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Glacial and postglacial geology near Lake Tennyson, Clarence River, New Zealand

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Abstract Otiran valley glaciers extended 15 km down the upper Clarence Valley in central Marlborough, South Island, New Zealand. A massive Otiran terminal moraine complex, composed of moraines of three glacial advances, impounds Lake Tennyson. The moraines are early and middle Otiran, and possibly late Otiran – early Aranuian in age, based on relative position and differences in moraine morphology, weathering rinds, and soils. Radiocarbon ages from a tributary (Serpentine Creek) suggest the latest major episode of aggradation in the Clarence Valley was in progress by 11.3 ka, and had ended by 9.2 ka. Postglacial history was dominated by incision of glacial outwash, deposition of small alluvial fans, and landsliding near the trace of the Awatere Fault. Fault scarps of the Awatere Fault and of unnamed parallel splays displace early Otiran moraines up to 19 m and early Holocene terraces up to 2.6 m.

Keywords glacial geology; Otira Glaciation; Clarence River; Awatere Fault; radiocarbon ages

INTRODUCTION

This paper describes Otiran glacial deposits on the upper reaches of the Clarence River (Fig. 1). The area studied includes the Lake Tennyson moraine complex and isolated exposures along the Clarence River and Serpentine Creek within 5 km of the lake outlet. Less detailed reconnaissance mapping in the Island Pass Creek and Serpentine Creek areas covers nonglacial deposits. A companion paper (McCalpin 1992, this issue) describes glacial deposits of the adjacent upper Wairau Valley. The purpose of this study was to refine the existing Quaternary stratigraphic chronology near Lake Tennyson to assist in dating paleoseismic displacements on the Awatere Fault.

METHODS

Quaternary deposits were mapped on 1:25 000 and 1:50 000 scale aerial photographs and later transferred to 1:25 000 topographic maps. Heights of deposits above modern stream level were measured with a stadia rod and Abney level. Weathering rinds were measured at seven stations on moraines, outwash terraces, alluvial fans, and landslides, using the methods of Whitehouse et al. (1986). Soil profiles were described at five locations on moraines. Six radiocarbon samples were collected at three sites, but only two ages bear indirectly on the glacial history. Field data for weathering rinds, soils, and radiocarbon ages are presented in McCalpin (in press).

STUDY AREA

Previous work

Otiran glacial deposits in the Clarence Valley are concentrated in a moraine complex immediately south of Lake Tennyson (Fig. 2), 15 km south of the headwaters of the Clarence River (42°13′S; 172°45′E; NZMS 260, sheet M31B). Quaternary deposits south of the lake were described and correlated by Suggate (1965) as part of a regional study. He identified three moraines, an outer (early Otiran?) moraine south of Princess Stream, and two broad parallel moraines of later Otiran age, which impound the lake itself. His correlation relied mainly on qualitative geomorphic comparisons of Lake Tennyson moraine morphology and outwash terrace heights to those of type areas (Suggate pers. comm. 1987).

LAKE TENNYSON MORAINE COMPLEX

The main features of the glacial geology south of Lake Tennyson (Fig. 3) are a 1.2 km wide compound terminal moraine impounding the lake, and narrower moraine remnants along Princess Stream to the south and west.

Waimean(?) moraines

The oldest moraines at Lake Tennyson, provisionally correlated with the Waimea Glaciation (Suggate 1965), occur at three localities: (1) a dissected ridge 0.6 km northeast of Maling Pass; (2) a poorly preserved boulder deposit on the hillslope 1.6 km south of Lake Tennyson (map unit gtw, Fig. 3); and (3) two small, flat-topped hills on the west side of the Clarence River 3.7 km downstream of the lake outlet. At all three localities, bouldery gravels of probable glacial origin occur beyond the limits of the better preserved Otiran moraines. Each landform is geomorphically subdued, dissected by erosion, and stands up to 70 m above the level of present drainages.

The extent of the Waimean(?) ice advance is uncertain south of Lake Tennyson. Anomalously large boulders occur on the hillside south of the lake up to 50 m above the crest of

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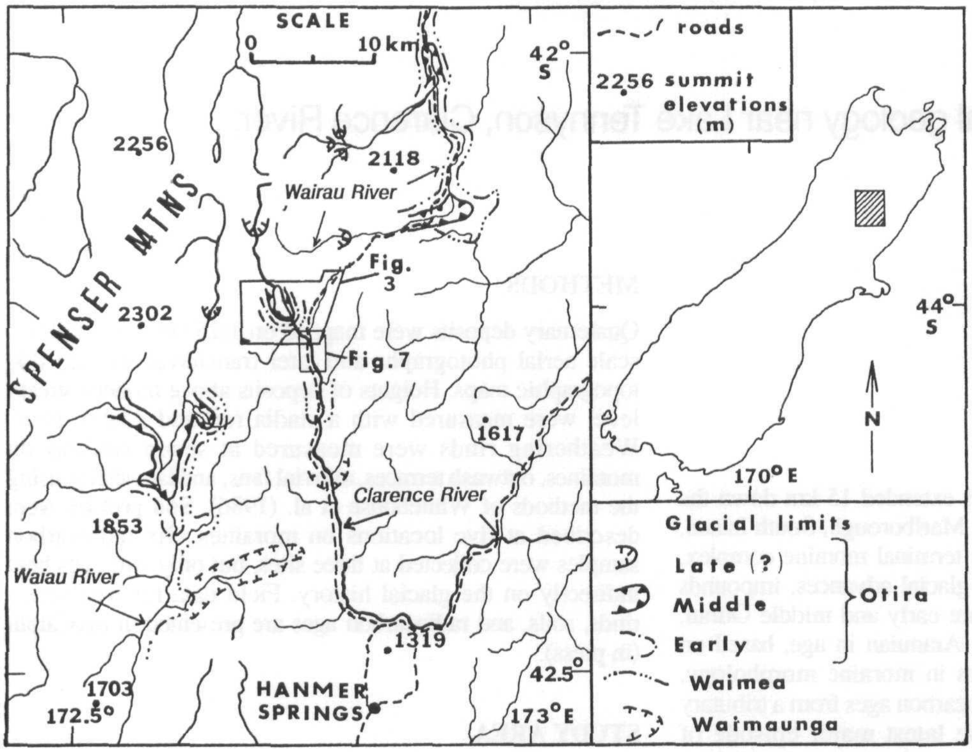

Fig. 1 Location map, regional drainage near Lake Tennyson, and glacial limits in the Clarence, Waiau and Wairau Valleys as interpreted by previous workers (Suggate 1965, fig. 16; Clayton 1968, fig. 5). Two proposed Waimean limits are shown in the Clarence Valley—an upvalley position (Suggate 1965) and a downvalley position (Clayton 1968). This study supports Clayton, but his late Otiran limit should be moved to the southern lake shore (see Fig. 3).

Fig. 2 Oblique aerial photograph of Lake Tennyson and the moraine complex, looking northwestward. The Clarence River flows southward (to lower left) out of Lake Tennyson, joined by Princess Stream (at left centre) and Serpentine Creek (bottom right). The early Otiran moraine (gto_1, Fig. 3) *is partially preserved south* (left) of Princess Stream, while the wide moraines impounding the lake are divisable into middle Otiran (gto_2) and late Otiran(?) – early Aranuian (gto_3) moraines. Braided channels of the middle Otiran outwash plain (ao_2) are visible in lower and left centre.

the outermost well-preserved Otiran moraine. Waimean(?) moraine remnants occur at least 3 km downvalley from the Otiran terminus, but their farthest extent is not known. Clayton (1968, fig. 5) tentatively identified the limit of his Horseshoe Glaciation (correlative with the Waimea) 11 km downstream from Lake Tennyson, beyond the limits of this study.

Early Otiran moraines

The oldest moraines with well-preserved ridge-like morphology are 1.4 km south of Lake Tennyson and on both valley walls of Princess Stream (map unit gto_1, Fig. 3). Each moraine is a single-crested, massive ridge with subdued hummocky topography along the relatively broad crest. Lateral moraines of Princess Stream and Lake Tennyson merge, indicating that their ice streams coalesced at this time. Outwash graded to these moraines is preserved as a small terrace 1.3 km SSW of the Lake Tennyson outlet (map unit ao_1, Fig. 3).

No radiocarbon-datable material was obtained from these moraines, which are more eroded and less completely preserved than are younger Otiran moraines upvalley. South of Lake Tennyson, the early Otiran moraine is separated from younger Otiran moraines by the extensive Princess Stream

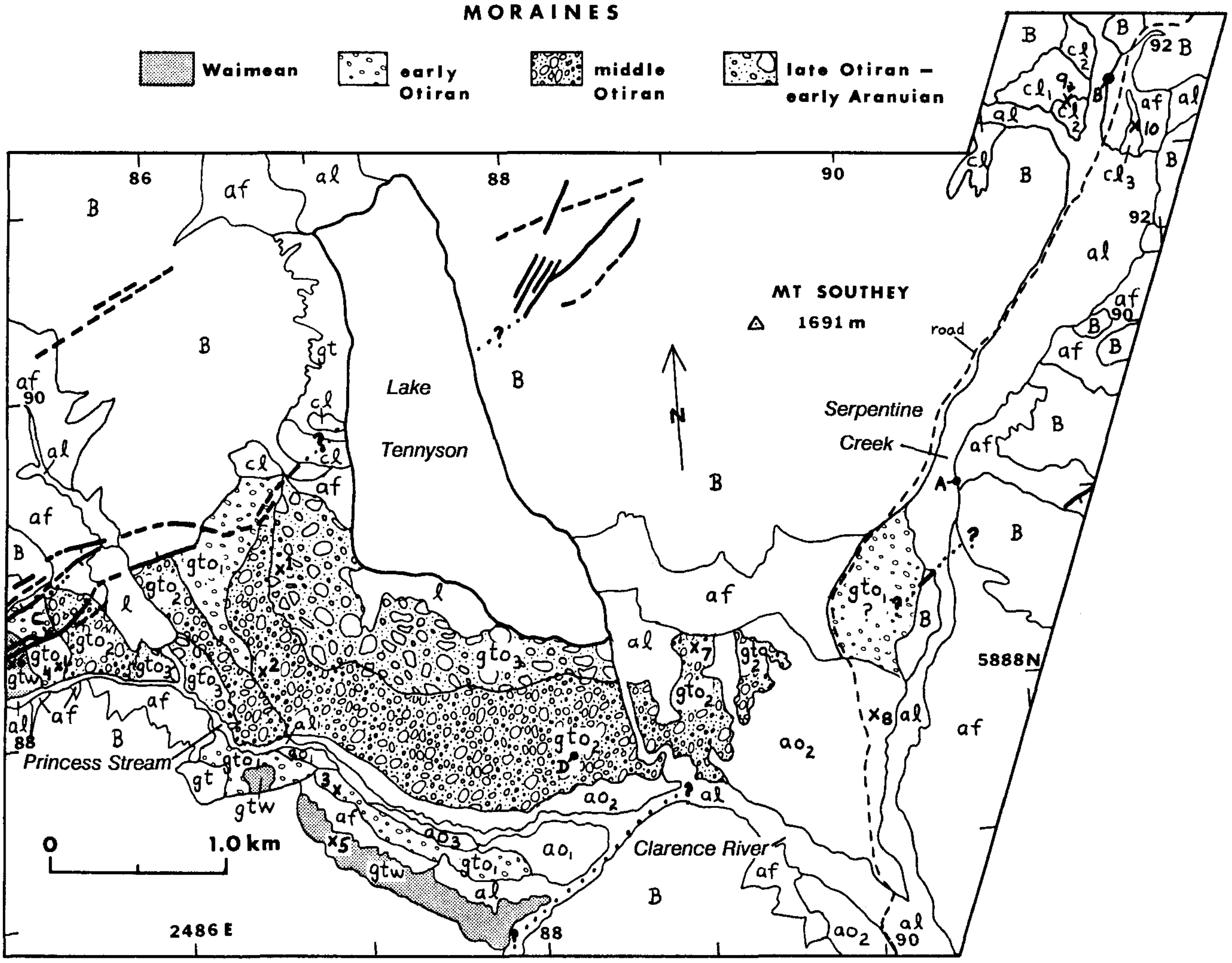

Fig. 3 Quaternary geologic map of Lake Tennyson and Serpentine Creek. Map unit abbreviations: gtw, Waimean till; gto_1, early Otiran till; gto_2, middle Otiran till; gto_3, Tennyson moraine (late Otiran or early Aranuian?); gt, Otiran till, undifferentiated; ao_1, early Otiran outwash; ao_2, middle Otiran outwash; ao_3, late Otiran – early Aranuian outwash; al, Holocene alluvium; af, Holocene alluvial fan; cl, landslide deposits, 1 = oldest; 3 = youngest; l, lake deposits; B, bedrock (Torlesse Supergroup). Heavy lines show Quaternary traces of the Awatere Fault, tick mark on downthrown side. Numbered "X"s are data stations referred to in Fig. 4 and 5. A•, location of Fig. 6 outcrop; B•, location of Fig. 7 outcrop; C•, Kumara 2_1 moraine displaced by Awatere Fault, vertical offset 13 m, dextral offset 19 m; D•, site of radiocarbon auger hole by McLea (pers. comm. 1990). Numbered ticks are NZMS 260 map co-ordinates.

outwash terrace (map unit ao_2, south of Lake Tennyson, Fig. 3). The position of the outwash suggests that Lake Tennyson ice retreated upvalley after depositing the early Otiran moraine, then readvanced, pushing Princess Stream into an ice-marginal position, and building the middle Otiran moraine (gto_2) while outwash (ao_2) was being deposited. Suggate (1965) attributed the moraine south of Princess Stream to an early Otiran advance, perhaps correlative with the Loopline advance on the West Coast (Suggate pers. comm. 1988), a conclusion supported by this study.

Middle Otiran moraines

The largest moraines at Lake Tennyson form a 0.7 km wide band of low, arcuate ridges and swales west and south of the lake (map unit gto_2, Fig. 3). Numerous closed depressions and small ponds occur in the swales, and moraine ridge crests are relatively narrow (3.0–3.6 m), irregular, and hummocky. Moraine sideslopes maintain maximum inner and outer slope angles of 27° and 18°, respectively. The outermost ridge of this moraine complex merges with the true left lateral moraines of Princess Stream, indicating that the two glaciers coalesced. Princess Stream lateral moraines are plastered against the inside of the more massive early Otiran moraines (map unit gto_1, Fig. 3) for most of their length, but multiple, low, ice-stagnation ridges occur on the valley floor. Multiple ridges in both valleys suggest a succession of recessions and readvances within this glacial episode. Outwash of this advance covers a 1 km wide plain southwest of Lake Tennyson (Fig. 2, and map unit ao_2, Fig. 3) and continues downstream as the main aggradation surface in the upper Clarence Valley. Correlation of gto_2 moraines and outwash with the middle Otiran (Kumara 2_2 deposits of Suggate 1965) rests mainly on their geomorphic position, large volume, and relative morphologic sharpness of ridges and channels.

The Tennyson moraine (late Otiran / early Aranuian?)

The youngest advance at Lake Tennyson left multiple moraine ridges which comprise a 0.5 km wide belt impounding the

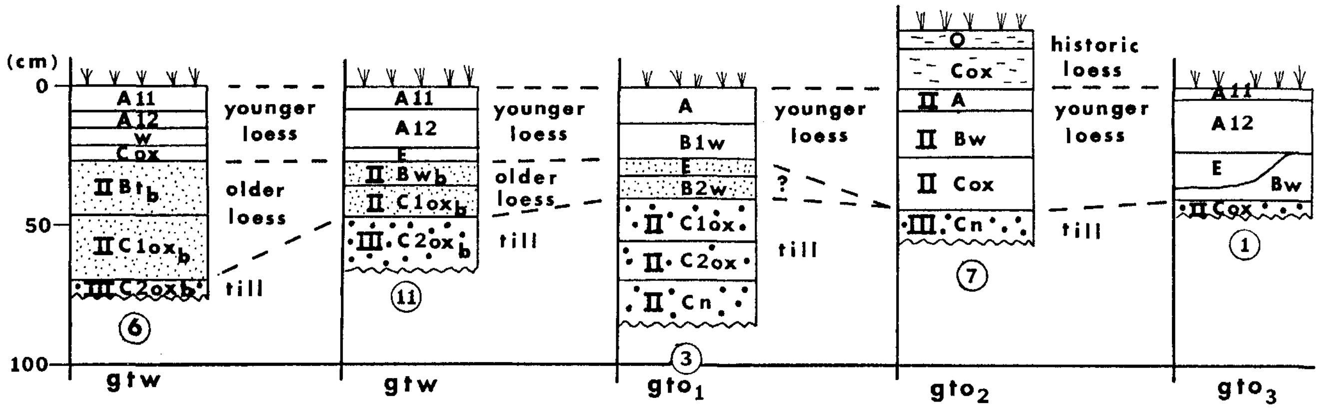

Fig. 4 Comparison of soil profiles from moraines ranging in age from Waimean(?) (gtw) to late Otiran–early Aranuian (gto_3). Circled numbers under profiles correspond to station locations on Fig. 3 and 8. Waimean(?) moraines typically have compound soils developed on an older and younger loess, whereas middle and late Otiran moraines exhibit only younger loess soils. The soil on the early Otiran (gto_1) moraine appears intermediate in development between older and younger soils.

present lake (map unit gto_3, Fig. 3). This moraine is informally termed the Tennyson moraine. To the west, ridges of this young moraine seem to override and, to the south, crosscut, the older middle Otiran moraine ridges. Moraines are morphologically sharp, have crest widths of 3.5–4.5 m, and maximum inner and outer slope angles of 28–30° and 20°, respectively. In Princess Stream, low lateral and terminal moraines of this advance are inset within slightly larger middle Otiran moraines. Outwash probably correlative with this advance (map units ao_3, al_2, Fig. 3) is confined to narrow valleys cut into middle Otiran till and outwash, and is preserved only as small, discontinuous terraces a few metres above modern stream level. Pollen data from bogs (McLea pers. comm. 1990) suggest that this moraine is considerably younger than the adjacent gto_2 moraine.

POST-OTIRAN DEPOSITS

Alluvial fans encroached upon the floodplains of Serpentine Creek and the Clarence River after deposition of latest glacial outwash c. 9.2 ka ago. These early Holocene fans are now incised, and inset younger fans are graded to modern stream level (fans not differentiated on Fig. 3). Several generations of landslides were deposited at the base of Island Saddle from source areas in the mountains to the west. These slides (cl_1, cl_2, and cl_3 on Fig. 3) originated in the Awatere Fault zone, where Torlesse greywacke has been crushed and sheared to clay. Radiocarbon ages and weathering-rind data from slides cl_2 and cl_3 (discussed later) indicate that they are late Holocene in age.

SOIL PROFILES

The degree of soil-profile development is commonly used to distinguish glacial and glaciofluvial deposits of different ages (Birkeland 1981, 1982, 1984a, 1984b; Shroba & Birkeland 1983; Knuepfer 1988; Rodbell 1990). Six soil profiles were described on deposits ranging in age from late Otiran(?) to Waimean (located on Fig. 3). Soils on Otiran moraines (gto_1, gto_2, and gto_3) exhibit A/Bw/Cox profiles developed in a cap of loess 25–40 cm thick (Fig. 4). Soils on Waimean deposits are more complex, consisting of an upper, Otiran-like soil in

Table 1 Selected field data for soils.

Soil no.	Parent material	Horizon*	Depth (cm)	Colour†	Texture‡
1	gto_3	A1	0–5	2.5Y4/4	t,l
		A2	5–23	10YR3/4	sl
LT = 40 cm		E	23–31	10YR7/1	si,g
Rub. = 45.3		Bw	31–40	10YR5/8	gl
		2Cox	40–43+	2.5Y4/4	stl
3	gto_1	A1	0–5	10YR3/6	t,l
		A2	5–17	10YR4/6	l
LT = 26 cm		E	17–21	10YR6/8	l
Rub. = 50.9		Bw	21–26	10YR5/8	l
		2C1ox	26–36	2.5Y4/4	gl
		2C2ox	36–50+	2.5Y4/4	stl
4	gto_1	A	0–13	10YR3/6	l,t
		B1w	13–26	10YR4/6	l
LT = 40 cm		E?	26–31	10YR6/6	l
Rub. = 51.6		B2w	31–40	10YR5/8	sl
		2C1ox	40–54	2.5Y5/4	gl
		2C2ox	54–70	2.5Y4/4	gls
		2C3ox	70–88+	2.5Y4/2	sg
6	gtw	A1	0–10	10YR4/6	l
		A2	10–16	10YR5/4	l
LT = 70 cm		Bw	16–21	10YR5/6	l
Rub. = 53.1		Cox	21–27	10YR4/6	l
		2Btb	27–47	2.5Y4/4	sl
		2C1oxb	47–70	2.5Y5/6	gls
		3C2oxb	70–75+	2.5Y5/4	gs
11	gtw	A1	0–8	10YR3/6	si
		A2	8–22	10YR5/4	si
LT = 46 cm		E	22–26	10YR6/6	si
Rub. = 54.5		2Bwb	26–35	10YR5/8	gsi
		2C1oxb	35–46	10YR5/6	gsi
		3C2oxb	46–65+	2.5Y5/4	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; st, stones; t, turf; 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 88 cm, the depth of the deepest described profile (after Birkeland 1982, p. 121).

loess, underlain by a buried soil developed on older loess. Aggregate thickness of the superposed loesses ranges from 46 to 70 cm.

Quantitative field data (Table 1) show only slight differences in soil texture, structure, and colour among soils that span an estimated time period of c. 150 ka. The clearest age indicator is the increase of soil reddening (rubification) with increasing age. Such a trend was also observed by Birkeland (1984b) in the Mount Cook area and by Rodbell (1990) in the Arrowsmith Range. However, the weak trends of other soil parameters with age over a span of c. 150 ka suggest that part of the older soils may have been removed or modified. Such removal has been termed "pedospheric stripping" by New Zealand soil scientists (Tonkin et al. 1974).

WEATHERING-RIND DATA

The thickness of weathering rinds on surface clasts generally increases with inferred deposit age (Fig. 5 and Table 2). A deposit "rind age" can be estimated from empirical equations relating mean and modal rind thickness to deposit age (Knuepfer 1988; equations in footnote of Table 2). Calculated rind ages for the Holocene landslides (Table 2) agree reasonably well with radocarbon ages from streamcut exposures (Table 3). The rind ages of the gto$_3$ moraine are slightly younger than the minimum radiocarbon age of 11 800 ± 110 yr B.P. This discrepancy could mean that the gto$_3$ moraine is of early Aranuian, rather than late Otiran age, or that rind thickness underestimates the true age of the moraine owing to some environmental factors. The rind ages of older moraines (gto$_2$, gto$_1$, gtw) are significantly less than ages estimated from regional correlation. For example, modal rind thickness on type middle Otiran outwash (the 20 ka Speargrass surface; Whitehouse et al. 1986) is 7.7 mm, compared with only 6.0 mm for the middle Otiran moraine at Lake Tennyson. The thinnner rinds at Lake Tennyson may result from past burial of some sampled clasts under loess, followed by more recent exhumation.

Histograms of rind thickness (Fig. 5) show subtle differences among Otiran and Waimean moraines. The Tennyson moraine (gto$_3$ in Fig. 5) carries clast rinds considerably thinner than those on the adjacent middle Otiran moraine. The implied age difference may be more consistent with an early Aranuian, rather than late Otiran, age for the Tennyson moraine. Rind histograms for early Otiran and Waimean moraines show many distinct modal peaks, suggesting that multiple ages of rinds are present in the samples. These multiple rind modes may be due to periodic rind spalling caused by fire, or by the addition of fresh surface clasts by frost heaving or rockfall (Whitehouse et al. 1986).

RADIOCARBON CHRONOLOGY

Seven radiocarbon ages are available, from deposits ranging in age from middle Otiran to late Holocene (Table 3). McLea (pers. comm. 1990) cored a bog on the gto$_2$ moraine (location D, Fig. 3) and obtained a basal peat radiocarbon age of 11 800 ± 110 yr B.P., which serves as a minimum age estimate for this moraine. This minimum age allows the possibility that the gto$_2$ moraine is of late Otiran (Kumara 3 equivalent, 13–14 ka) age. However, morphologic and weathering-rind data summarised previously indicate that gto$_2$ is significantly older than gto$_3$, and must predate the latest glaciation as dated by the radiocarbon ages described below.

Six radiocarbon samples were dated from cuts in the Serpentine Creek area (Table 3 and Fig. 3). Stratigraphic interpretation of one streamcut (Fig. 6) suggests Serpentine Creek began to aggrade with relatively fine alluvial gravels at 11 310 ± 130 yr B.P. (Beta-30062) and retained an aggraded, peaty, stabilised floodplain until about 9160 ± 120 yr B.P. (Beta-30061), when large alluvial fans began to encroach the floodplain. Aggradation in Serpentine Creek may have been caused by: (1) deposition of the Lake Tennyson moraine (gto$_3$, age $\ll$ 11.8 ka) and associated outwash in the Clarence Valley, which raised the base level for Serpentine Creek; (2) some unidentified local base-level disturbance (landsliding, alluvial fan encroachment); or (3) an increase in sediment yield from upstream in the Serpentine Creek drainage basin, caused by either landsliding or climatic change. If the aggradation was related to glacial climate (directly by glacial outwash, or indirectly by paraglacial mass movements; Church & Ryder 1971), then the last cold-climate period in the area may have occurred from c. 9.2 to 11.3 ka.

Two Holocene ages from superposed landslide deposits in Serpentine Creek (Fig. 7; 2830 ± 80 yr B.P.; Beta-31591 and 3130 ± 80 yr B.P.; NZ 7639) are roughly correlative with ages

Table 2 Weathering-rind data from surface clasts on landslides and moraines.

Deposit	Station no.	LSM (mm)	Mean (mm)	Apparent age (yr B.P.) (LSM)*	Apparent age (yr B.P.) (Mean)†	Radiocarbon age‡ (yr B.P.)
cl$_3$	10	1.0	0.67	973 ± 70	629 ± 62	<2830 ± 80
cl$_2$	9	2.6	1.89	3467 ± 399	2497 ± 360	2830 ± 80 to 3130 ± 80
gto$_3$	1	4.5	4.57	7192 ± 1000	8081 ± 1465	<11 800 ± 110
gto$_2$	2	6.0	5.57	10 545 ± 1597	10 514 ± 1991	c. 20 ka
gto$_1$	3	6.0	5.10	10 545 ± 1597	9350 ± 1736	c. 60 ka
gto$_1$	4	7.0	6.50	12 944 ± 2044	12 911 ± 2525	c. 60 ka
gtw	5	7.0	6.2	12 944 ± 2044	12 124 ± 2348	c. 150 ka

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

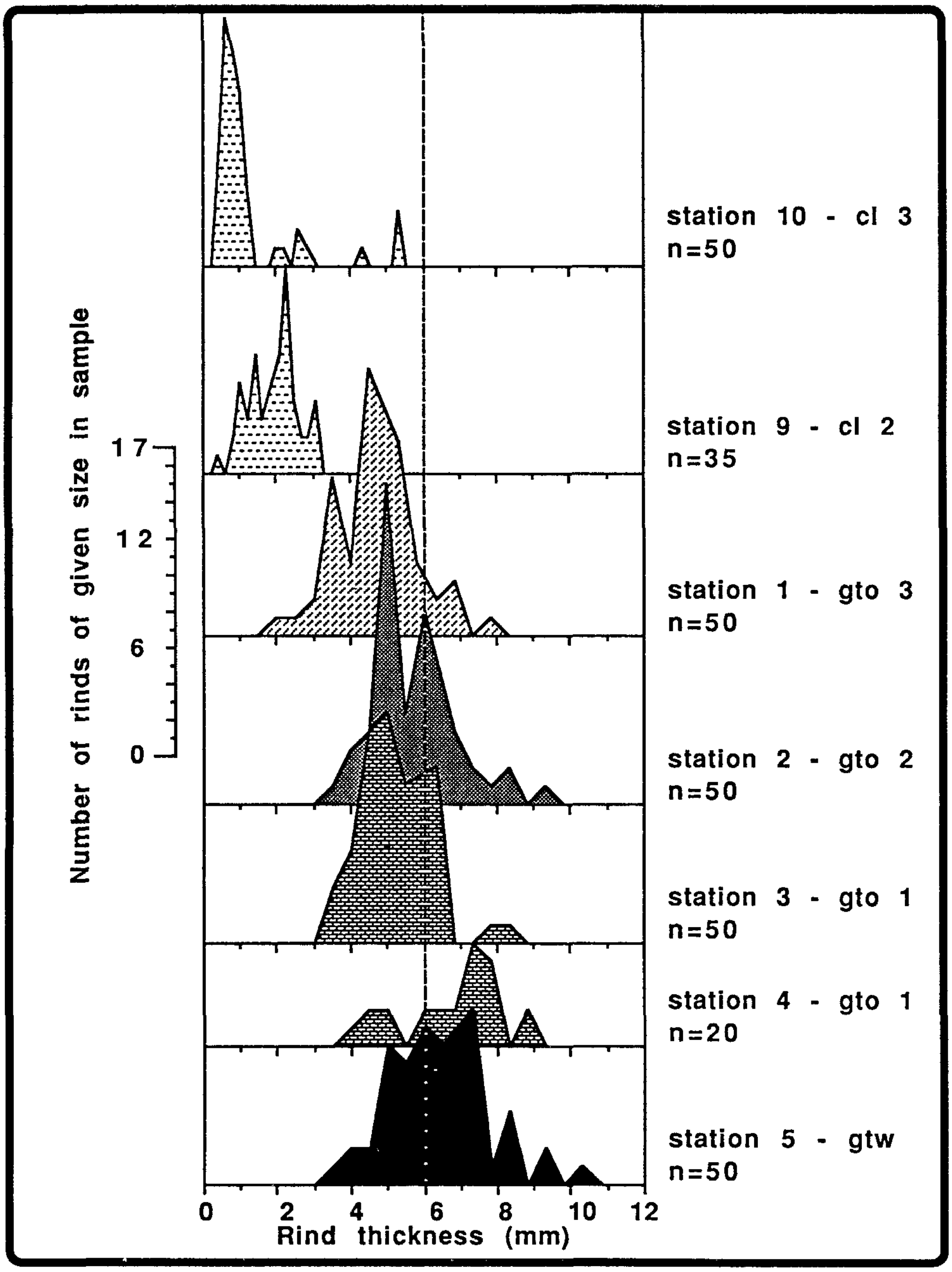

Fig. 5 Histograms of weathering-rind thicknesses on surface clasts from Quaternary deposits near Lake Tennyson. Station numbers and deposit abbreviations are the same as on Fig. 3. Deposits of similar age have a similar shading.

that bracket the penultimate surface-faulting earthquake on the Awatere Fault, as dated by Knuepfer (1987) at the Saxton River, 35 km to the northeast. This temporal coincidence, and the position of the landslide source area in the Awatere Fault zone, led McCalpin (1989) to speculate that one or both of these landslides were triggered by seismic shaking, although heavy rains could also have been the trigger.

Two radiocarbon ages from a peat and forest bed on terrace T_3, 6.7 km downstream on the Clarence River (Fig. 8 and 9; 1870 ± 100 yr B.P.; NZ 7641 and 2680 ± 60 yr B.P.; Beta-30064), indicate a late Holocene age. The older sample was collected from the base of a 0.75 m thick section of peat, which may represent an early channel fill, whereas the younger sample came from a thinner peat which probably accumulated on the terrace surface after the channel was filled.

POST-OTIRAN HISTORY AND THE AWATERE FAULT

The main traces of the Awatere Fault cross Lake Tennyson near its centre, and displace Otiran moraines on the west side of Lake Tennyson and post-Otiran alluvial fans and lake deposits near Princess Stream (Fig. 3). A series of upslope-facing fault scarps displaces the crest of the early Otiran lateral moraine west of Princess Stream (location C, Fig. 3); the largest scarp displaces the moraine crest 19 m dextrally and 13 m vertically (south side up). Additional displacement occurs along a parallel fault trench at the moraine/bedrock contact, but cannot be quantified. Small downslope-facing scarps, 1–2 m high, traverse the post-Otiran deposits on the valley floor of Princess Stream, and may represent only the latest faulting event.

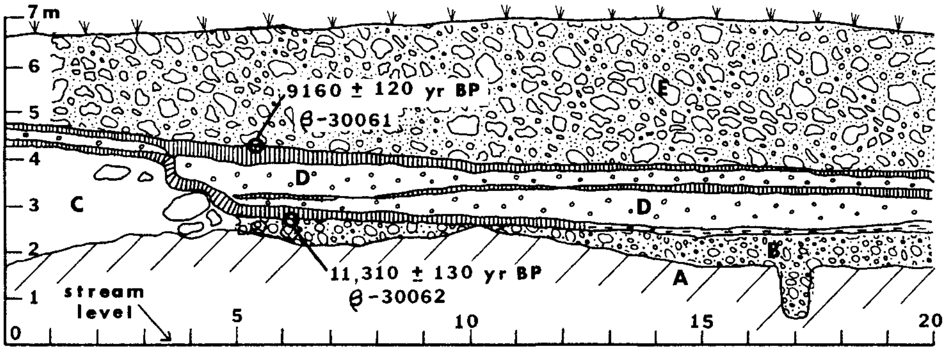

Fig. 6 Streamcut on the eastern side of Serpentine Creek (location A in Fig. 3). A, covered; B, pebble gravel; C, diamicton, early Otiran(?) till; D, fine gravel and sand, with interbedded clay (horizontal dashes) and peat beds (vertical lines); E, alluvial fan gravel, underlies surface of afy_1, early Holocene alluvial fan. Radiocarbon ages bracket the inferred period of floodplain aggradation between 9.2 and 11.3 ka; details of radiocarbon ages are given in Table 3.

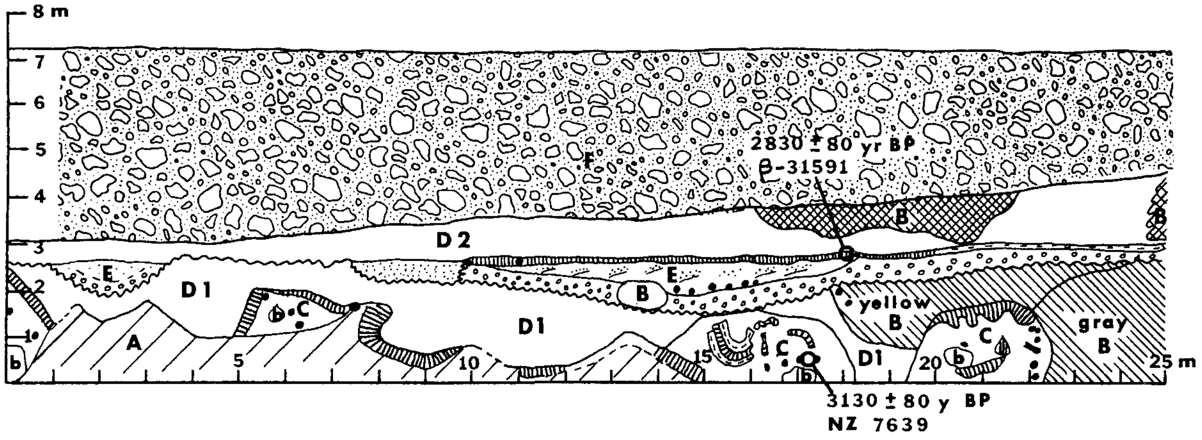

Fig. 7 Streamcut on the eastern side of Serpentine Creek (location B in Fig. 3). A, covered; B, blocks of crushed and sheared greywacke bedrock; C, chaotic landslide deposit with gravel, sand, silt, clay, contorted peat beds, stumps, logs and branches, correlated with map unit cl_2 on Fig. 3; D1, diamicton, debris flow?; D2, similar to D1 but contains lenses of shattered greywacke, correlated with map unit cl_3 on Fig. 3; E, stream gravels and sands, cut unconformably (jagged line) into underlying units D1, C and B, overlain by thin clay (horizontal dahes) or peat (vertical lines); F, alluvial fan gravel. Diagonal ruled and cross-hached areas are shattered blocks of greywacke bedrock. Radiocarbon age 3130 ± 80 yr B.P. is from a log in unit C, probably a valley-floor forest overrun by landslide cl_2. Radiocarbon age 2830 ± 80 yr B.P. immediately predates landslide cl_3.

Table 3 Radiocarbon ages from the upper Clarence Valley and Serpentine Creek.

Lab. no.[1]	Radiocarbon age[2] (years B.P.)	Pretreatment	Material	Locality[3]	Stratigraphic setting
NZ 7641	1870 ± 100[4]	Hot H_2O, hot H_3PO_4 extraction.	peat and small branches	Clarence River N31/902852	Base of in-place peat atop 4.3 m terrace[4].
Beta-30064	2680 ± 60[4]	Hot HCl, NaOH, HCl soakings.	wood	Clarence River N31/902852	Top of overturned(?) block of peat.
Beta-31591	2830 ± 80	Hot HCl dispersion, distilled H_2O rinse.	peat and twigs	Serpentine Creek N30/917913	Underlies younger landslide[5].
NZ 7639	3130 ± 80	Hot H_2O, hot H_3PO_4 extraction.	wood	Serpentine Creek N30/917913	Tree trunks incorporated into basal part of older landslide[5]
Beta-30061	9160 ± 120	Hot HCl dispersion, distilled H_2O rinse.	peat	Serpentine Creek N31/906891	Overlies rounded river gravel; underlies alluvial fan[6].
Beta-30062	11 310 ± 130	Hot HCl dispersion, distilled H_2O rinse.	peat	Serpentine Creek N31/906891	Underlies rounded river gravel[6].

[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] Map grid location, NZMS 260 series.
[4] Samples from same deposit; age differences may result from differences in type of material, pretreatment, or exact stratigraphic position; see Fig. 9.
[5] See Fig. 7
[6] See Fig. 6.

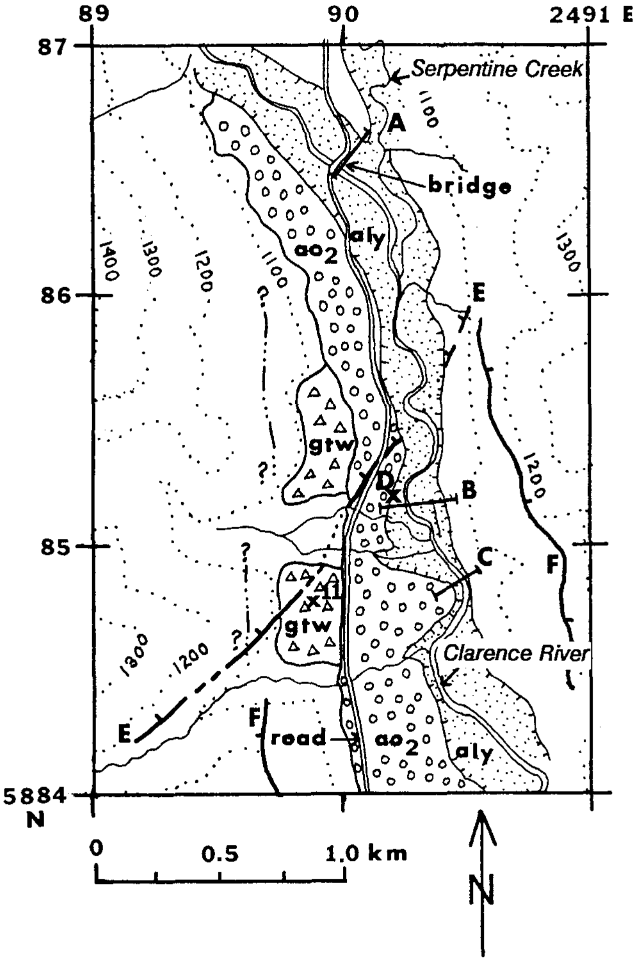

Fig. 8 Quaternary geology of the Clarence River downstream from the confluence with Serpentine Creek. Heavy lines show Quaternary fault scarps. A, B, and C indicate locations of topographic profiles of Fig. 9; D, location of two radiocarbon dates on peat (see Table 3); E, scarps of an unnamed fault parallel to the Awatere Fault; F, uphill-facing "ridge rents" (sackung?) in bedrock, perhaps a result of gravitational spreading into the Clarence Valley during seismic shaking. Map units are the same as in Fig. 3; unit aly is subdivided into terraces T_1, T_2, T_3, and T_4 in profiles of Fig. 9. Numbered grid ticks are NZMS 260 map co-ordinates.

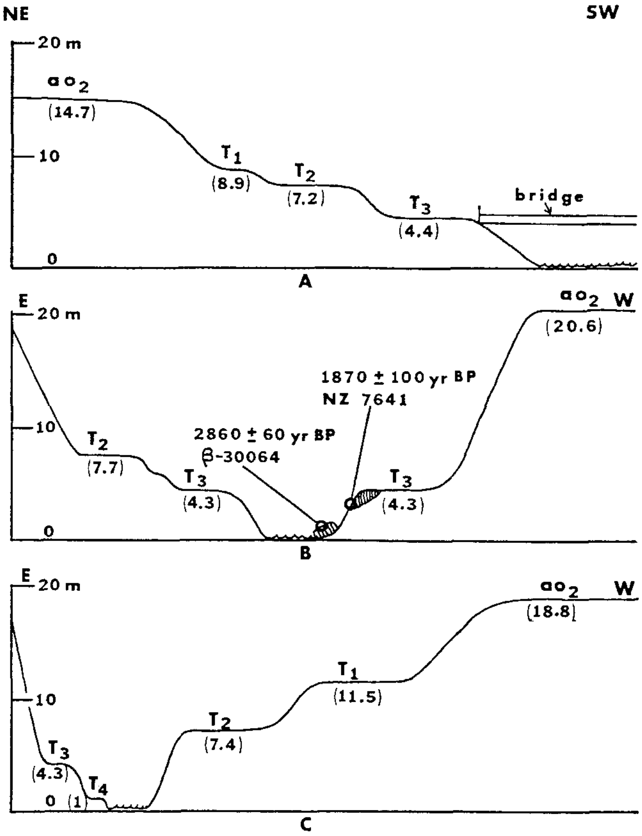

Fig. 9 Topographic profiles of terraces on Clarence River; horizontal dimension not to scale. Letters A, B and C refer to locations on Fig. 8. ao_2, middle Otiran outwash, main aggradation surface in the upper Clarence Valley. T_1 through T_4 are terraces cut into middle Otiran outwash. T_1 may be outwash from the Tennyson moraine. Height of terraces above modern stream level (in metres) given in parentheses. Difference in terrace heights upstream versus downstream of fault is attributed to Holocene faulting (see text for discussion).

Subsequent to the deposition of the extensive middle Otiran aggradation surface downstream from Lake Tennyson, the Clarence River has downcut 15–20 m. Four strath terraces have been formed (Fig. 8 and 9), several of which have been faulted by an unnamed fault that parallels the Awatere Fault. The two older alluvial surfaces (ao_2 and T_1 on Fig. 8) have different heights above modern stream level on the upstream versus the downstream side of a fault scarp. The differences in height of ao_2 on either side of the fault scarp (4.1–5.9 m, Fig. 8) are similar to the height of the fault scarp itself as it traverses the ao_2 surface (5.5 m). Terrace T_1 appears to be 2.6 m higher downstream than upstream of the fault, suggesting it also has been vertically displaced. Terraces T_2 and T_3 occur at the same height on either side of the scarp, so do not appear to be displaced (Fig. 9). These geometric relations suggest that two episodes of surface faulting have occurred: (1) faulting with about 2.9 m of vertical displacement between the deposition of ao_2 (c. 18–20 ka) and T_1 (c. 9.2–11.3 ka); and (2) additional faulting with about 2.6 m of vertical displacement between the deposition of T_1 and T_2 (c. 6.0–6.6 ka; Fig. 9). Ages of terraces can be estimated by the apparent incision rate of the Clarence River below the middle Otiran outwash surface (Fig. 10). No evidence of dextral displacement (such as offset of the ao_2 or T_1 terrace risers) was observed on this fault strand, although dextral offset on the main trace of the Awatere Fault at Princess Stream exceeds vertical displacement. This small fault scarp coincides closely with the epicentral location of the 1990 February 10 Lake Tennyson earthquake sequence (M_L 6.0, 5.7, 5.7). Those earthquakes produced no clear zone of surface fault rupture, but did create ground fissuring with small, inconsistent vertical displacements on bedrock ridges (Wood et al. 1990). Aftershocks of that sequence defined a 17 km long zone, roughly parallel to the mapped fault scarp, and exhibited dextral stike-slip focal mechanisms. The disparity between the vertical displacement inferred for the prehistoric fault scarp, and the dominantly dextral slip in the 1990 events, suggests either that: (1) the mapped fault scarp is not related to the 1990 causative fault; or (2) the mapped scarp was created along the 1990 causative fault but during paleoearthquakes of larger magnitude and different sense of slip than the 1990 sequence.

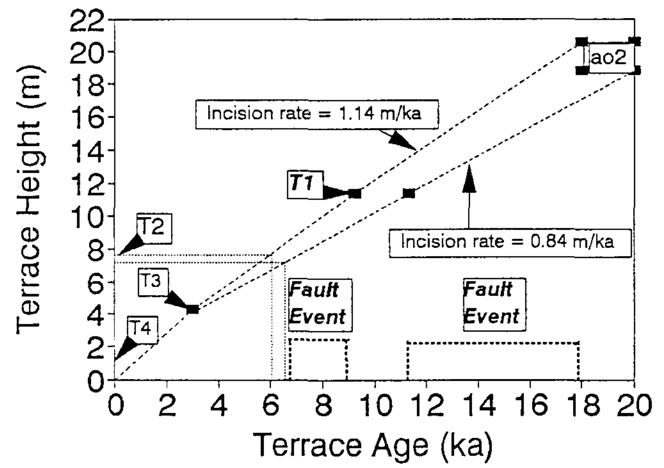

Fig. 10 Stream terrace heights above the Clarence River as a function of age. Terrace heights are from cross-sections B and C in Fig. 9. Inferred age of ao_2 (18–20 ka) is from regional correlation to middle Otiran deposits dated elsewhere (Whitehouse et al. 1986); ages of T1 and T3 are based on radiocarbon ages from Table 3. The apparent incision rates are used to interpolate the age of T2 (fine dotted lines). The inferred time periods for the two faulting events, as bracketed by dated terraces, are shown by heavy dashed lines.

CORRELATION WITH OTHER DATED MORAINES IN NEW ZEALAND

The two older radiocarbon ages (9160 ± 120 yr B.P.; Beta-30061 and 11 310 ± 130 yr B.P.; Beta-30062) which bracket the latest aggradation are significantly younger than commonly accepted ages for the latest Otiran glaciation in Marlborough, Westland, and Nelson (13 000–14 000 yr B.P.; Suggate & Moar 1970). This age discrepancy has two possible explanations: (1) the radiocarbon-dated beds represent only local aggradation of Serpentine Creek unrelated to glaciation; or (2) the latest glaciation in the Clarence Valley was not of late Otiran (Kumara 3 equivalent) age, but of early Aranuian (Holocene) age. Workers in Canterbury and Westland have dated several prominent moraines at between 10 250 yr B.P. and 12 414 yr B.P. (Mercer 1988; Basher & McSaveney 1989; Burrows 1989; McSaveney & Whitehouse 1989; Table 1). Mabin (1987, p. 89) stated that, about 11 500 yr B.P. "glacial advances was causing aggradation in the upper reaches of many mid-Canterbury valleys". If the aggradation dated at Serpentine Creek was indeed caused by latest glacial aggradation of the Clarence River, then it would follow that the Tennyson moraine (being the youngest moraine in the Lake Tennyson complex) would be early Aranuian in age. Pollen diagrams from bogs on the Tennyson moraine (McLea pers. comm.) confirm that the gto_3 moraine was deposited in the last cold-climate period to affect this area.

Several observations suggest that the Tennyson moraine is of late Otiran, rather than early Aranuian age: (1) the Tennyson moraine abuts the middle Otiran moraine, whereas early Aranuian moraines described by McSaveney & Whitehouse (1989) occur far upvalley from Otiran moraines; (2) soils on the Tennyson moraine are similar to those on the middle Otiran moraine; and (3) if the Tennyson moraine is of early Aranuian age, where is the moraine of the late Otiran ice advance? Resolution of this correlation dilemma will have to depend on future, more detailed geochronologic studies both here and elsewhere in the northern South Island.

CONCLUSIONS

Mapping and subdivision of Otiran moraines in the upper Clarence Valley generally confirm the work of Suggate (1965). The compound moraine at Lake Tennyson is mainly middle Otiran, while the inner one-third may be either late Otiran or early Aranuian in age. Poorly preserved early Otiran and Waimean(?) moraine remnants occur south of the compound moraine and along the margins of the Clarence Valley. Numerical and relative-dating techniques such as weathering-rind thickness and soil development have potential for differentiating Pleistocene moraines, but there are limitations. Soil-profile development distinguishes Waimean(?) moraines, which carry compound soils developed on two loess units, from Otiran moraines, which carry a simple soil developed on one loess unit. Among early and middle Otiran moraines and older post-Otiran terraces, soils are similar and are not reliable age indicators. In contrast, weathering rinds can distinguish deposits of late Otiran(?) and younger ages, but on deposits of middle Otiran age or older, rinds have apparently reached a steady-state(?) modal thickness of about 6–7 mm. Two radiocarbon ages bracket the latest episode of valley aggradation in Serpentine Creek (perhaps correlative with the latest glacial advance), between about 9.2 ka and 11.3 ka. Radiocarbon dating of early Aranuian moraines elsewhere in the South Island (McSaveney & Whitehouse 1989; Table 1) also has yielded ages within this range. It is not possible to physically connect the dated aggradation site to the youngest moraine at Lake Tennyson, however, so it is not certain that the 9.2–11.3 ka ages constrain the age of latest glaciation. However, one radiocarbon age from the Tennyson moraine complex, and seven late-glacial radiocarbon dates from the adjacent upper Wairau Valley, also cluster in the range 9.2–12.6 ka (McCalpin 1992, this issue), supporting the idea of an early Aranuian advance.

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