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Quaternary deposits and landscape evolution in northeast Southland, New Zealand

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ABSTRACT

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Three kinds of Quaternary sediments are present in northeast Southland: aeolian deposits, terrace gravels, and hill slope colluvium. The aim of this paper is to review and describe the Quaternary sediments and erosion pattern of northeast Southland and reconstruct the likely climate under which sedimentation and erosion occurred.

Aeolian deposition occurred intermittently from 250,000 yr B.P. but stratigraphic studies indicate widespread erosion of loess in the period 80,000–25,000 yr B.P. before a final period of loess accumulation in the late Otiran ($\delta^{18}O$ stage 2).

Terrace gravels are attributable to two sources. A younger suite of three terraces is attributed to aggradation phases of the Mataura River. An older suite of three more weathered terraces is attributed to aggradation by a river flowing eastwards through the Waimea Plains from Lumsden to Gore. The river is named the Lumsden River. At about 180,000 yr B.P. this river ceased flowing through the Waimea Plains.

Colluvium on hill slopes is regionally stratified into two layers. The lower deposits are identified as weathered sand and gravel sized colluvium derived from argillite and siltstone screes, dated as being formed before 29,000 yr B.P., and attributed to $\delta^{18}O$ stage 4. The upper, stonier deposits are attributed to $\delta^{18}O$ stage 2.

The erosion and deposition pattern of aeolian deposits, terrace gravels and slope colluvium cannot be explained by a temperature drop of c. 5°C calculated for the last glacial period. We conclude that on lowlands vegetation cover was periodically limited by extreme droughts and cold windy conditions, causing erosion of previously-deposited loess and encouraging scree formation on slopes. During these periods the severe climate of northeast Southland approximated to that of a cold desert.

Introduction

Lowering of temperature by about 4–5°C based on snowline depression during the last glaciation (Porter, 1975; Soons, 1979) would mean that the tree line in Southland would have been at about 300 m altitude (McGlone and Bathgate, 1983) and areas of northeast Southland above this altitude would have had grass or shrubland vegetation. Observations by the authors on aeolian and colluvial deposits suggest however that much of the northeast Southland landscape was unvegetated at times during glacial periods, i.e., that the influence of the climate on vegetation was greater than can be explained by a fall in mean annual temperature of 5°C alone. Other climate factors such as wind and precipitation must have had a strong influence on the sedimentation pattern and it is the purpose of this paper to review and describe the Quaternary sedimentation and erosion events of northeast Southland and reconstruct the likely climate at this time.

Review of geology and Quaternary climate

Geology and physiography

The northeast Southland area considered in this paper is approximately that area northeast of a line joining Lumsden and Edendale (Fig.1). The

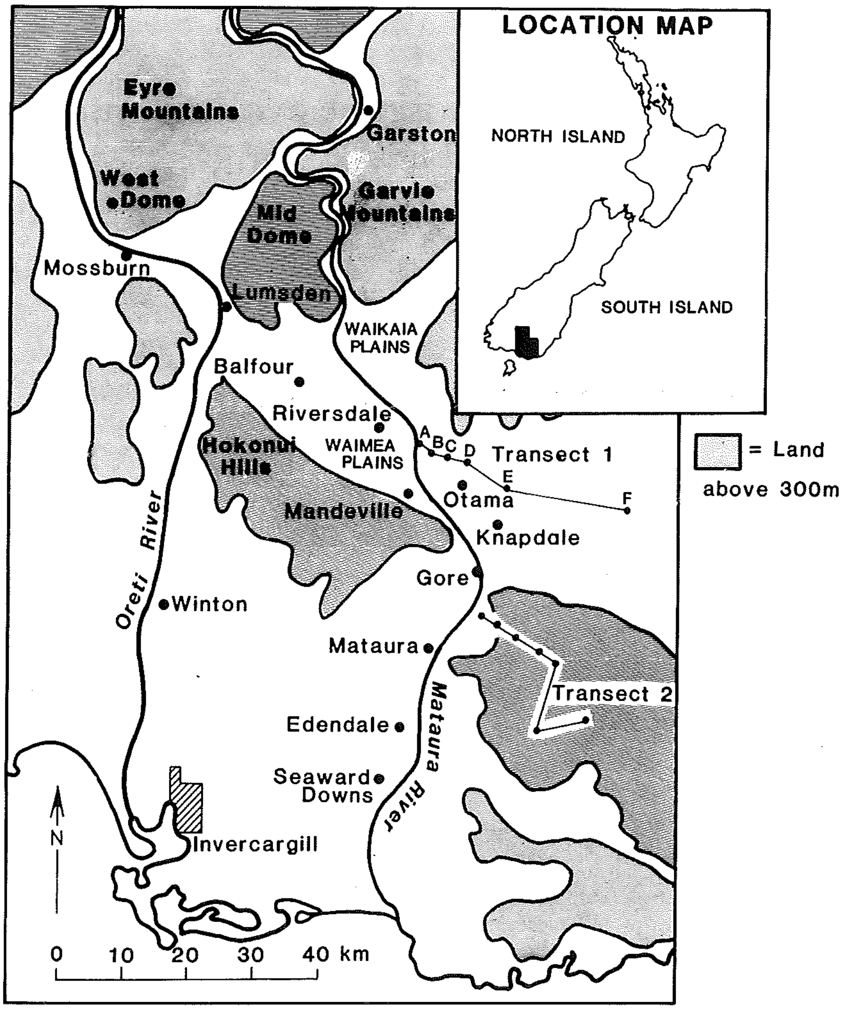


Fig.1. Location map, showing location of loess transect *1* (see Fig.2) and loess transect *2* (described by McIntosh and Eden 1988).

town of Mandeville, at the centre of the area considered, occurs at 46°00'S, 168°49'E. The southern part of the area is dominated by the Hokonui Hills formed from the Triassic and Jurassic tuffaceous greywacke rocks of the Southland syncline and the northern part is dominated by the Eyre and Garvie Mountains formed from predominantly schist and greywacke rocks (Wood, 1966). Between these two hilly and mountainous areas lie the Waikaia Plains, Waimea Plains and the downlands around Otama and Knapdale. The underlying rocks in these areas are mostly Permian argillites and siltstones overlain by varying thicknesses of Tertiary marine and estuarine deposits, and Quaternary loess and gravels (Wood, 1966). None of the area was glaciated during the last glaciation. The nearest permanent snow was on the tops of the Eyre and Garvie mountains and a valley glacier briefly occupied the Mataura valley at Garston (Wood, 1966).

Present climate

The present climate of Southland is governed by the interaction of the prevailing westerly winds with physiography. The western ranges have a rainfall of about 8000 mm but in the rainshadow areas of the east around Winton and the Waimea Plains rainfall is one tenth of this figure (Sansom, 1984) and soils with a storage capacity of 100 mm experience a moisture deficit of about 90 mm over the three summer months (R. Aldridge, pers. comm.). Mean annual temperature at Gore, at 123 m altitude, is 9.7°C and the warmest summer months (January and February) have a mean temperature of 14.0°C. The coolest winter month (June) has a mean temperature of 4.4°C. Air frosts of −8.9°C have been recorded in the period 1943–1980 (N.Z. Meteorol. Serv., 1983). The tree line occurs at about 1000 m altitude and in most places erosion of soils and rocks below this altitude is minimal under the predominant pasture and forestry land uses, an exception being gully and sheet erosion on Mid Dome (Fig.1).

Past climate

From pollen and vegetation studies McGlone and Bathgate (1983) concluded that in the period 12000 yr B.P. to 9400 yr B.P. temperatures were 4–5°C lower, but that extremely cold intervals occurred. In the southern hemisphere westerlies were stronger at mid- and low latitudes close to the last glacial maximum (Newell et al., 1981; Petit et al., 1981; Salinger, 1983; Bowler and Wasson, 1983; Wasson, 1983) with estimates of increased windiness varying from 17 to 80% higher than at present. The increased windiness is attributed to northward shift of the circumpolar westerly belt (Thiede, 1979) which up to 14,700 yr B.P. caused significantly higher oceanic sedimentation rates than at present (Stewart and Neall, 1984). Salinger (1983) concluded that the stronger regional westerly circulation at 18,000 yr B.P. produced a cool moist climate in the west and south of the South Island giving higher rainfall in southern New Zealand, but very dry conditions on the east coast. Stewart and Neall (1984) suggested a date of 14,700 yr B.P. for a return to a present-day wind pattern, based on evidence of a core at 40°S, a substantially earlier date than the 9400 yr B.P. suggested by McGlone and Bathgate (1983) for Southland.

Quaternary deposits

The cooler climate of the glacial periods was accompanied by an erosion and sedimentation pattern on lowlands that differed markedly from that prevailing today. Loess deposits of glacial age are widespread in northeast Southland below 300 m altitude (N.Z. Soil Bureau, 1968; Bruce et al., 1973) and deposition of loess stopped about 10,000 yr B.P. (McGlone and Bathgate, 1983). The main source of loess is likely to have been the floodplains of major rivers, which had braided, shifting channels and were therefore largely unvegetated during glacial periods. The main sources of alluvium from which loess was derived are shown by Bruce et al. (1973, map 5). Bruce (1973) considered that loess deposition episodes were interrupted by periods of wind and fluvial erosion of loess. He called the wind erosion process "pedosphere stripping" because (he argued) it affected only A and B horizons, leaving the compact subsoils largely intact. In addition to loess, aeolian deposits in the form of dunes were recognised by Bruce (1984) in the Chatton district.

Although hilly and steep land would be expected to be more sensitive to erosion than soils in loessial material, the origin of slope colluvium in Southland has not been studied. For example Leamy (1973) does not mention any Southland studies in his review of papers on Quaternary processes.

Extensive terraces are recognized as being caused by aggradation of river gravels during cold climate episodes (Suggate, 1965). In the Mataura catchment Willett (1948) identified four terraces south of Gore. Wood (1966) divided the terraces into more weathered (h1) terraces of the "penultimate and older" glaciations and less weathered (h2) deposits of the last glaciation.

Aeolian deposits

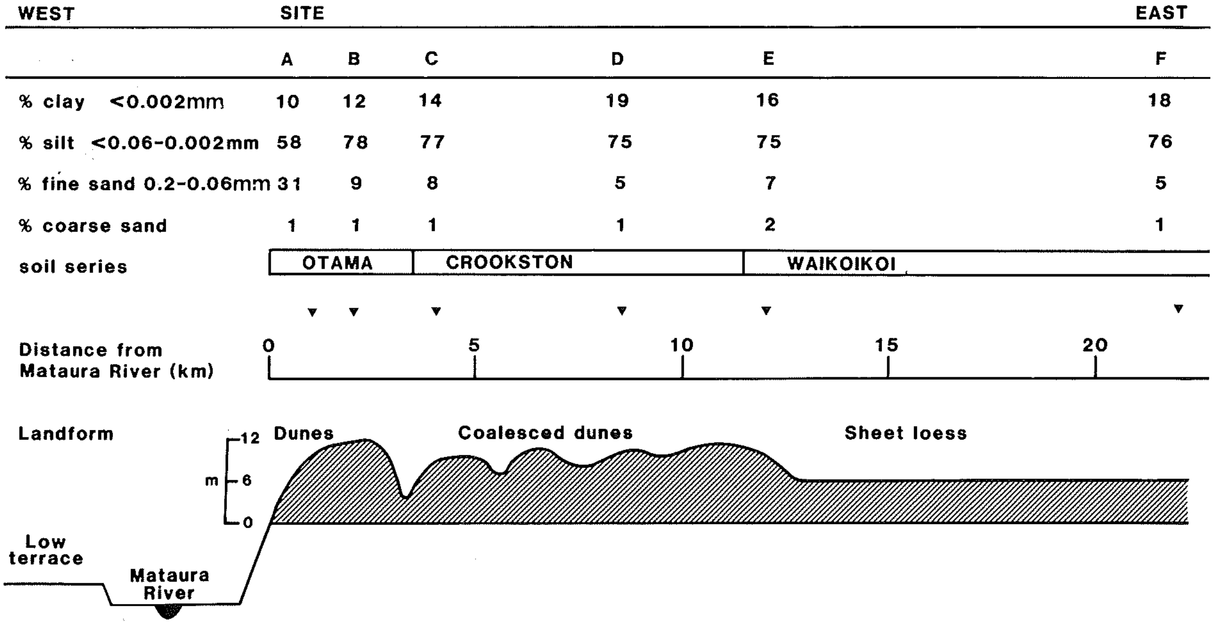
Nature and distribution

Loess deposits more than 1 m thick are widespread below 300 m altitude (Wood, 1956; Bruce et al., 1973) and local up to 400 m altitude (McIntosh, unpublished data) but notably absent from large areas of the Waimea and Waikaia Plains. Wood (1956) noted that local rocks were a source for loess deposits near Gore but Bruce (1973) emphasised regional sources. Both authors, however, agreed that the loess had been chiefly deposited by westerly winds. The main evidence for a westerly source was the occurrence of loess east of the Oreti and Mataura Rivers (NZ Soil Bureau, 1968), which are assumed to have been major carriers of loess-forming silt and fine sand.

McIntosh and Eden (1988) demonstrated that the mantle of loess over the tuffaceous greywacke rocks of eastern Southland was derived from two sources: (1) Mataura floodplain deposits, composed of sediment derived from the schist and greywacke rocks of northern Southland; and (2) a local source composed of minerals derived from tuffaceous greywacke. The relative importance of the sources could be estimated by the ratios of key minerals. A plot of selected ratios (Eden et al., 1987) showed that with increasing distance eastward (see Transect *2* in Fig.1) local sources provided a greater proportion of the loess. The increasing "dilution" of the windborne Mataura source loess by tuffaceous greywacke loess with increasing distance eastwards confirmed that winds from a westerly quarter carried the loess.

East of the Mataura River near-source deposits are generally thicker and contain more fine sand and less clay than distal deposits (Fig.2), confirming a westerly origin. Topographic relationships also support a westerly origin for the aeolian deposits. Near-source aeolian deposits occur in the form of dunes on the southwest side of terraces often with long axes parallel to terrace margins (*V*, *W*, *X*, *Y* in Fig.3), but also as isolated deposits (Fig.3). Dunes *P*, *Q* and *Z* in Fig.3 are associated with minor valleys to the west or southwest, and the dune swarm (*R*, *S*, *T*, *U*) lies 200 m north of an east–west ridge, i.e. at a point where south–west winds would decrease in speed and drop a proportion of their suspended or saltating sediment. A feature of these dunes is their unusually high silt content, for example a subsoil sample from a dune closest to the Mataura River (Fig.2) contained 4% clay (< 0.002 mm), 56% silt (0.002–0.06 mm) and 40% fine sand (0.06–0.2 mm).

Near-source deposits have alternating eluvial zones and clay-enriched lamellae attributed to intermittent flushing of clay as the deposits accumulated (Kemp and McIntosh, 1989). In contrast distal loess has a fragipan, clay coatings and eluvial lenses, and polygonal structure below about 50 cm depth, with grey veins (gammations of Taylor and Pohlen, 1979) following prism boundaries (Fig.4). Veins may be multiple and bisect each other (Fig.4). Lamellae show no evidence of disruption



WEST	SITE					EAST
	A	B	C	D	E	F
% clay <0.002mm	10	12	14	19	16	18
% silt <0.06-0.002mm	58	78	77	75	75	76
% fine sand 0.2-0.06mm	31	9	8	5	7	5
% coarse sand	1	1	1	1	2	1

Fig.2. Texture and thickness of diagrammatically displayed aeolian deposits in a transect east of the Mataura River near Otama (transect 1, Fig.1).

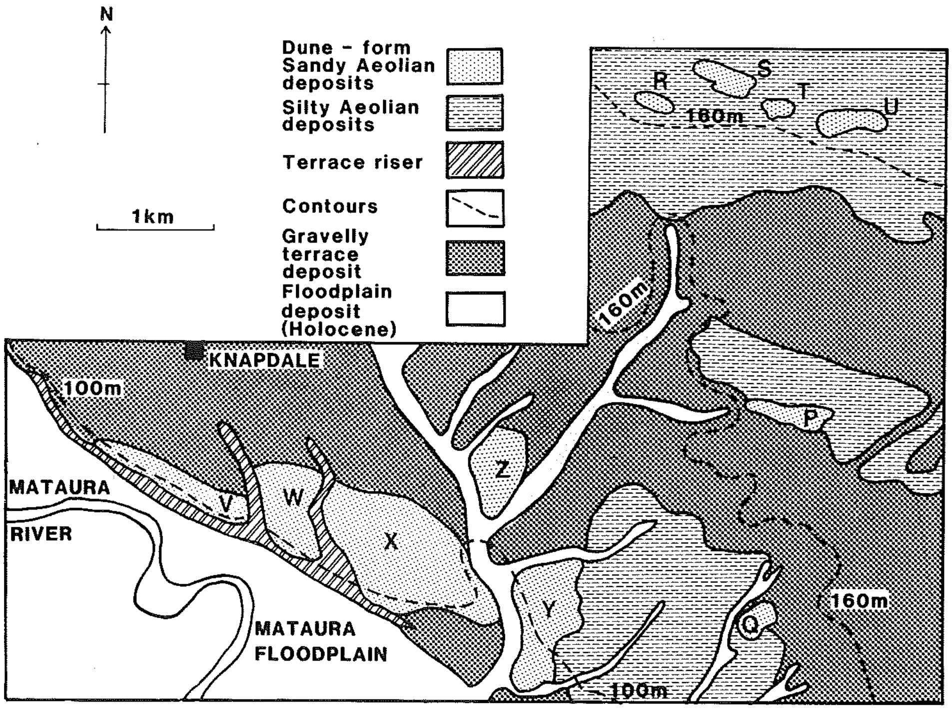


Fig.3. Dune-form aeolian deposits in the Knapdale district, northeast Southland (in part after Bruce (1984) and McIntosh and Eden (1988)).

and in the rare cases where fine stratification is visible in the loess (Fig.5) the layers are planar and not disrupted.

An ubiquitous feature of near-source aeolian deposits is the presence of burrows of soil fauna (Fig.6), macroscopically resembling those identified by European pedologists as cock-chafers (grass grubs) (De Bakker, 1979, p. 173; Brussard and Runia, 1984), but here identified as being caused by the burrowing action of the larva of the earth-moth *Eudonia*, probably *Eudonia sabulosella* (B. Patrick and A. Harris, pers. comm.), a grassland moth.

On rolling sites the most recent loess layer often overlies older layers unconformably or is separated from them by a stone line (Fig.7 and Bruce, 1973).

Reconstruction of past climate from aeolian deposits

The absence of charcoal in the aeolian deposits, except at rare places adjacent to gullies (Bruce, 1973) implies that at the time of sediment accumulation forest was absent. The widespread occurrence in near-source aeolian deposits of probable *Eudonia sabulosella* burrows indicates that these insects were abundant during accumulation of these lowland aeolian deposits, implying that at least seasonally, adequate moisture was available for the proliferation of this grassland species. Limited grassland cover is also likely because the dunes have not been highly mobile (they occur adjacent to, or within 1–2 km of likely source areas) and have rounded forms, characteristics of vegetation — stabilised dunes in the wetter parts of Australia (Bowler and Wasson, 1983). The dunes themselves possibly accumulated as sand-sized aggregates of silt. This would explain their unusual particle size distribution. The stratification of loess (Fig.5) and lack of any parent material disruption resembling structures induced by permafrost (e.g. ice-wedges, cryoturbation lobes) (Van Vliet, 1982) at any altitude argues against permafrost even on uplands where mean annual temperature lower than 0°C might have been expected in the last glaciation. One explanation of features

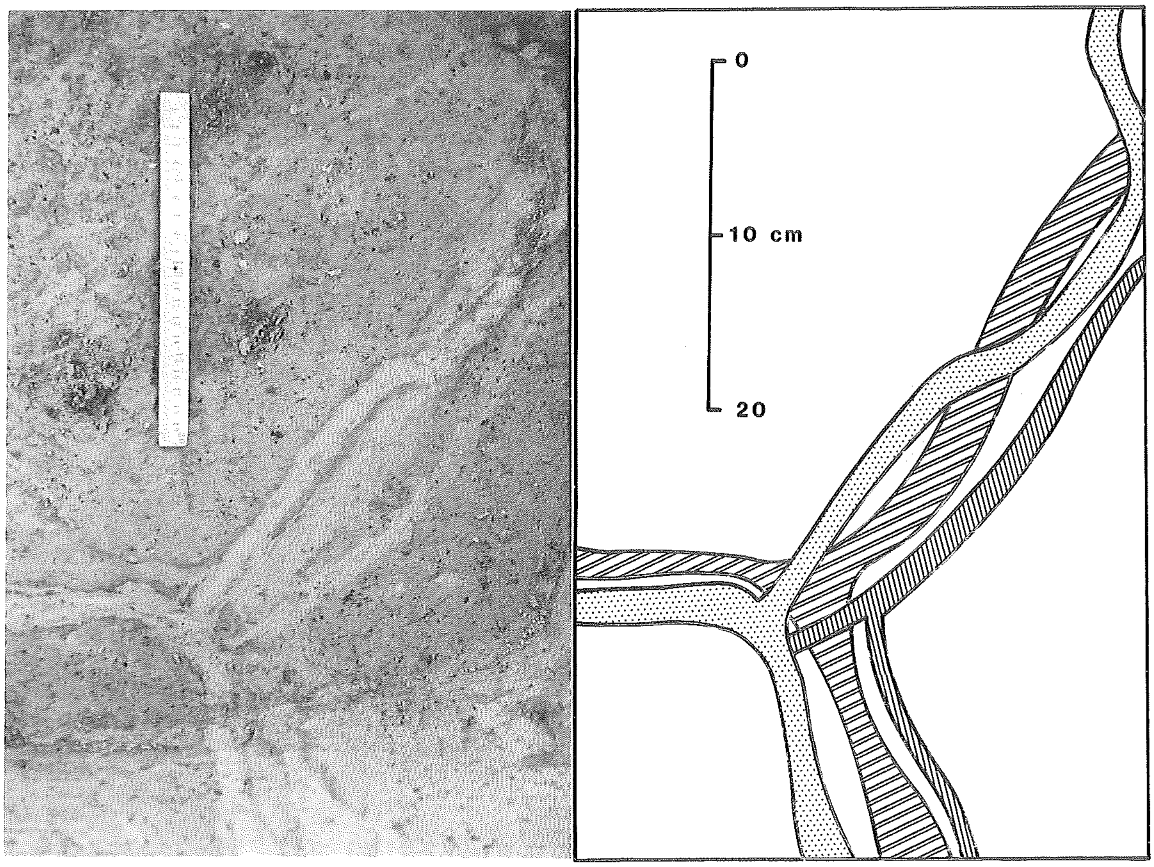


Fig.4. Bisecting veins in a fragipan formed in loess, northeast Southland. Three vein-forming events are evident.

such as clay lamellae and eluvial zones is that they are produced by the flushing effect of melting snow and seasonally frozen soil moisture (Kemp and McIntosh, 1989) and multiple polygonal grey veins can be explained as the product of water saturation and gleying following repeated cracking due to desiccation.

The topmost loess layer (which elsewhere contains Kawakawa tephra, dated at 20,000 yr B.P. (Eden and Frogatt, 1988)) lies unconformably over older deposits (Fig.7), indicating that a widespread erosion event preceded the latest episode of loess deposition dated at approximately 25,000–12,000 yr B.P. (Eden and Frogatt, 1988). We suggest that this erosion event may have coincided with the extremely dry conditions deduced as being responsible for formation of widespread fine colluvium on hill slopes before 29,000 yr B.P. (see p. 19) and that wind erosion as described by Bruce (1973) was the most likely erosion process. As a fragipan having bulk density of up to 1.7 t/m^3 is widespread in loess in northeast Southland a mechanism of fragmenting this horizon is required, before wind-erosion can operate. Both lenticular ice segregations forming a platy and lenticular structure at the soil surface (Van Vliet, 1982) and needle ice raising porous aggregates (Gradwell, 1957) would produce fragments liable to deflation. Both mechanisms require a vegetation-free surface and very dry conditions with heavy overnight frosts.

Terrace gravels

Nature and distribution

Terrace gravels (Fig.8) were correlated by plotting their heights with respect to the present Mataura River gradient (Fig.9), by making field

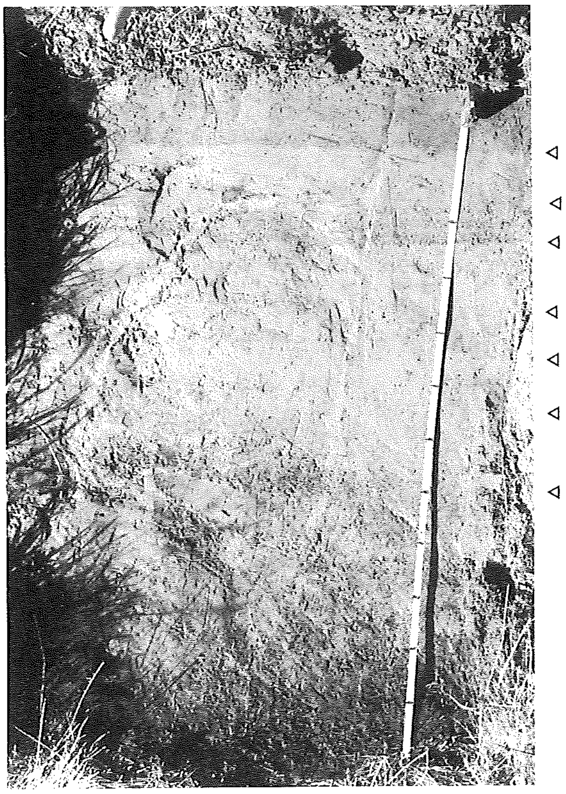


Fig.5. Loess deposit with fine layering, Waimea Plains. Coarser bands indicated. Marked intervals on tape are 10 cm.

observations of the weathering of clasts and matrix, by observations of pedological development of soils, and by chemical and mineralogical characterisation of soils formed in terrace gravels (Table 1).

The clasts in these terraces were classified as weakly weathered if they could be broken only by using a hammer, moderately weathered if they could be cut with a spade with difficulty and strongly weathered if they could be easily cut with a spade or knife. Pedological criteria used to identify and correlate terraces were (1) the presence of a Bw horizon (FAO, 1974); (2) the presence of clay skins, forming a Bt horizon (FAO, 1974); (3) strength of reaction to the NaF field test (Fieldes and Perrott, 1966) which is a field measure of the presence of poorly-ordered Fe and Al oxides and hydroxides in clays; (4) abundance of large pores 1–5 mm diameter.

Using the above criteria six terraces were identified (Fig.8) and correlated (Fig.9). They fall into two suites: (1) a suite of three terraces (terraces 1–3) having a similar gradient to the present Mataura River, weakly weathered clasts, soils with Bw horizons, a strong reaction to the NaF test and abundant large pores; (2) a suite of three

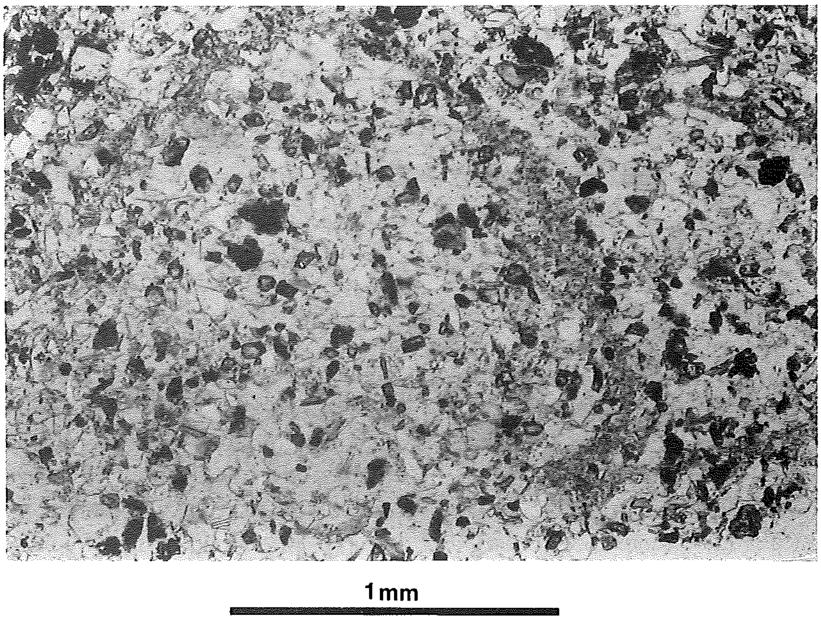


Fig.6. Fossil burrows of soil fauna in near-source loess, tentatively identified as being formed by the larva of the cranbid moth *Eudonia sabulosella*.

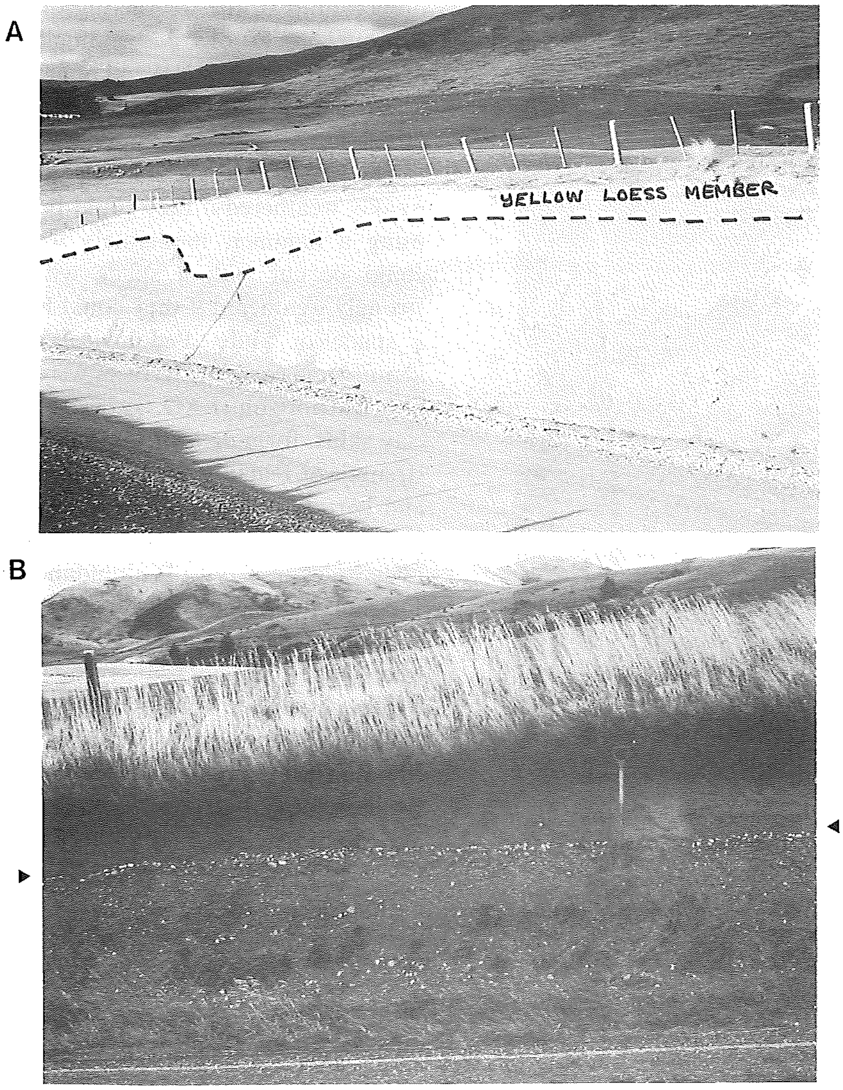


Fig.7A. Yellow loess member (Bruce, 1973) overlying older loess layers unconformably. B. Stone line (indicated) below last loess accumulation.

terraces (terraces 4–6) of gentler gradient than the present Mataura River, having moderately to strongly weathered clasts, weak reaction to the NaF test, and an absence of large pores (pores are generally filled with weathered matrix).

Trends in the chemical and mineralogical parameters are also evident from Table 1. The first suite of terraces has a mixed clay mineralogy of chlorite, mica and kaolin minerals but the second suite is dominated by kaolin minerals (Table 1). Phosphate retention increases from 12% in floodplain soils to 58% in terrace 2, but is lower in the second suite of terraces. These mineralogical and chemical changes are consistent with transformation with time of primary clay minerals firstly to poorly-ordered allophanic minerals and secondly to relatively stable secondary clay minerals (Tardy, 1982).

Both field and laboratory observations therefore support the conclusion that the second suite of terraces is older than the first.

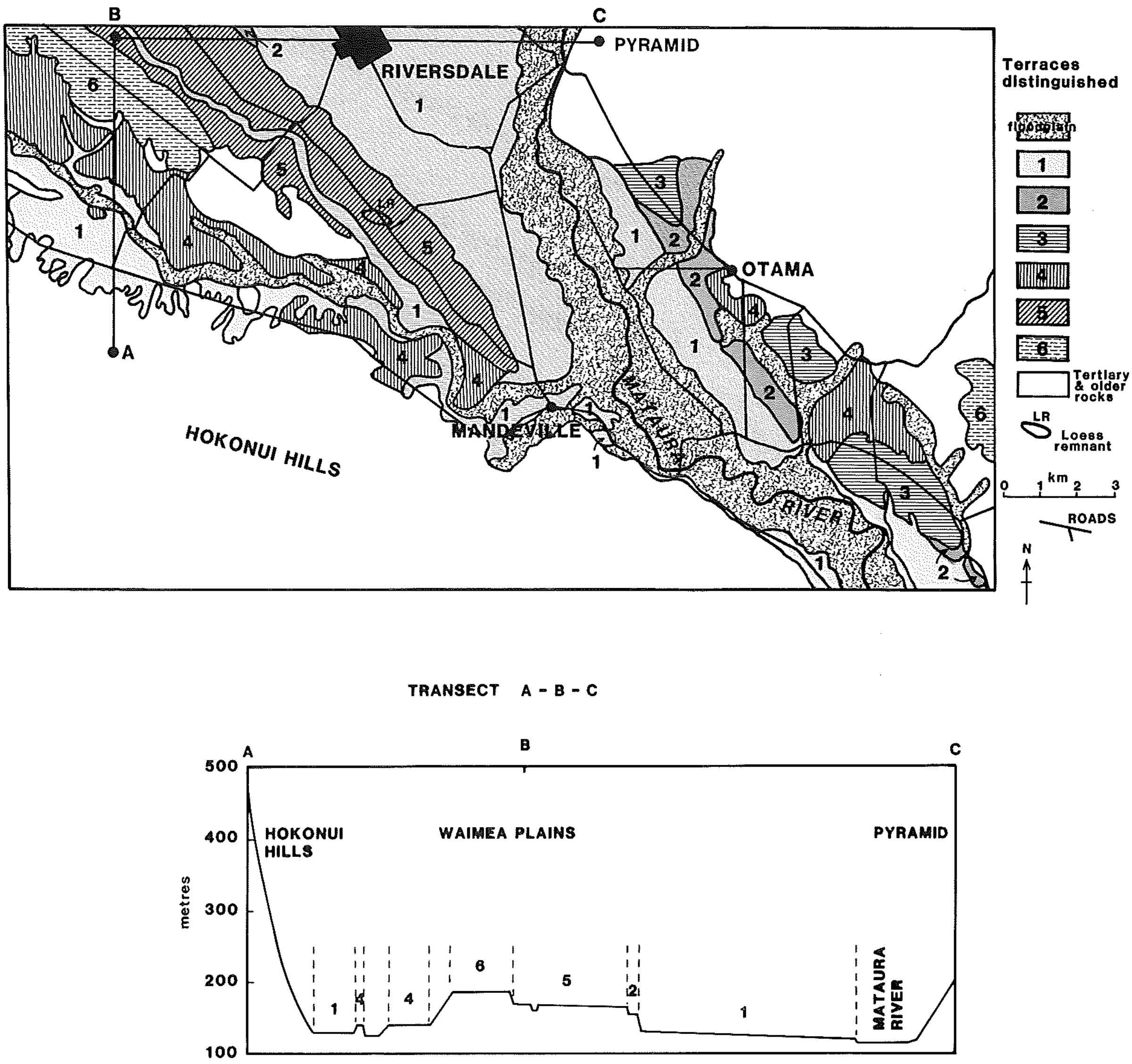


Fig.8. Map and section of terraces in the Mandeville district, where they have been mapped in detail.

Paleogeographic reconstruction

All terraces are formed from several metres of gravel and are extensive over kilometres and are attributed to aggradation events.

The weakly weathered nature of the soils and gravels of terraces 1–3, and their similar gradient to the present Mataura River, indicates that these terraces were formed by recent aggradation episodes (probably last glacial) of the Mataura River. In contrast, the strong weathering and shallower gradient of terraces 4–6 suggest they were formed by the much older aggradational episodes of a river of dissimilar gradient.

The occurrence of strongly weathered terrace 4 gravels from Lumsden to Balfour indicates that a river (here named the Lumsden River) flowed in a southeasterly direction from Lumsden through the Waimea Plains towards Gore. A Lumsden River derived from an ancestral Oreti River flowing through the Waimea Plains is an obvious possibility (Fig.1) but the abundance of schist and

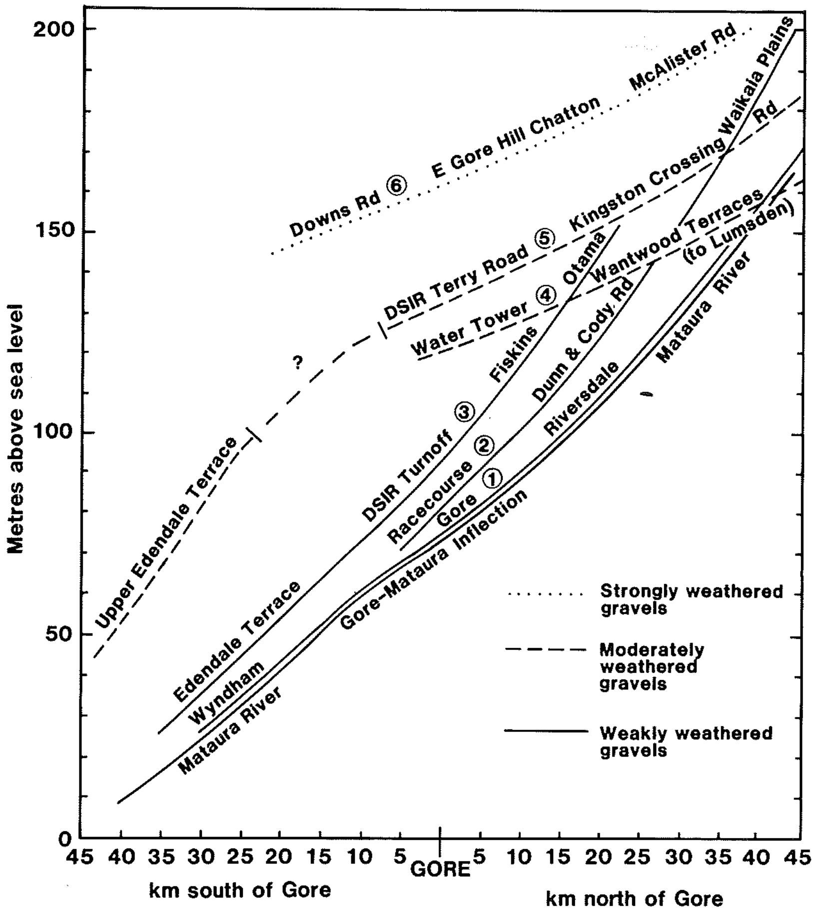


Fig.9. Gradients of terraces in northeast Southland.

quartz rocks in the gravels of terrace 4 indicates a major source of gravels other than the Oreti River, which at present is sourced in the Paleozoic greywacke rocks of the Eyre and Thompson Mountains.

The Mataura River has its headwaters in the schistose eastern Eyre Mountains (Fig.1) and then flows through a valley previously occupied further north by the Wakitipu Glacier, which is also likely to have supplied the Mataura River with schistose sediment during glacial times. At present the Mataura River changes course abruptly at Mid Dome, to flow in a narrow gorge through the Garvie Mountains before reaching the Waikaia Plains (Fig.1). However, the absence of gravels of terrace 4 age in the Waikaia Plains suggests the Mataura River has, prior to the deposition of younger gravels than those of terrace 4, taken an alternative route from Mid Dome. The most likely alternative route is via a major, presently unoccupied, valley west of Mid Dome (Fig.1). We conclude that the Mataura River was a tributary of the Lumsden River during the aggradational episode which formed terrace 4, and is the source of the abundant schist and quartz found in terrace 4 gravels. As terraces 5 and 6 have a similar clast composition to terrace 4, terraces 5 and 6 are considered to be derived from the same sources.

The absence of similarly aged gravels to those of terraces 1–3 in the western Waimea Plains from Balfour to Lumsden (Fig.9) indicates that after the deposition of terrace 4 gravels the Lumsden River changed course to flow south (as the Oreti River) via Winton (Fig.1). (The presence of terrace gravels of similar weathering status to terrace 4 at O'Shannessy Road, Winton, suggests that the Lumsden

TABLE 1

Weathering characteristics of floodplain deposits and terrace gravels in northeast Southland.

	Floodplain	Terrace		
		1	2–3	4–6
Field criteria				
Bw horizon developed	No	Yes	Yes	No
Reaction to NaF field test	Weak	Strong	Strong	Weak
Bt horizon developed	No	No	Yes	Yes
Weathering of clasts	Weak	Weak	Weak	Moderate to strong
Large pores (1–5 mm)	Abundant	Abundant	Abundant	Few
*Laboratory criteria**				
Dominant clays in clay fraction (%)				
Mica	**44**	26	17	3
Chlorite	19	**32**	16	4
Kaolin	7	10	**19**	**61**
Phosphate retention (%)	12	23	58	44

*These data are for 0–100 cm depth, at single sites on the floodplain, terrace 1, terrace 2 and terrace 5. Methods followed Blakemore et al. (1981) for phosphate retention and Wells and Smidt (1978) for clay minerals.

River diverted to follow the present course of the Oreti River no later than $\delta^{18}O$ stage 6). The relative timing of this event to that of the inferred change of course of the Mataura River at Mid Dome is uncertain. However, as both Mataura River and Lumsden River diversions occurred between the aggradation of terraces 4 and 3, and cut-off of sediment supply from the Mataura is likely to have led to decreased aggradation by the Lumsden River, the diversions of both rivers are assumed to have been coincident, on the present evidence.

Stony deposits of all ages display alluvial sedimentary features unaffected by cryoturbation or ice-wedge structures. There is therefore no evidence for permafrost during any terrace aggradation episode in northeast Southland.

Age of terrace gravels

Volcanic glass has been identified at 2 levels in a loess remnant on terrace 5 (Eden et al, in prep). These authors matched glass chemistry with the chemistry of dated and undated North Island tephras, and the oldest tephra present has been identified as Mt Curl Tephra (c. 240,000–250,000 yr B.P.; Pillans, 1988) (Fig.10). Consequently terrace 5 is at least this age, and is attributed to the Waimaungan Glaciation ($\delta^{18}O$ stage 8) (Fig.11). Terrace 4 occurs southwest of Terrace 5 (Fig.8) and may have been the source of the loess (loess 3) that was deposited with the Mt Curl and also the source of the loess deposited with the Griffins Road Lower and Griffins Road Upper Tephras (Fig.10) on terrace 5. Although Terrace 4 is here attributed to the early Waimean Glaciation ($\delta^{18}O$ stage 6) it appears that an earlier aggradation phase of this terrace approximately contemporaneous with Station Loess of Eden (1987) may have been the source of Loess 3 (Fig.10). By counting back cold climate episodes Terrace 6 is attributed to the Porikan glaciation ($\delta^{18}O$ stage 10).

The simplest chronology for terraces 1, 2 and 3 is to attribute them to 3 stadials in the Otiran, as recognized in Rangitikei and Marlborough (Fig.11). Each terrace, during aggradation, was likely to have been a source of loess, but no loess of "Rata" or "Porewa" age is recognized in northeast Southland (Eden et al., in prep.). We therefore deposits occur on upper midslope positions in places forming a fragipan (Fig.13) but on lower midslope and toeslope positions thick, less stony moderately weathered sandy colluvium (typically containing 3–6% gravels by weight) derived mainly from particles of argillite and siltstone predominates, and overlying layers of stony colluvium are absent (Fig.14A). A ^{14}C date of 29,140 yr B.P. was obtained from charcoal at 40–80 cm depth in the moderately weathered sandy colluvium at a site at 410 m altitude (map reference NZMS 260 F46 090 308). This date should be regarded as a minimum age for the sandy colluvium.

Climatic implications

We suggest that the less stony weathered sandy colluvial deposits of regional extent on both uplands and lowlands formed originally in an identical manner to the recent colluvium illustrated in Fig.14C, that is, as fine screes on unvegetated slopes, as suggested by Zenses (1986) for fine screes of the last glaciation in Europe.

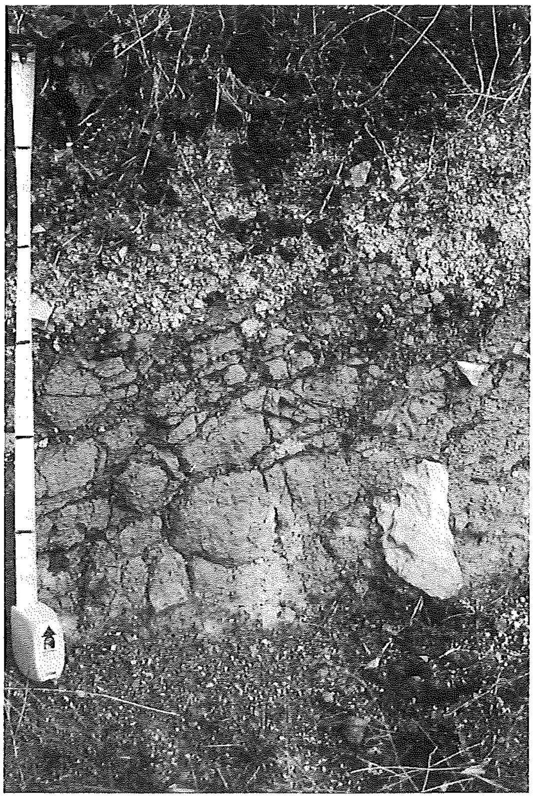
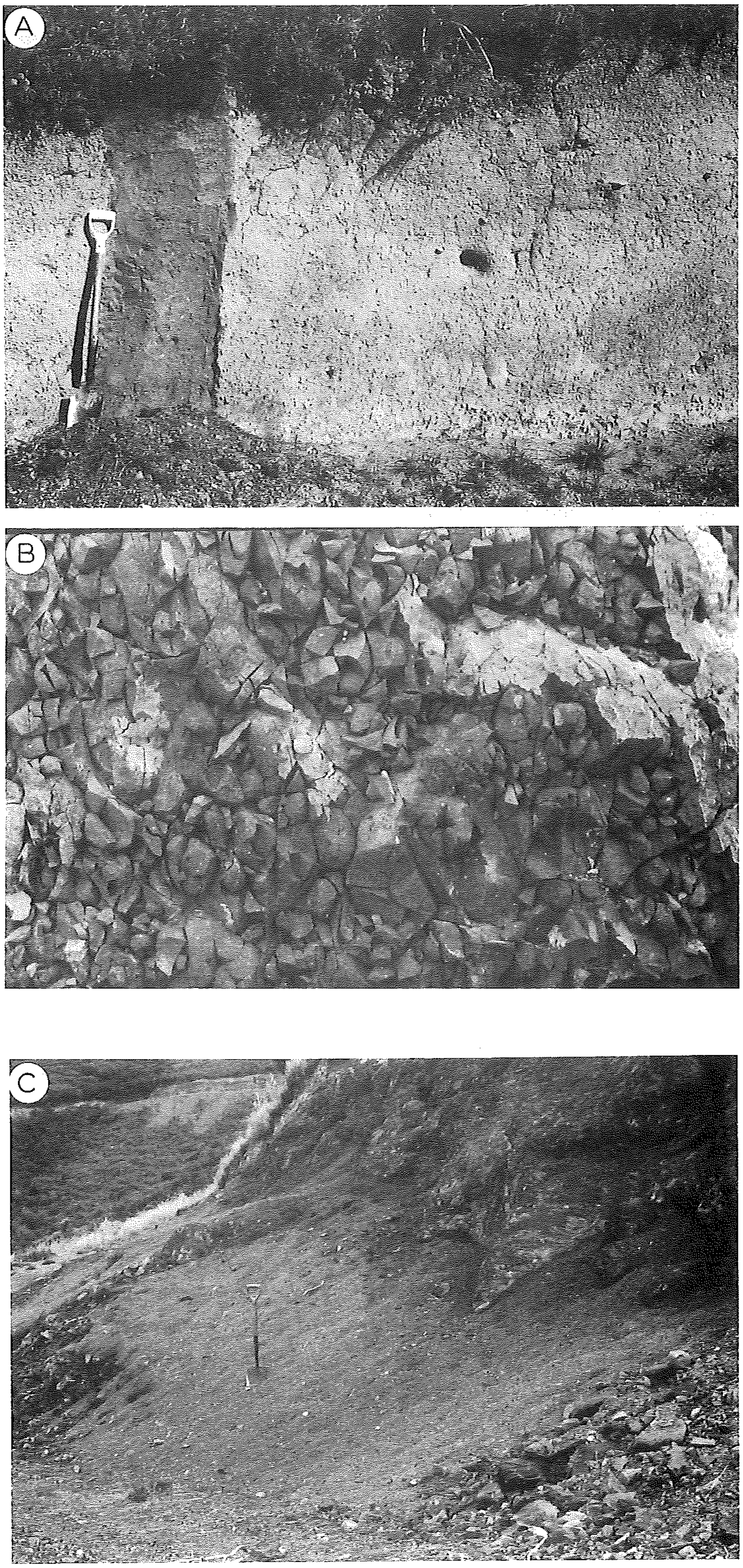


Fig.13. Upland fragipan developed in tuffaceous greywacke slope colluvium. Scale is marked at 10-cm intervals.

A fine scree of gravel-sized argillite and siltstone grains rapidly develops (Fig.14C) where road cuttings cut into finely jointed argillite and siltstone (Fig.14B). These fresh screes weather rapidly, and after one or two years the gravel has disintegrated into largely sand and silt-sized particles and some (3%) clay. The requirements for the formation of these fine scree deposits are variation in temperature causing cracks to develop along joints in the in-situ rocks, thereby loosening rock fragments, and lack of vegetation, allowing fragments to move downslope.

Lack of vegetation, necessary for screes to form, cannot be attributed to a lowering of temperature of 5°C alone: extreme droughts must have prevailed to limit vegetation cover. A similar conclusion was reached by Harris (1975) when considering the origin of stratified screes in Canterbury. The 29,000 yr B.P. date obtained for the fine screen places this period of extreme drought in the Otiran Glaciation before ^{18}O stage 2 and we tentatively attribute it to δ^{18}O stage 4 (Fig.11). To account for the stony deposits overlying the weathered fine screes on lowlands a process capable of fracturing and dislodging sandstone blocks from ridges on a regional scale is required. We suggest that the process was freeze and thaw, in an environment as cold as, but wetter, than that prevailing during the formation of the fine screes previously deposited. There is evidence for such a climate in the late Otiran and early Aranuian deposits and pollen record of western Southland (McGlone and Bathgate, 1983). These authors concluded that in the period 12,000–9400 yr B.P. the climate was periodically both warm and wet enough for forest growth, but strong westerlies and the passage of intensely cold airmasses (Petit et al., 1981; Salinger, 1983) during the growing season prevented forest expansion. Pollen records older than 12,000 yr B.P. are not available for Southland, but support for

Fig.14(A) Deep weathered sandy scree deposit at 400 m altitude. (B) Finely jointed argillite, fragmenting to form recent scree (fine scale divisions are millimetres). (C) composed chiefly of gravel and sand-sized particles.


A
B
C

McGlone and Bathgate's interpretation can be deduced from the work of Heusser et al. (1981) in southern Chile, who found that precipitation increased by up to fivefold after 16,000 yr B.P. but that mean summer temperatures, while more variable than at the peak of the last glaciation (c. 20,000 yr B.P.), were periodically as cold. Heusser et al. remarked that in the South Island of New Zealand "successive climatic events correspond remarkably with those from the Chilean record".

As the stony deposits do not overlie the fine scree deposits on uplands, we conclude that the late Otiran was a period of erosion on uplands, resulting from instability due to snow melt and alternating freeze and thaw. The presence of fragipans in gravelly upland colluvial deposits (Fig.13) has been attributed to periglacial conditions by many European researchers (e.g. Fitzpatrick, 1976; Matthews, 1976), the processes inducing compaction being freeze–thaw and associated redistribution of fines. As all shady hill slopes (of 22°C or greater slope) in the study area, and sunny slopes above 370 m altitude, would have had a mean winter soil temperature of less than 0°C during the last glaciation (R. Aldridge, pers. comm.) we suggest that gravelly upland fragipans in northeast Southland have a similar periglacial freeze-thaw origin.

Synopsis

A tentative chronology of Quaternary deposition and erosion in northeast Southland is summarised in Table 2. About 350,000 yr B.P. the Oreti River, joined by the Mataura River at Lumsden, formed the "Lumsden River" which flowed eastwards through the Waimea Plains and southwards via Gore, and aggraded 3 terraces during δ^{18}O stages 10, 8 and 6. Between 180,000 yr B.P. and 120,000 yr B.P. (i.e. during δ^{18}O stage 6) the Oreti began flowing south via Winton (aggrading a terrace in the Winton area) and the Mataura River diverted to its present course east of Mid Dome, and flowing south via Gore, aggraded 3 terraces in the Otiran.

Loess is likely to have accumulated coincident with each terrace-building episode of the Oreti, Mataura and Lumsden Rivers but before the onset of δ^{18}O stage 2 a severe climatic event, which combined the effect of needle ice and ice lensing with high wind speeds, is suggested as causing erosion of most loess deposited in the early Otiran. As a result of the erosion of loess the most recent loess layer (Yellow loess member of Bruce 1973) overlies older loess layers (δ^{18}O stage 6 or older) disconformably or unconformably. The absence of thick loess from large areas of the Waimea and Waikaia Plains has been previously explained as being due to these areas being source areas for loess rather than areas of deposition (Bruce, 1973). However the evidence of wind erosion in loess remnants indicates that this model is too simple: the loess cover may have been thick and extensive at one time, but erosion has removed it.

A ^{14}C date on extensive weathered fine scree deposits on hilly slopes indicates that the screes formed before 29,000 yr B.P., probably during δ^{18}O stage 4. The screes were formed by disintegration of siltstones and argillites under cold and very dry conditions, with little vegetation present. On lowlands these deposits were overlain later by stonier colluvium. The stonier deposits were probably partly derived from freeze–thaw action on sandy ridges in a cold but slightly wetter environment and may date to the late last Glacial (δ^{18}O stage 2). On uplands stony deposits do not overlie the fine scree deposits, indicating that erosion prevailed on uplands during the period of wetter climate (δ^{18}O stage 2). The extensive loess erosion by wind which occurred before the last major period of loess deposition may have coincided with the formation of the extensive fine screes on hill slopes, inferred to have occurred during (δ^{18}O stage 4).

Neither the late glacial vegetation sequence in western Southland (McGlone and Bathgate, 1983) nor the sedimentation and erosion pattern in northeast Southland can be explained by a fall in temperature of c. 5°C alone. The evidence presented indicates that during the last glaciation erosion was extensive not only on uplands but also on lowlands at 100–200 m altitude, implying not only absence of forest, but absence, or discontinuous cover, of grasslands and shrubs over wide areas. Extreme droughts and high winds during

TABLE 2

Tentative chronology of erosion and sedimentation events in northeast Southland.

NZ Stage*	$\delta^{18}O$ Stage	Approx Date (yr B.P.)	Erosion/Sedimentation event	Inferred climate
Aranuian	1	Present	Mataura River degrading. Little erosion on hills.	Warm and wet
		9400		
		14,000		
Otiran	2		Freeze–thaw on hills; stony screes of regional extent; erosion on uplands; fragipans formed in upland stony deposits. Last major terrace formed (terrace 1) by Mataura River with braided channel. Extensive aeolian deposits to east of Mataura River, some in dune form, up to 13 m thick.	Cold and wet; variable
		16,000		
	3,4		Extensive fine screes of regional extent. Extensive wind deflation of loess on lowlands, possibly punctuated by periods of loess deposition. Major terraces formed by Mataura River (terraces 2 and 3).	Periodically very cold and dry and very windy
		80,000		
Oturian (Interglacial)	5		Weathering and soil formation.	Warm and wet
		120,000		
Waimean	6		Mataura River diverts to present course east of Mid Dome and Lumsden River flows south via Winton (as Oreti River), probably sometime in this interval	Cold and dry
		180,000		
			"Lumsden River" forms last major terrace (terrace 4). Loess traps Griffins Road Upper tephra.	
		200,000		
Terangian (Interglacial)	7		Weathering and soil formation	Warm and wet
		220,000		
Waimaungan	7?		Loess from precursor of terrace 4 of "Lumsden River" traps Griffins Road Lower and Mt Curl Tephra	Cold and dry
		250,000		
Waimaungan	8		"Lumsden River" forms major terrace (terrace 5)	Cold and dry
		280,000		
Interglacial	9		Weathering and soil formation	Warm and wet
		340,000		
Porikan	10		"Lumsden River" formed from ancestral Oreti and Mataura Rivers forms major terrace (terrace 6) in Waimea Plains	Cold and dry.

*Suggate (1965) and Suggate and Moar (1970).

$\delta^{18}O$ stage 4 would explain not only the scree deposits but also the disconformity or unconformity between the most recent loess layer and underlying loess and the stone line. During this time the climate of northeast Southland approximated to that of a cold desert.

The cold and slightly wetter conditions which produced the stonier colluvium overlying the fine screes are attributed to the late Otiran, as are the near-source coarse-textured aeolian deposits in the form of dunes, containing evidence of abundant insect larvae of grassland provenance. Both McGlone and Bathgate (1983) and Heusser et al. (1981) (describing Chilean climates) recognise the period 12,000 to 9400 yr B.P. as subject to extreme climate fluctuation, with temperatures sometimes as cold as at the glacial maximum. These conditions are consistent with a southerly shift of the circum-polar westerly belt after 14,700 yr B.P. (Stewart and Neall, 1984), but with occasional returns to extreme glacial conditions limiting forest return at inland sites.

The conclusion from this study that northeast Southland suffered extreme drought during the last glaciation is at odds with Salinger's (1983) prediction of higher rainfall in Southland during periods of stronger westerly winds. However, as lower sea levels resulted in much wider coastal plains, to the extent that Stewart Island was linked to the mainland (Fleming, 1979), and the southern ocean was cooler, the sedimentation pattern can be explained by the increased "continentality" of northeast Southland during the last glaciation, with lower rainfall, less cloudiness and greater solar radiation than at present combining with greater windiness to increase evaporation.

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