat underlying 3m terrace.
Beta-30059	9180 ± 110	Hot HCl, NaOH, HCl soakings.	wood	N30/938955	Underlies pre-latest-glacial scree[4].
Beta-30057	9460 ± 150	Hot HCl dispersion, distilled water rinse.	soil-peat	N30/942955	Immediately overlies youngest till[5].
NZ 7640	9620 ± 80[6]	Hot water, hot 3% H_3PO_4 extraction.	wood	N30/938955	Incorporated in lower part of youngest till[4].
Beta-30058	9720 ± 80[6]	Hot HCl, NaOH, HCl soakings.	wood	N30/938955	Incorporated in lower part of youngest till[4].
NZ 7660	9800 ± 86	0.5N NaOH, 1.6M H_3PO_4.	soil-peat	N30/956957	Immediately overlies youngest till/kame gravels[7].
Beta-30060	10,070 ± 170	Hot HCl dispersion, distilled water rinse.	soil	N30/938955	Underlies youngest till[4].
NZ 7671	10,200 ± 89	Dilute NaOH, dilute acid.	peat	N30/938955	Incorporated in upper part of youngest till[4].
Beta-30056	12,600 ± 160	Hot HCl dispersion, distilled water rinse.	peat	N30/942955	Underlies youngest till[5].

[1]NZ, DSIR Physical Sciences; Beta, Beta Analytic Inc., Coral Gables, Florida, U.S.A.
[2]Based on $T^{1/2}$ = 5568 years; uncorrected for mean residence time effects or calendar years.
[3]NZMS 260 grid co-ordinates.
[4]See Fig. 8.
[5]See Fig. 7.
[6]"Blind" replicate analyses on same piece of wood; age differences may be a result of differences in pretreatment.
[7]See Fig. 6.

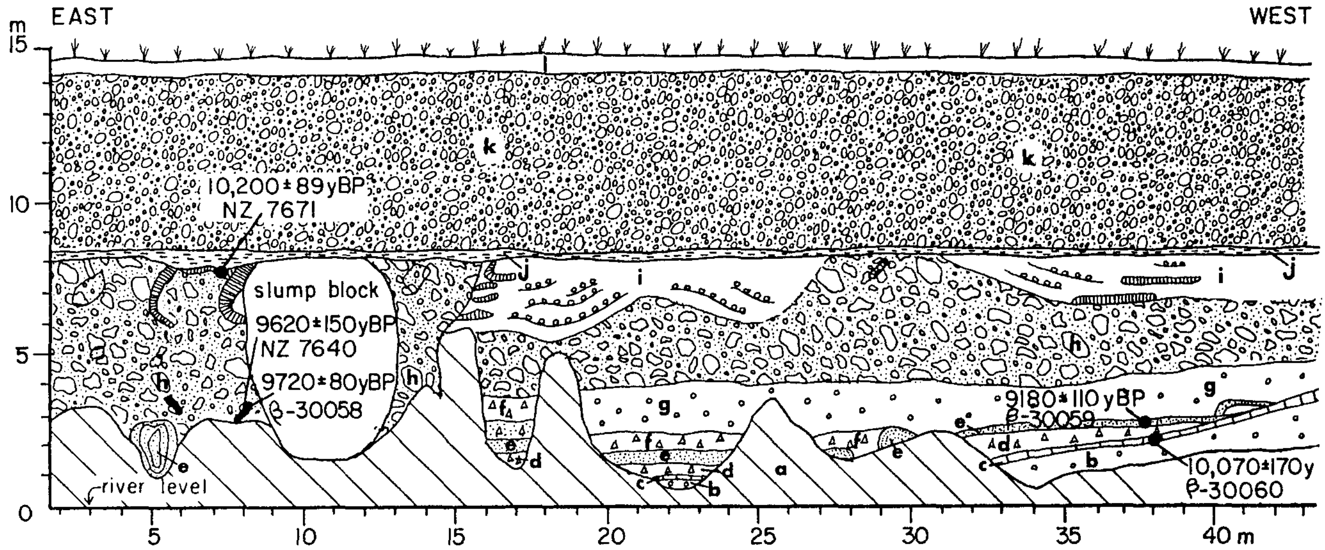

Fig. 10 Sketch of the western of two streamcuts in the upper Wairau Valley (location A, Fig. 2). Cut exposes postglacial terrace gravel (k) overlying a thin lake bed (j). Latest glacial till (h, i) overlies preglacial scree (b, g), debris flows (d, f), and alluvium (e). Peat beds are marked by close vertical hachures, tree trunks by solid black area. a, covered slope. Radiocarbon dates bracket latest glacial till between about 9.6 and 10.2 ka, but stratigraphic age reversals are common.

advance are poorly expressed as low moraine and outwash remnants, 1–2 km upvalley from the Waimean(?) moraines. Early Otiran outwash was shed down the Alma River and eastward down Travellers Valley. The middle Otiran advance is marked by a well-preserved terminal moraine loop which impounds a marshy basin including Lake Sedgemere. All outwash of this advance was shed southward down Tarndale Valley and the Alma River. The northern part of the middle Otiran terminus abutted a large ice-dammed lake in the Wairau Gorge, into which fan-deltas prograded at an elevation of about 1040 m. The well-preserved terminal moraines at the mouths of four tributaries to the Wairau River may represent a late Otiran advance. The latest ice advance built a subdued terminal moraine-kame complex at the confluence of the Wairau River and Island Gully. Radiocarbon ages from three exposures of latest glacial till bracket the latest advance between about 9.5 and 10.2 ka. This age range is similar to that documented by McSaveney & Whitehouse (1989) for early Aranuian ice advances elsewhere in the Southern Alps, and may correlate with the Younger Dryas global cooling episode.

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