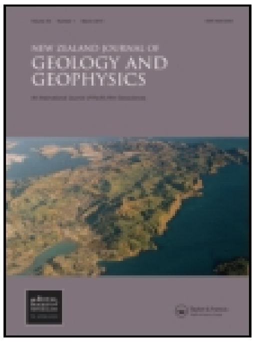

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STUDIES ON SOME GLACIAL MORAINES IN NEW ZEALAND—2.

AGES OF MORAINES OF THE MUELLER, HOOKER, AND TASMAN GLACIERS (S79)

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ABSTRACT

The criteria (lichen measurements, geomorphology, vegetation cover and degree of weathering of rocks) used for comparing and dating moraine ridges near the Mueller, Tasman and Hooker glaciers at Mount Cook are briefly discussed. Characteristic landforms, indicating that episodes of glacier expansion have occurred, include sharp-crested lateral moraines.

A description is given of the chronology of moraine ridges formed by periods of expansion of the three glaciers during the last 700–800 years, illustrated by maps, diagrams and photographs. There have been marked expansions of one or more of the glaciers in A.D. mid 12th century, mid 13th century, mid 15th century, mid 16th century, early and mid-to-late 17th century, mid and late 18th century, early, mid, and late 19th century and about 1930. There may have been other minor expansions during this time span.

INTRODUCTION

An earlier paper (Burrows & Orwin 1971) discussed the procedure for establishing lichen-growth curves which could be used to construct chronologies for the moraine surfaces around the termini of the Mueller, Hooker, and Tasman glaciers at Mount Cook. The present account describes the results obtained by applying the method of lichen measurement in this area. The previous paper should be consulted for the growth curves and a location map.

CRITERIA FOR COMPARING AND DATING MORAINIC SURFACES

The main method for chronometry of surfaces during this study was: (a) Lichen measurement. Details of the methodology are discussed later.

During the fieldwork several other criteria were used to make local correlations: (b) Geomorphic evidence. Connected moraine ridges or partly fragmented ridges, the lines of which could be projected onto other fragments, were important for the identification of synchronous surfaces. In addition, the positions of successive distinct moraines (mentioned in more detail later) are useful for establishing a relative chronology, assuming that the oldest moraines in a sequence are those farthest from the present glacier. (c) The degree of vegetation cover and kinds of plant species present. The main differences are briefly outlined below, but are not treated at length in the text. The assemblages of cryptogamic plants on boulders, mainly lichens and some mosses, are useful for this purpose and Orwin (1970; 1972) has carried out some basic work on the lichen communities.

Vascular plant cover on the moraines is also useful but a good deal of variation in vegetation is possible according to differences in exposure, altitude, slope (and consequent stability), and texture of the morainic debris. There has also been considerable human interference with the vegetation, mainly by the use of fire. The finer textured portions of moraine on undisturbed sites at lower altitudes have become completely vegetated within about 100 years. At first, sparse vegetation is present consisting of mosses (*Racomitrium lanuginosum, R. crispulum*), short grasses (*Poa colensoi, Notodanthonia setifolia*), and herbs such as *Epilobium melanocaulon*. Within about 50–100 years the herbaceous vegetation becomes denser and low shrubs such as *Gaultheria crassa* enter the succession. *Coriaria angustissima* is important in places. After 200 years a dense growth of shrubs is usually present, including *Podocarpus nivalis, Phyllocladus alpinus, Dracophyllum uniflorum, D. longifolium*, and many other species. Stands of *Discaria toumatou* may be important. Sites about 300 years old or more, may carry low forest, dominated by *Podocarpus hallii, Hoheria glabrata*, and *Griselinia littoralis. Phormium cookianum*, the shrubs mentioned above, and others such as *Senecio eleagnifolius, S. cassinoides, Olearia nummularifolia, Pseudopanax colensoi, Pittosporum anomalum*, and *Coprosma* spp. are also often present.

Exposure to extreme conditions of wind, drought, and cold delays succession. At altitudes above about 1000 m, scrub may develop in sheltered and sunny sites but the main vegetation cover after about 300 years is a dense growth of the tall grasses *Chionochloa flavescens* and *C. pallens* and a rich flora of herbaceous plants including *Celmisia* spp., *Aciphylla* spp., and *Ranunculus lyallii*. Coarse, bouldery moraine, even at low altitude, may remain unvegetated, except by lichens and mosses, for up to 800 years. Surfaces older than about 75 years have a noticeable pink coloration which contrasts with the grey of younger surfaces. On surfaces older than about 150 years the individual rocks are closely covered by lichens and mosses so that the weathering colour is less evident and the boulders appear to be dark. However, some portions of rock show a pale orange coloration, apparently caused by a tiny crustose lichen, and this is very noticeable on surfaces about 300 years old or more.

MORAINIC LANDFORMS

An examination of the moraines near the glaciers at Mount Cook reveals some complex geomorphological situations and it is necessary to explain these briefly to clarify the descriptions of chronologies. For the purposes of this discussion the term moraine will refer only to the deposited landform.

The abundance of supraglacial and shallowly buried englacial debris in the glaciers permits the formation of very extensive morainic features, especially lateral and latero-terminal moraines. Well-preserved examples of these morainic features occur near the Mount Cook glaciers. In places there has been modification or partial destruction or burial of these moraines by subsequent glacial or other processes and, often, only short fragments remain of what clearly were once extensive moraine ridges. In other places, ridges several kilometres in length are virtually unmodified, after recession of ice from them, except by growth of vegetation. Each of the three glaciers is unique in several respects. The course of the Mueller Glacier, in its middle reaches, lies along a narrow, cliff-bound valley from which it emerges into a wide valley in the terminal area. The glacier has not been confined by mountainsides there during the series of oscillations which occurred within the last millenium and its moraines rise about 150 m above the outwash gravels which form the valley floor. In contrast, the Hooker Glacier is confined by valley walls along its whole length, and its lateral moraines form a series of terraces perched at various altitudes on the valley sides. The Tasman Glacier occupies a wide valley and, in its lower reaches, the glacier has not been large enough or powerful enough to quite fill the total width of the valley in the last thousand years. On the west side there is a long, continuous, lateral moraine, and outside it, in places, short sections of parallel ridges the crests of which are not greatly dissimilar in altitude. Outside the moraines, between them and the mountainside, is a depression of variable depth. The depth depends on the amount of fill in the form of alluvium from mountain torrents, avalanche detritus, debris flows, and screes falling from steep slopes above (Fig. 1). I propose that such a depression be called a paraglacial valley rather than "ablation valley", the term in common use for such a feature (Embleton & King 1968, p. 346). The feature was formed during glacial expansion, and it is unrelated to ablation. In a few places this valley, with a height difference of nearly 60 m between the moraine crest and its floor, is virtually free of debris fill and the outer face of the moraine makes visible contact with bedrock. Elsewhere, alluvium and colluvium from the mountainsides above partly fill the valley, masking any contact with bedrock (Fig. 2). In a few places minor outwash from the glacier surface also contributes to the fill. Similar paraglacial valleys are present on the east side of the Tasman valley between the Beetham valley and Novara Corner. Similar but smaller-scale features are often present between parallel moraine ridges. Small, intermorainic paraglacial depressions are present outside many of the Hooker lateral moraines and, in that valley, portions of the older moraines have been destroyed or masked by colluvium and alluvium including fluvioglacial outwash from adjacent small glaciers.

Near the terminus of each of the three glaciers the moraine complex consists of successive series of bouldery ridges. Many of these are sharply defined, but others are less well differentiated and have low relief.

It is necessary to distinguish between two terms which express the growth of a glacier. I use the term **expansion** in preference to advance when no evidence exists for forward movement of the glacier snout. During an expansion the ice volume increases and the trunk of a glacier thickens (Speight 1921; Lawrence & Lawrence 1965; Nye 1963). At this time it is likely that some forward movement usually occurs. Often there is evidence from lateral moraines that there have been former periods of increase in

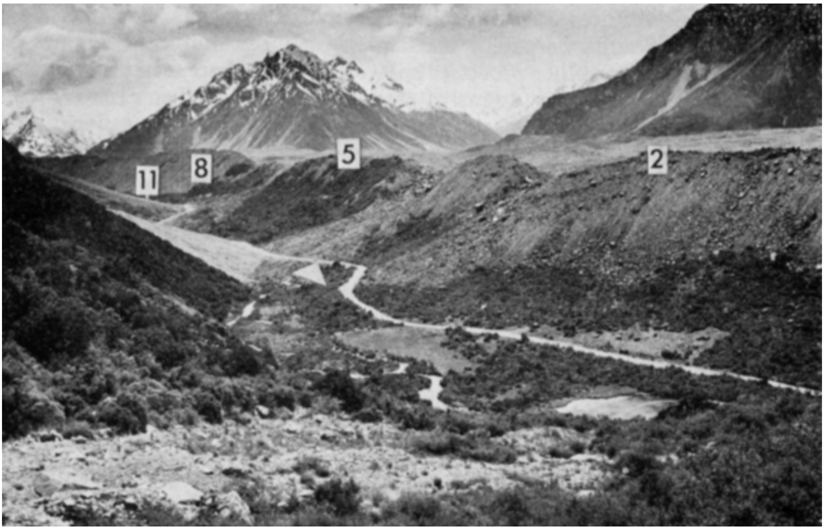

FIG. 1—Paraglacial valley, Tasman Glacier, occupied by Ball Hut Road and Blue Stream. Car (arrow) gives scale. Two small run-off channels lie above it. Bare moraine (2) dates from about A.D. 1890. Scrub-covered moraines date from (5) about 1750, (8) mid 15th century, (11) mid 12th century.

N.B. The numbering of moraines in all photographs and diagrams indicates these ages: (1) A.D. 1930, (2) 1890, (3) 1850, (4a) 1820, (4b) 1770–1790, (5) 1730–1750, (6a) mid-late 17th century, (6b) early 17th century, (7) 16th century, (8) 15th century (9) 14th century, (10) 13th century, (11) 12th century.

ice volume, but the evidence for whether or not forward movement of the glacier snout occurred is lacking because subsequent events have destroyed the terminal moraines.

It is probable that sharp-crested lateral and latero-terminal moraines are formed only during periods of vigorous expansion when there are both forward and upward directional components in the movement of the ice stream. As the ice rises the moraines at the side of the glacier are formed as "levees", their proximal side derived from debris plastered into place immediately adjacent to the ice and their distal side from loose debris which falls from the raised glacier surface. When the glacier recedes, the moraines are often left as sharp-crested ridges (Fig. 3). These lateral ridges are often strong enough to stand at steep angles (Fig. 2). This led Embleton & King (1968, p. 346), mistakenly, to suppose that the lateral moraines of the Mount Cook glaciers were ice-cored. In effect the till of which they are composed is like a weak form of concrete.

Some geomorphic features offer conclusive proof that certain moraines were formed during glacier expansion. It is sometimes easy to see from the general morphology and different stages of vegetation development of a series of terminal loops that earlier surfaces have been partially overridden

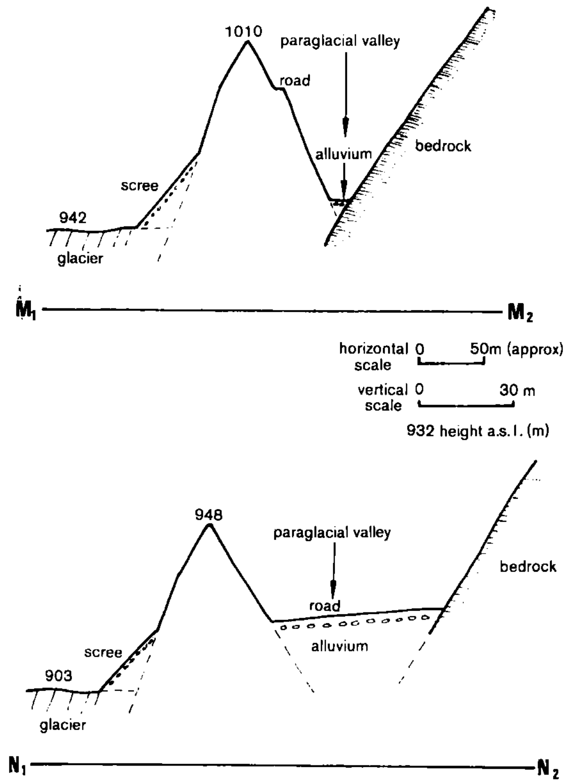

FIG. 2—Tasman moraines, cross-section at M_1–M_2, (see Fig. 14), west side of Tasman Glacier. Deep paraglacial valley almost unfilled by debris. Moraine crest formed about 1890. Section at N_1–N_2, (Fig. 14), showing paraglacial valley partly filled with alluvial gravel.

by later advances. This is evident, for example, at the terminus of the Hooker glacier (Fig. 4). In other places it is apparent from the alignment of ridges that a renewed advance of the glacier has pushed well beyond an earlier terminal position, cutting across the line of the older moraines, sometimes at quite an obtuse angle, for example, at the Tasman glacier (Fig. 5).

In the case of lateral and latero-terminal ridges it may be inferred that renewed expansion has occurred from the relationships of new ridges to older moraines. There are several possibilities known from direct field evidence in the Mount Cook moraines. Some of the possibilities are illustrated by Fig. 1, 12, and 20 (i.e., a new moraine crest inside and lower than on old crest; a new crest level with or higher than an old crest, with an intermorainic paraglacial valley between them; a new crest partially or completely burying an old crest). The causes of difference between these lateral moraine forms seem to be related to interaction between the magnitude of the glacier expansion and the amount of rock debris present at the margin of the glacier. There is also interaction with older features which offer resistance to the movement of ice.

FIG. 3—Sharp crest of lateral moraine of Tasman Glacier, formed about 1890. Distal side to left. The ice level has shrunk some 75 m below the crest of the moraine since 1914.

Renewed expansion may also cut into and destroy an earlier moraine or moraines. Because this is an erosional event, there is only circumstantial evidence that it may have occurred among the Mount Cook moraines, namely the absence in places of moraines or portions of moraine which could have been expected to be present from evidence which occurs elsewhere.

Trim lines, formed when an expansion of a glacier clears a surface of vegetation, and revealed by glacier shrinkage, are only present in the middle and upper reaches of the trunks of the Mount Cook glaciers, for example near Kea Point at the Mueller and at the Beetham corner at the Tasman. The bare surfaces have been maintained by continued erosion of till from the steep, exposed slopes.

Two other features are formed during periods of glacial expansion. A spillover occurs when the ice rises higher than part of the crest of an existing moraine and breaches it, and a lobe of ice is extended down a trough at an angle to the main direction of flow. Loops of moraine are formed round the ice lobe. One large and one smaller spillover are present among the Mueller moraines (Fig. 6, 7) and many, very small spillovers have influenced the shape of the crests of Mueller and Tasman lateral moraines. The crests of moraines are also breached in places by transient streams flowing from the ice surface at times of maximum expansion and these are known as **runoff channels** (Fig. 1). Large runoff channels are present at the Kea Point spillover at the Mueller Glacier and near Blue Lakes at the Tasman Glacier.

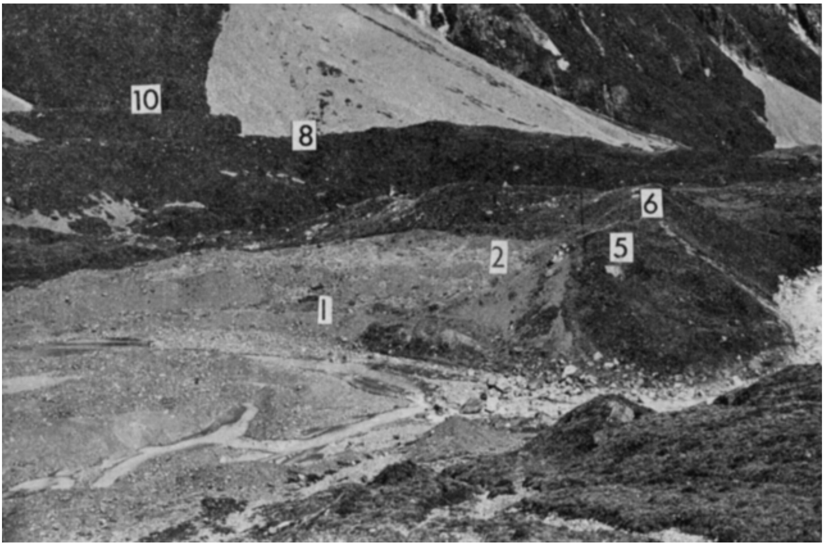

FIG. 4—Terminal area of Hooker Glacier. Bare moraines date from (1) about 1930, (2) about 1890, and vegetation-covered moraines from (5) about 1750, (6) 17th century, (8) 15th century, (10) 13th century.

A corollary of the successive periods of growth of the Mount Cook glaciers is that, after each distinct expansion, there has been a period of shrinkage. This is best demonstrated by the recession of the glaciers which has occurred within the last fifty years. It is also demonstrated by the moraines of the Hooker Glacier, the oldest of which are highest on the valley walls. Even though each of the growth intervals of the Hooker so recorded has been followed by massive shrinkage, each prominent lateral ridge is the result of a renewed expansion because the relative positions of most of the remaining terminal ridges show that they were formed during advances. Many of the lateral moraines have paraglacial valleys outside them, also, and their sharp-crested ridges must have been formed by an expanding glacier.

The sharp-crested expansion features may be distinguished, by the boldness of their form, from those formed during retreat of glaciers. Recessional moraines are less regular in distribution, smaller, and interspersed with considerable areas of outwash gravel, forming terraces which often contain kettleholes. Examples occur among the 15th century moraines of the Hooker Glacier and in surfaces formed recently at the terminus of the Mueller Glacier.

Bare, steep, lateral moraine walls, proximal to the glacier, are formed by glacier recession, and small- or large-scale erosion of these is continuous. In places, release of support by the glacier during shrinkage causes massive collapse of long sections of lateral moraine.

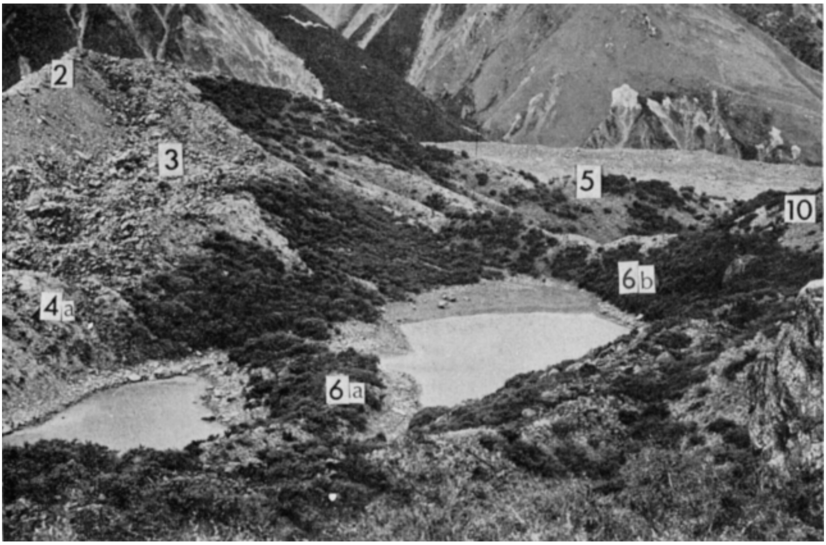

FIG. 5—Blue Lakes area, Tasman Glacier. Latero-terminal moraines date from (2) about 1890, (3) about 1850, (4a) about 1820, (5) about 1750, (6a) mid 17th century, (6b) early 17th century, (10) 13th century. The 18th century ridge cuts across the line of the early 17th century ridge at right angles.

AGES OF THE MORAINES

Surfaces of unknown age were traversed and, as far as was possible, all likely boulders were examined for lichens. Measurements of lichen thalli were made and the ages of the surfaces, derived from the single largest diameter measurement for each species, were extrapolated from the *Rhizocarpon geographicum* and *R. candidum* growth curves (Burrows & Orwin 1971), Appendix 1 contains the measurements. Chronologies of surface ages and glacial events were then constructed. The greatest age estimate from either lichen species is adopted for each surface. On some younger surfaces and all surfaces older than 200 years it was often difficult to find more than one or two large thalli so that dates on these depend on few measurements. The question of the reliability of the dates should be mentioned here. In the text the lichen dates are given at their face value to the nearest five years. On the maps these values are used for dates from the mid 17th century onwards and may be accepted as being reasonably reliable. Before this, dates are taken to the nearest third of a century on the maps and referred to as early, middle or late. This indicates the degree of reliability. On the older surfaces the dates obtained in this way are probably best regarded as minimal but, if several measurements from different parts of the same moraine ridge agree, this strengthens the view that the lichen age may be close to the true age. From the results so obtained, maps (Fig. 13–16) were drawn showing the position of moraine ridges which mark the limits of distinct periods of glacial expansion.

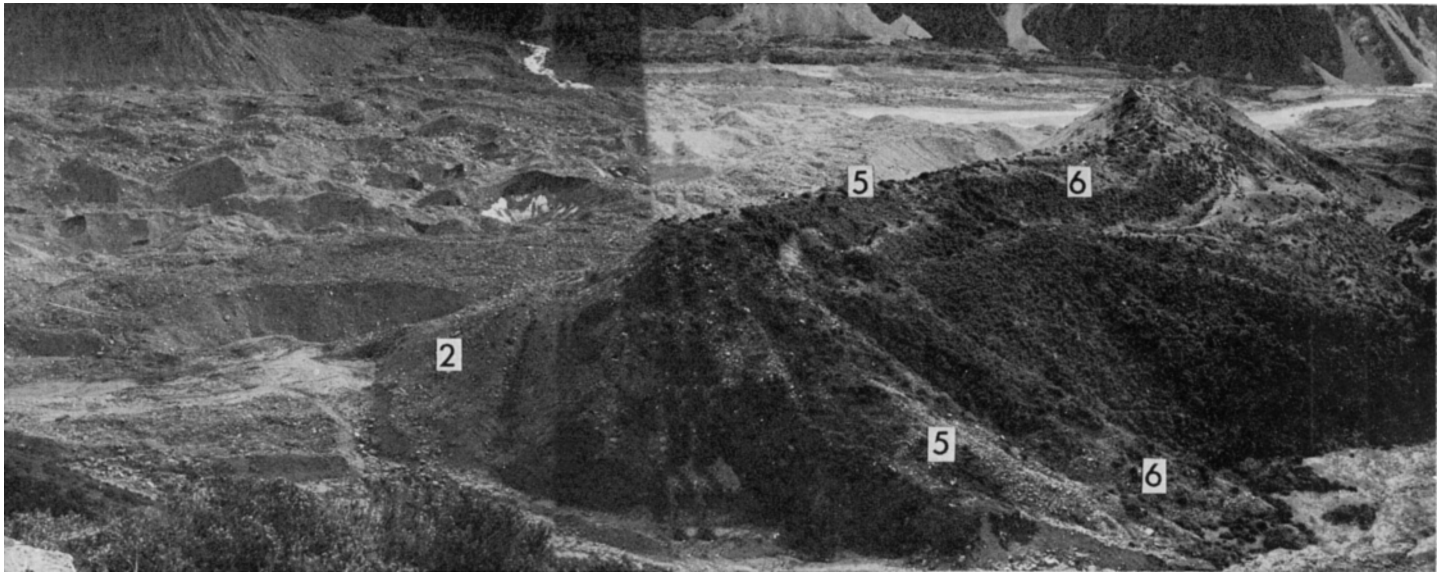

FIG. 6—White Horse Hill and the Mueller Glacier from the Sealey Range. Kea Point spillover in foreground. Surfaces formed (2) about 1890, (5) about 1750, and (6) in 17th century.

FIG. 7—White Horse Hill from Foliage Hill. Buses give scale. Kea Point spillover on left. (a) White Horse Spillover, (b) King Memorial, and Terminal moraine loop, probably formed in 17th century.

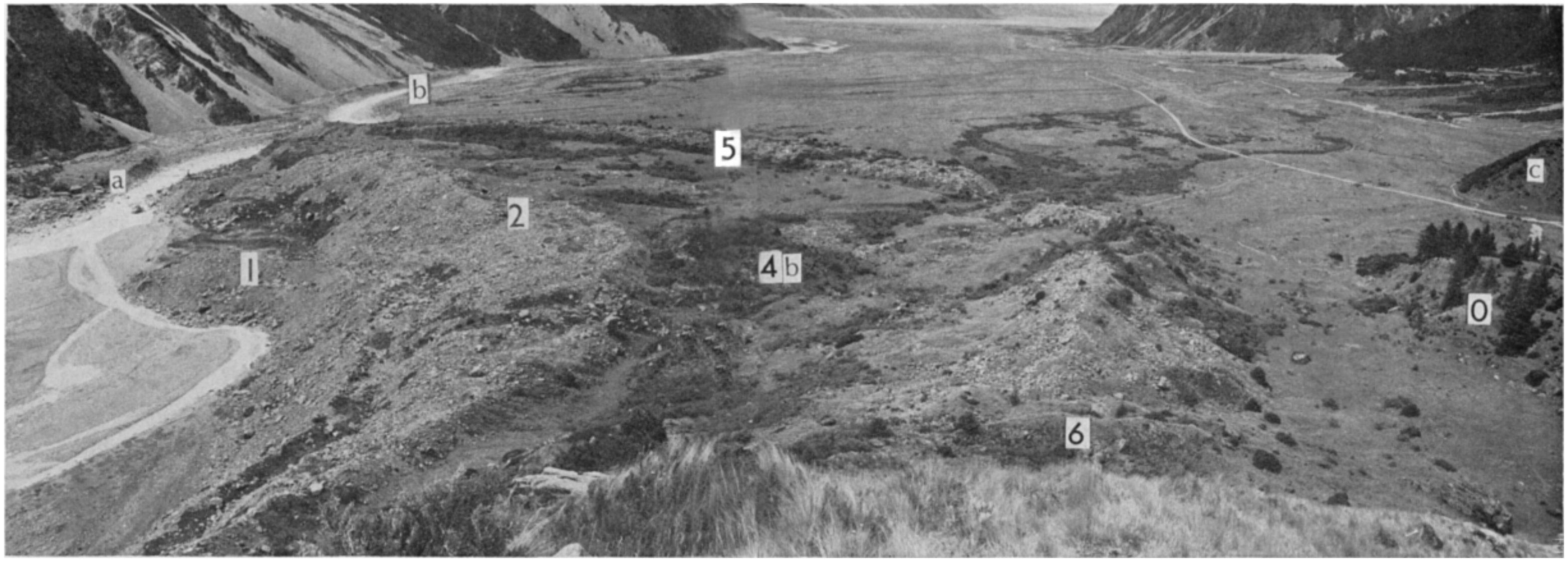

FIG. 8—Terminal moraine loops of Mueller Glacier from White Horse Hill. Moraines formed (1) about 1930, (2) about 1890, (4b) about 1790, (5) about 1750, (6) probably in 17th century, (0) before A.D. 1440 (a) First swing-bridge, (b) Hooker river, (c) Foliage Hill

FIG. 9—Terminal area of Mueller Glacier between swing-bridges. Moraines formed (1) about 1930 (2) about 1890, (3) about 1850, (5) Recessional moraine from mid 18th century advance. Old channels of the Hooker River are evident. Mueller Glacier terminus on left. Eugenie Glacier and moraines (arrow).

Over the period of about the last 200 years the sequence of glacial phenomena may be traced in considerable detail, but this is not feasible for older surfaces. Only the most prominent moraines are mapped for these older surfaces, although in some places some small moraine fragments are interpolated between the main moraine ridges.

MUELLER GLACIER

Figure 5–12 illustrate the main features of the Mueller moraines, Fig. 13 shows the moraine ridges which mark the expansions of the Mueller glacier over at least the last 600 years.

The chronological sequence at the Mueller Glacier and an interpretation of the glacial events represented by the moraines follows.

1. Foliage Hill is a portion of a very old moraine surface which could not be dated.

2. A fragmentary low ridge (D on Fig. 13) lies between Foliage Hill and White Horse Hill. It is part of a moraine crest buried by outwash and possibly represents the limit of the earliest of the more recent glacial expansions. Another fragment (E on Fig. 13) appears to be a correlative section of a wide moraine loop and yielded a lichen date of A.D. 1350. The moraine loop is probably older, however, because the younger of two ridges immediately inside it (C on Fig. 13) was formed earlier than the mid 15th century.

3. The southern flank of White Horse Hill consists of parallel ridges from at least seven periods of glacial expansion (Fig. 7). Until about 80 years ago this area was covered with forest and scrub (which was then burnt). Little boulder material is exposed that has not been influenced by this tall vegetation so that many surfaces could not be dated by use of lichens. A date of A.D. 1440 was derived from growth rings of trees of *Podocarpus hallii* (Lawrence & Lawrence 1965) on the sixth prominent ridge outside the main crest and there may have been a time lapse of at least 100 years before this species became established. Attempts to obtain cores from large trees on some younger moraines in the series were unsuccessful because all trees investigated had rotten hearts.

A lichen date of A.D. 1545 was obtained from the fourth ridge below the crest of White Horse Hill.

4. An extensive and probably multiple advance built a ridge parallel with, but higher than these earlier moraines. A date of A.D. 1670 was obtained from its crest, and one of A.D 1590 from the trough on its outer flank.

At this time there was considerable spillover of ice at the Kea Point end of White Horse Hill. The alignment of moraine fragments from earlier expansion periods suggests that this area had been the site of recurrent spillovers. It is likely that an intermittent outwash stream was also present here during these early periods of glacier growth.

The 17th century advance almost certainly extended beyond the end of older terminal moraines. An undated ridge sloping steeply down from the eastern end of White Horse Hill and two low fragments in front of the main outer loop of terminal moraine are probably attributable to this advance. Similarly, several minor moraines near the base of Mount Wakefield, each higher than the one formed previously, probably belong to the 17th century advance and seem to show that a number of oscillations occurred.

The 17th century material has not been dated for the long, north lateral moraine, but its presence can be inferred from the nature and height of the crest of the ridge. Small spillovers from a subsequent advance in the 18th century have breached this ridge in several places. A date of A.D. 1445 (possibly a minimal age) was obtained from near the outermost side of an undifferentiated moraine dump outside the main north lateral moraine, but little indication could be gained of the sequence of early expansions on this side of the glacier.

5. The highest ridge on White Horse Hill and on the north side of the Mueller was built by a major advance achieving its maximum about A.D. 1740. During this advance ice spilt over both at Kea Point and at the east end of White Horse Hill, forming minor loops. The main outer limits of the Mueller moraines were formed by this advance (Fig. 8). A low, but wide loop of terminal moraine reflects the effect of loss of power of the glacier and splaying out of the ice as it extended beyond the confining barriers of the high lateral moraines during this advance. The loop consists of about five sub-parallel ridges of low relief, possibly representing a "washboard" moraine (Flint 1957). Lawrence & Lawrence (1965, p. 19) suggest from tree ring evidence that "ice advanced to the east wall of the Hooker valley after 1730, and remained there from 1745 to 1785". A lichen date of about A.D. 1735 on the outermost part of the loop near the foot of Mount Wakefield verifies the date of the advance.

6. After about A.D. 1750 the glacier retreated, but about 1770–1790 another oscillation built a smaller moraine loop which has since been almost completely destroyed except for some short, prominent fragments. A jumble of recessional moraine occupies the area between the limits of mid and late 18th century advances. Outwash channels amongst this represent temporary positions of the Hooker River during this period. South of the loop near the east end of White Horse Hill is a small outwash plain with irregular surface, formed in the late-18th to late-19th centuries. The 1790 ice expansion did not quite rise to the crest of White Horse Hill. Small ridges dated at about 1805 and 1790 occur lower than the mid 18th century crest at the distal end of the main north lateral moraine. Subsequent oscillations have not attained the heights reached by the 17th and 18th century advances.

7. A renewed advance about 1840–1850 built low ridges at the end of the north lateral moraine and east of the track between the swing-bridges over the Hooker River (Fig. 9). Material from the same advance on the south side of the Hooker River (near the first swing-bridge) has subsequently been much disturbed by meltwater streams.

From the historical record left by Hutton (1888) it appears that this advance built prominent lateral ridges inside the main lateral moraines about 15 m below their crests (Fig. 10). A ridge was also extended across the base of the White Horse spillover at this time (Fig. 11). The ice remained

FIG. 10—Small lateral moraine formed about 1850 and also reached by an advance of the glacier about 1890. The moraine is perched about 75 m above the glacier on the proximal side of a moraine formed about 1750, White Horse Hill, Mueller Glacier.

at this level till about 1860, but by 1888 had shrunk about 15 to 30 m below it. During retreat from the 1850 limit, the Hooker River formed a channel which is now followed by the track between the two swing-bridges (Fig. 9). At this stage the glacier was first seen by Europeans (Haast 1862). It is difficult to judge from Haast's and Hutton's accounts how much terminal retreat had occurred between 1862 and 1888.

8. Some of the early and mid-19th century deposits were destroyed or obscured by the rising of the ice level and by outflows of water from the terminal area of the glacier at a variety of points about A.D. 1888–1890. The ice again rose to the level of the lateral ridges formed inside the main lateral moraine in the mid 19th century, and terminal loops were deposited near the swing-bridges (Fig. 8, 9). A bulge of ice extended into the gap formed by the Kea Point spillover trough but there was no real spillover of ice (Fig. 6). Ross (1893) noted that the Hooker River flowed under the ice at the terminal face of the Mueller Glacier at this time. The river has been forced towards the base of Mount Wakefield during each of the advances of the Mueller Glacier in the last 300 years and this has been a potent factor in causing erosion of ice at the terminus. Haast reported this in 1862 and Hutton in 1888.

The terminus retreated but the ice level remained high for some time after 1890 and flood-water from the glacier surface flowed out at Kea Point in 1891 (Ross 1893) and again in 1913 (Du Faur 1915). Figure 12 shows

FIG. 11—White Horse spillover. The moraine ridge across the base of the spillover was formed about 1850 and ice reached it again about 1890.

the relationships of the 18th, 19th, and 20th century surfaces (south of the first swing-bridge), in section, the relationship of surfaces on White Horse Hill and the surfaces between the two swing-bridges.

9. General downward wasting then occurred, with a halt in recession or slight expansion of the ice about 1913–1916, which left a small ridge at the west end of White Horse Hill. In 1930 a small advance built ridges some 9–10 m lower than those from the 1890 advance (Fig. 8, 9). Subsequently there has been continued shrinkage to the present day. A loss of ice of some 105 m (vertically) has occurred since about 1890, but the terminal face has retreated comparatively short horizontal distances since that time, varying from about 365 m on the southern side to about 60 m at the northern side. The trunk of the glacier at present is composed mainly of stagnant, debris-covered ice with numerous collapse ponds.

It seems possible that the ice volume of the glacier was similar when the outer (older) moraines and the highest, much younger crests were formed. The addition of successive accretions to the thickness of the lateral moraines on their inner sides, which has occurred at White Horse Hill during each ice expansion, might cause subsequent expansions of similar, or even of lesser magnitude, to form higher moraines than those of the earlier expansions. This is visualised as being the result of increasing constriction of the ice within the decreasing space between the opposing moraine walls of the glacier. None of the early (pre-17th century) terminal moraines are left, so it is not known how far down-valley the glacier extended, but the form of younger moraines suggests that terminal moraines

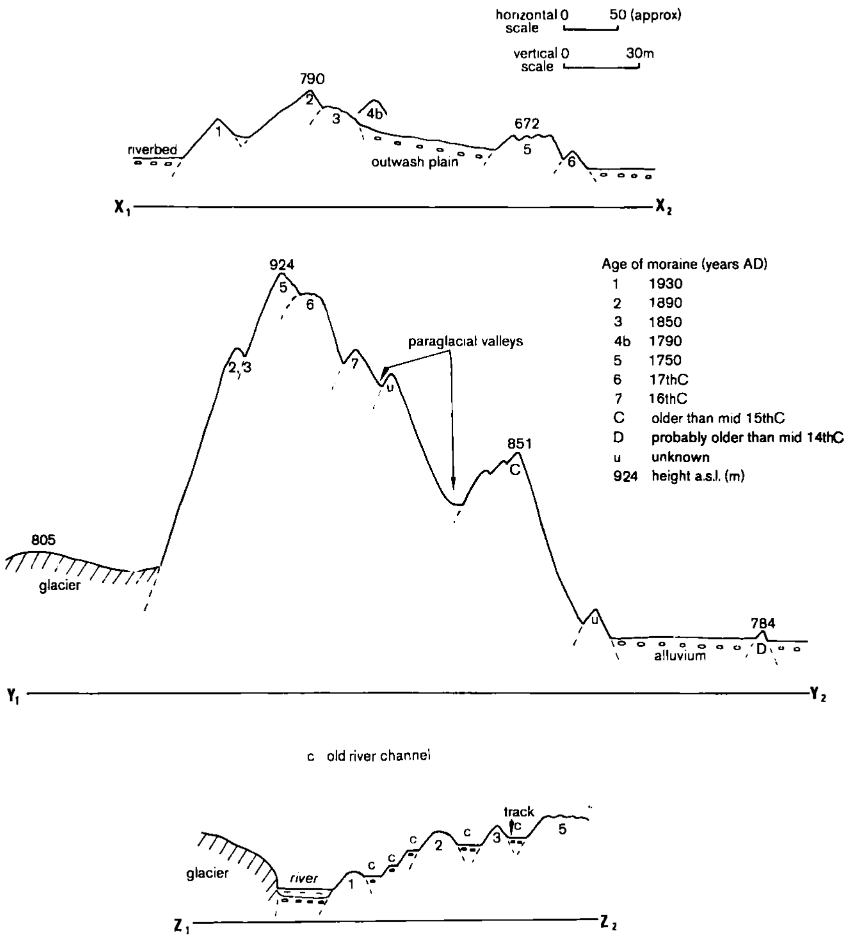

FIG. 12—Mueller moraines, cross-sections at X_1–X_2, Y_1–Y_2 and Z_1–Z_2, (see Fig. 13).

from advances prior to the 17th century may have lain at the eastern end of White Horse Hill. It seems likely that the 17th century and mid 18th century advances were greater than some earlier expansions because they pushed out beyond the presumed earlier terminal positions.

TASMAN GLACIER, WESTERN SIDE

Fig. 1–3, 5, 14, 15, 17–20 illustrate the main features of the Tasman moraines. Figure 14 shows the limits of expansions of the Tasman Glacier on its western side, near the terminus, over at least the last 800 years. Figure 15 shows the moraines between the terminus and Ball Hut, and the moraines on the eastern side of the glacier near the Murchison Valley. The best-preserved moraines are the latero-terminal ones lying on its south-west margin, but there is little or no development of ridges near the front of the glacier. This may be because the most recent advances have destroyed earlier moraines, but terminal moraines proper may never have been formed. Large terminal moraines were not formed during the last advance and, since then, there has been continued removal of debris by meltwater streams and by the sinking of large boulders into the outwash plain (Speight 1940). The sequence of surfaces and glacial events on the western side is:

1. A small fragment, some 450 m south of the main moraine is undated.

2. Two sections of a ridge, one near the four tarns known as Blue Lakes and the other near the source of the Blue Stream, are both dated at A.D. 1150. Two lichen measurements on different segments of moraine give the same date so that this is possibly close to the true date. There is an older, undated fragment outside the 12th century ridge near the Blue Stream source.

3. A high ridge bounding the area in which lie the Blue Lakes is dated at A.D. 1295 so that an extensive advance appears to have occurred in the late 13th century (Fig. 17). This ridge is about as high as the late 19th century one, which is the most prominent at the Tasman. A radiocarbon date (NZ 711) of 684 $\pm$ 48 years B.P (about A.D. 1266) was obtained from wood buried in the lateral moraine near Ball Hut by an expansion of the Tasman Glacier (I. C. McKellar pers. comm.). The exposure of wood is some 21 m below the crest of the late 19th century moraine but there is no indication of the final height to which the glacier rose at the time when the wood (identified as *Podocarpus nivalis*) was buried. It lies above a well-defined but shallow soil horizon (Fig. 18). One stem had 70 growth rings. This, and the depth of soil, suggests that the pre-existing moraine, of very similar form to the present crest, was in existence for at least 100 years. There has been considerable erosion of till from the steep glacier side of the moraine recently, but sufficient remains to show that accretion of till occurred beside the glacier during the advance of the mid 13th century and this has been adequate to protect the old soil from destruction up to the present time.

4. Two sections of ridge near Blue Lakes and the source of the Blue Stream are dated at A.D. 1430 and 1445, respectively.

5. The crest of a low bouldery ridge separating the main Blue Lake from the other three tarns gave a date of 1620, and a date of 1580 was obtained from its outer side (Fig. 19). An indistinct line of moraine between this ridge and the 13th century ridge may mark the 15th century expansion in this locality.

A small, low loop inside the early 17th century ridge separates each of the other three tarns. It is dated at 1655. A short fragment, forming the outermost latero-terminal ridge nearer the terminal face of the glacier, yielded a date of 1670. It appears, from the morphology of the moraines, that a mid to late 17th century advance pushed out at least 365 m beyond what had been the terminal position of the glacier for several hundreds of years. It is gauged from this and the relative heights of the ridges that the mid to late 17th century advance, and others in the 18th and 19th centuries were greater than most earlier ones, although the 13th century moraine is as high as the highest of these ridges and higher than the 17th century ridges. It may be that similar volumes of ice were present during the 13th, 17th, 18th, and mid to late 19th century expansions, but the last three may have continued for longer periods and the glacier terminus thus could advance further.

6. Another advance occurred about 1730–1750. Sections of mid 18th century moraine survive near the terminus of the glacier and near Blue Lakes, and others form portions of the outer face of the long lateral ridge between Blue Lake and Ball Hut.

7. A low but distinct ridge bordering the eastern margin of the Blue Lakes is dated at about A.D. 1820 and another rather undifferentiated but distinct moraine mass inside it and higher than it, at A.D. 1850 (Fig. 5). A small fragment of moraine near the present terminus also probably dates from the mid 19th century. Expansions at these times apparently overrode moraine from the 18th century in the vicinity of the Blue Lakes.

8. The most prominent and complete ridge of moraine was formed during an advance about 1880–1890 and it is clear that the glacier then topped a long lateral moraine between Blue Lakes and Ball Hut, (the crest of which was formed in the 18th century, but which also contained material from older advances), spilling debris down its outer face in all but a few protected places (Fig. 1). Small ice spillover troughs and runoff channels breach the lateral moraine in several places. (They are also present among the older moraines.) A report by Broderick (1906) that the terminus had advanced between 1890 and 1906 and a similar statement by Bell (1907) probably refer to the latter stages of the advance. The ice level remained high, probably till about 1914 (Harper 1934), after which shrinkage began. At some time before about 1930 the original Blue Lake, mentioned by Haast (1862) and other early writers, which lay in the paraglacial valley near the source of the Blue Stream, was drained. This was presumably caused when the ice of the Tasman glacier shrank down below a critical level (Speight 1940). The tarns now known as Blue Lakes rise following rain and their water is probably derived from the glacier.

There is no clear evidence for the occurrence of other minor expansions of the Tasman Glacier in the early part of the 20th century although some small, indistinct ridges lie inside and lower than the late 19th century crest. As Skinner (1964) pointed out, some 80 m of thickness of ice has been lost from the surface of the Tasman Glacier near Ball Hut by ablation, but the terminal face of the glacier has retreated very little and there has been less downward shrinkage near the terminus. The trunk of the glacier from about the Murchison Valley junction downward appears to be stagnant, is thickly covered with debris, and has many collapse features.

TASMAN GLACIER, EASTERN SIDE

Between the Beetham and Murchison valleys there is a long lateral moraine with a paraglacial valley outside it, partly filled by alluvial gravel derived from the mountainside above. The moraine ridge has two crests at the Novara Corner and this condition extends north to near the Dorothy Stream (H. Wilson pers. comm.). One of the crests, only sparsely vegetated, was formed about 1890. The other, covered in subalpine scrub and grassland, was not dated along its whole length during this study. The section near the Novara Corner was formed in the 18th century and the rest was probably also formed at this time. An undated, short section of a third, older ridge is also present near the Dorothy Stream. The Murchison Valley enters the Tasman Valley almost at right angles and since the Tasman ice has not been confined by mountainsides or moraines here, it has bulged out into this space on an arc over 1·7 km wide and about 600 m deep. (Fig. 15). The Murchison River is forced into a course alongside the flanks of the Liebig Range by the Tasman ice further down-valley, but about 2 km downstream from the Murchison bulge there is a concavity in the margin of the glacier presumably compensating for the expansion of ice into the bulge. Here, and round the margin of the bulge, parallel moraine ridges are preserved, each higher than the previous one as they become successively younger. Often only short fragments exist, but the record extends back at least 500 years and seems to demonstrate that, throughout this time, each successive expansion of the Tasman Glacier was more substantial than the previous one. At the Murchison bulge the main outer loop dates from the mid 18th century. A minor ridge of slightly pink-weathered moraine between this and the next prominent ridge probably dates from the mid 19th century, but lichens (and vascular plant cover) are sparse on this part of the moraine. The highest ridge dates from about A.D 1890 and in several places this advance buried all of the earlier moraines. At the Novara Corner both 1750 and 1890 moraines were breached by run-off channels, falling steeply to the Murchison riverbed. A series of short fragments of older moraine, partly covered by scrub, partly by grassland, is preserved here. The oldest gave a date of A.D. 1565 and two ridges inside it gave dates of 1610 and 1655, respectively. Then there is a rise to 1750 and 1890 surfaces; Fig. 20 shows the relationship of these ridges in section.

At the concavity down-valley from the bulge, the oldest surface yielded a date of A.D. 1485. There appear to be traces of 17th century surfaces here, also. The glacier has, during the 18th and late-19th century expansions, risen to the top of pre-existing moraine ridges and spilt over them, only

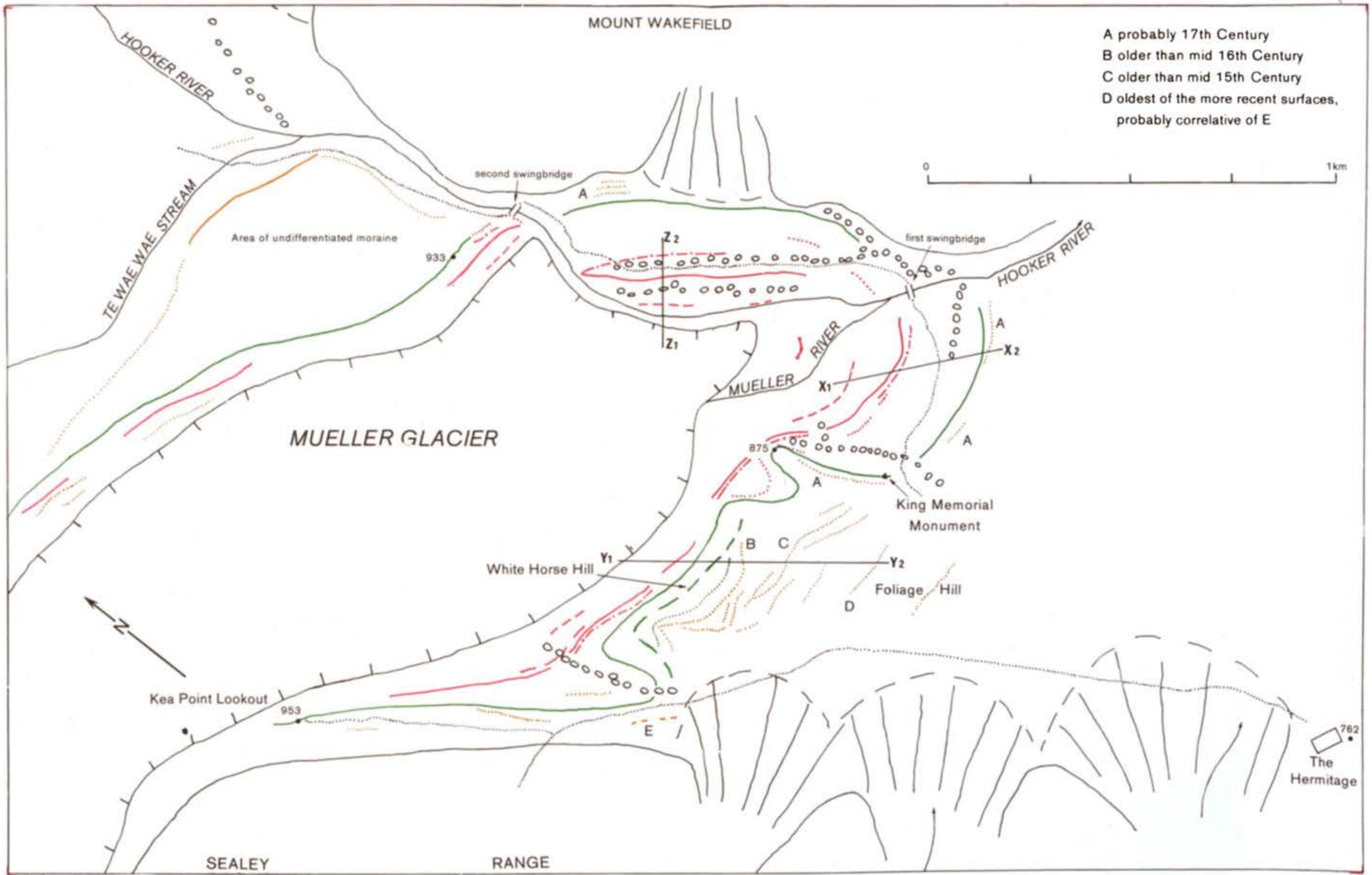

FIG. 13—Moraines marking limits of the Mueller glacier. The base maps for Figures 13, 14, 15, 16 were constructed by tracing the main features from aerial photographs, photographically enlarging the tracings, and sketching in the finer detail with the aid of aerial photographs and ground checks. The legend for all four figures is included with Fig. 14.

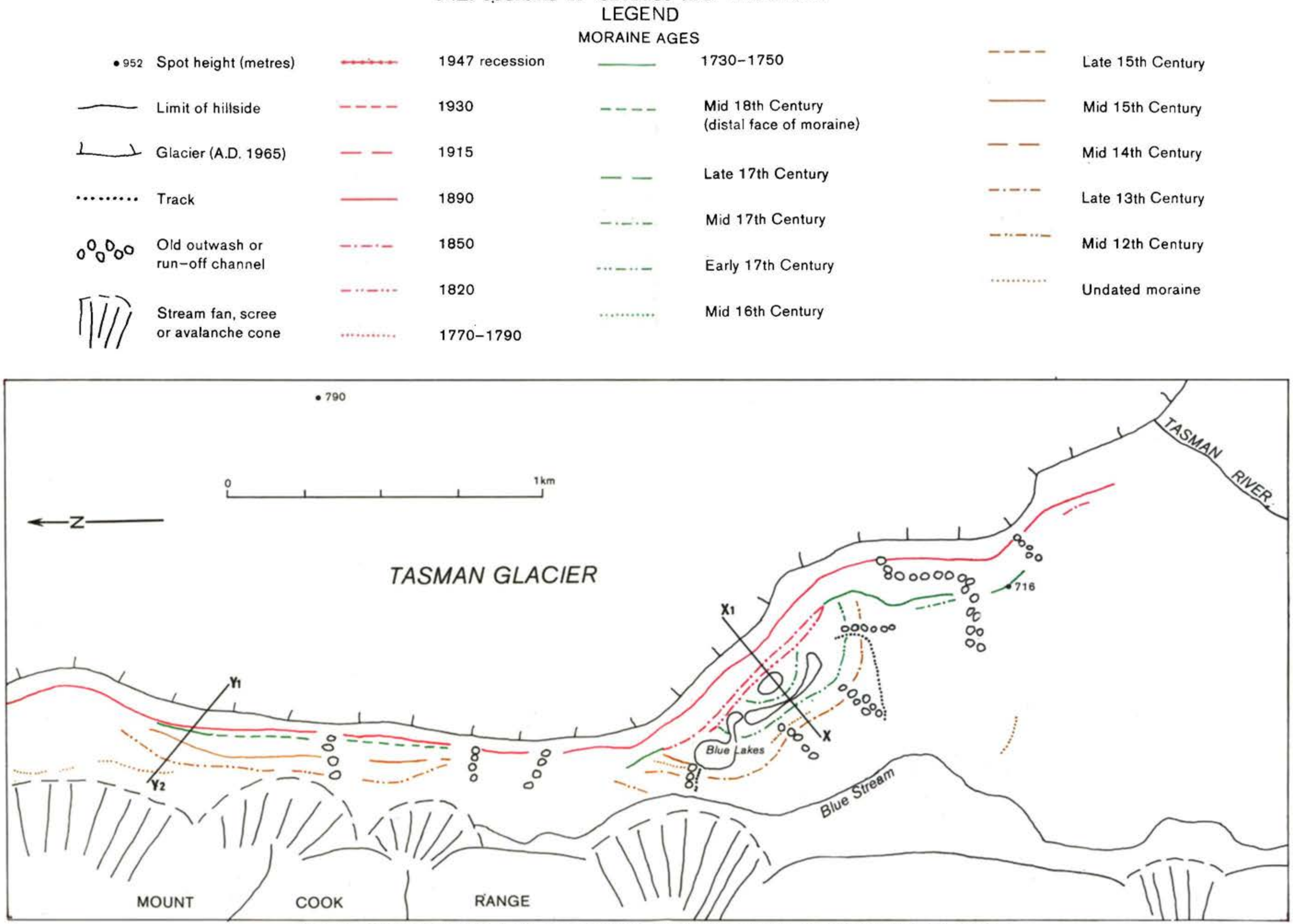

FIG. 14—Moraines marking limits of the Tasman glacier, western side, near Blue Lakes and terminus.

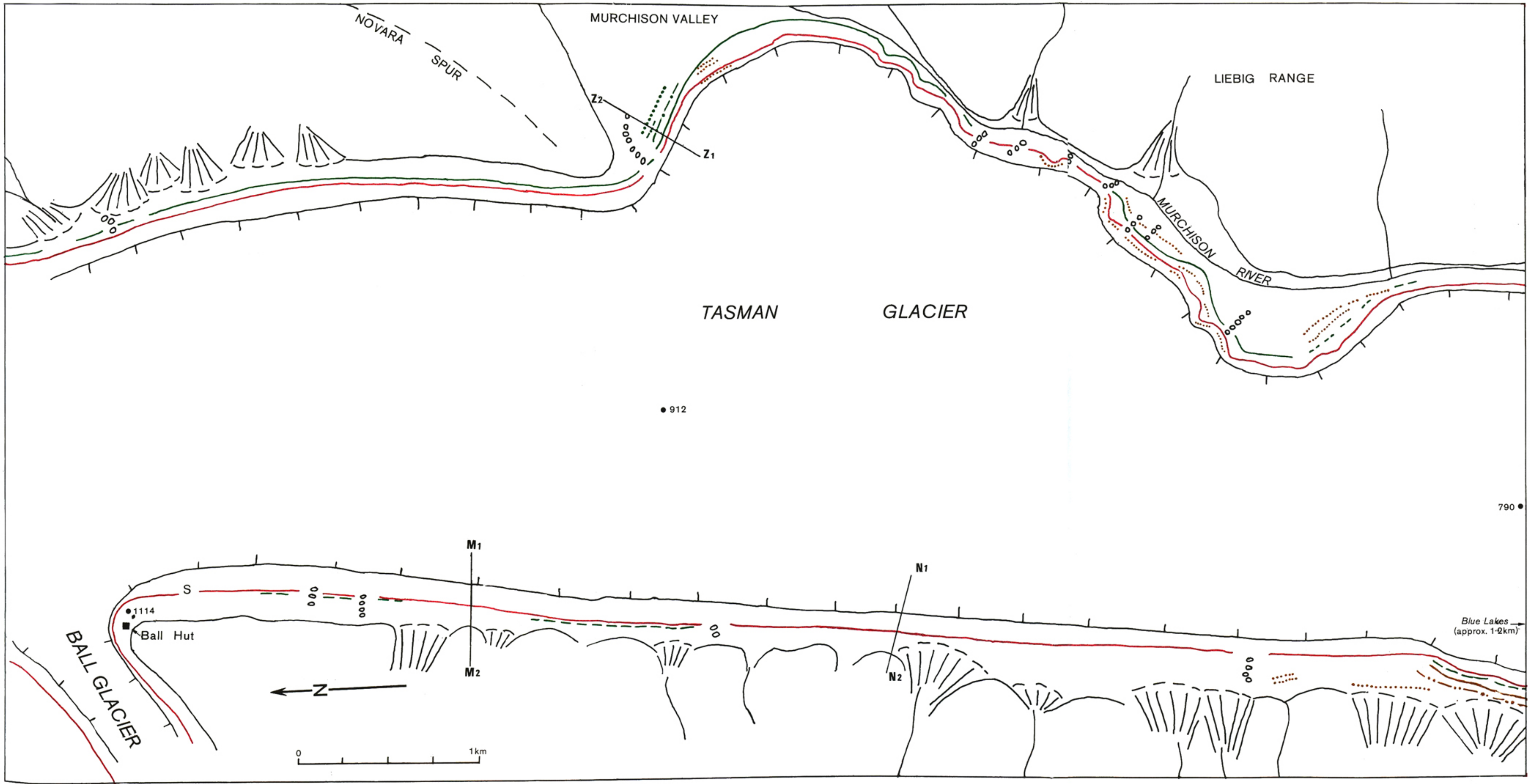

Fig. 15—Moraines marking limits of the Tasman glacier between Blue Lakes and Ball Hut.

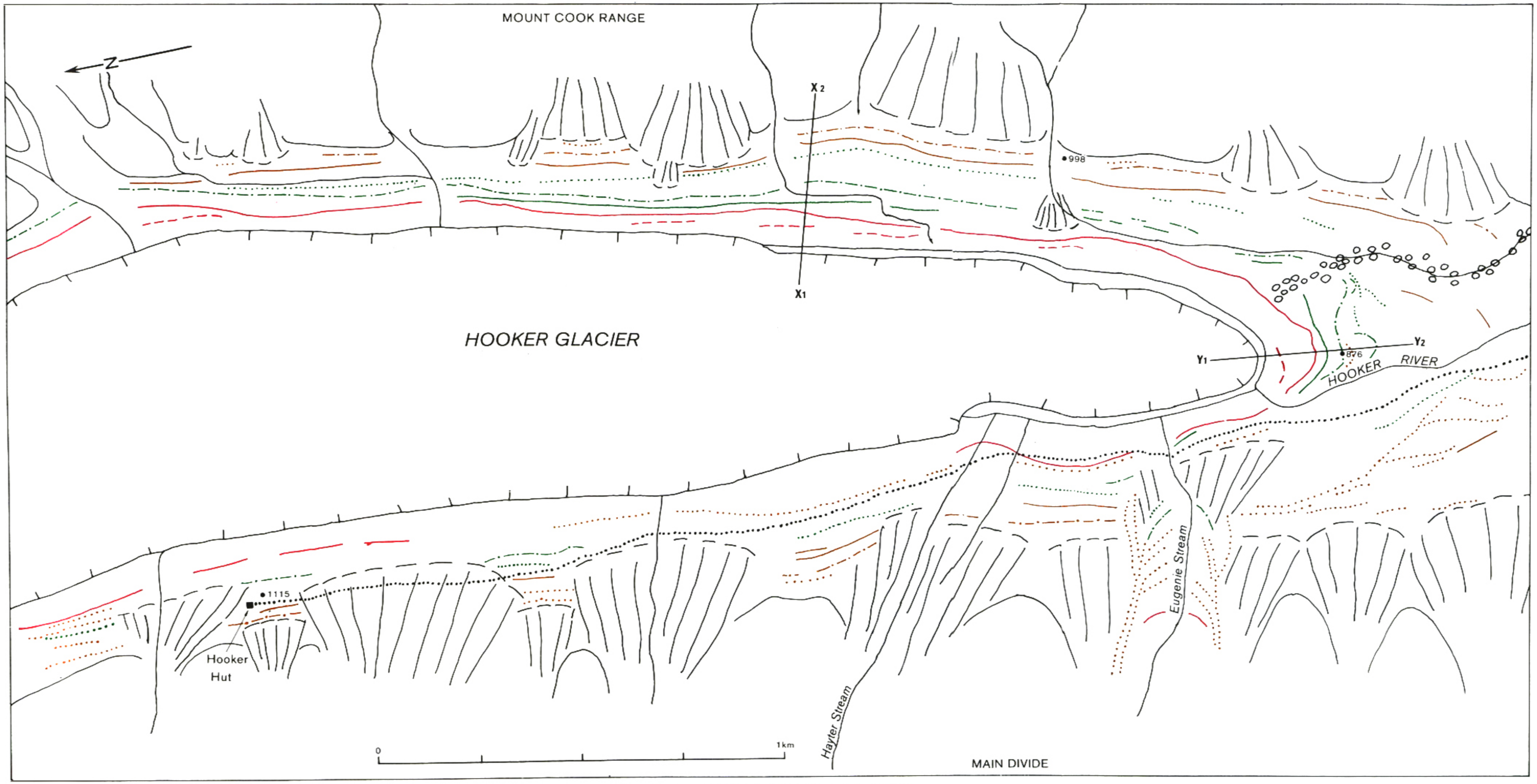

Fig. 16—Moraines marking limits of the Hooker glacier.

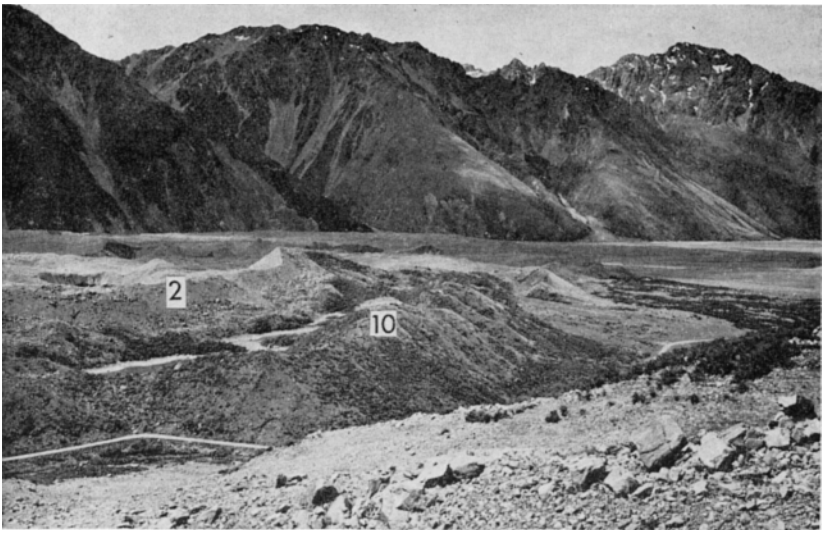

FIG. 17—Tasman lateral and latero-terminal moraines in Blue Lakes area. Moraines formed (2) about 1890, (10) 13th century.

partially masking the older surfaces. The ice here was probably relatively free of marginal debris because there has been less burial of older surfaces by superficial detritus than has occurred on the western side of the Tasman Glacier. The crests of the remaining morainic features probably consist of formerly englacial material let down as the ice shrank from its maximum extent. Several large run-off areas are present. The contrast in vegetation cover on these moraines is very marked, with only those surfaces older than the 18th century having a close cover of scrub.

A short section of undated moraine lies on the east side of the Murchison River about 1·4 km from the terminus of the glacier. This is scrub-covered and was formed in the 18th century or earlier.

There is no clear evidence for minor 20th century advances on this side of the glacier although there are some small ridges near the 1890 crest and others over 30 m lower than it, possibly resulting from halts in recession. The ice near the Murchison bulge is in a state of collapse and a lake lies within the loop formed by the moraine.

HOOKER GLACIER

Figures 4, 21–23 illustrate the main features of the Hooker moraines, Fig. 16 shows the limits of advances of the Hooker Glacier over at least the last 750 years.

The Hooker moraines differ from those of the Mueller and Tasman glaciers in that the oldest laterals are perched high on the valley walls,

FIG. 18—Section cut in Tasman lateral moraine near Ball Hut (S in Fig. 15). Soil with exposed wood (arrows).

about 136 m above the present glacier, and the younger moraines are each successively lower. As was noted earlier these ridges each result from distinct glacier expansions. The Hooker has the best-preserved terminal and lateral moraines of the three glaciers studied. Some of the lateral ridges, though broken by stream courses or avalanche chutes or partly covered by colluvial cones, may be followed for a distance of more than 3 km.

1. The highest lateral moraine on both eastern and western sides of the glacier is very fragmentary and has not been dated.

2. A more continuous prominent ridge just below it has yielded a date of about A.D. 1275 on both sides of the glacier (Fig. 21). In the terminal area on the east side, the late 13th century ridge slopes downward and its distal extent disappears beneath extensive screes. The 13th century lateral ridges are at equivalent altitudes on both sides of the valley.

3. The next prominent lateral ridge is dated at about A.D 1450. In the terminal area the farthest extent of intact terminal moraine dates from this time and there is a confused area of recessional moraine and outwash plain of similar date behind this.

4. Dates of A.D. 1505 to 1520 were obtained from the next prominent lateral ridge on both sides of the glacier. A small fragmentary loop of terminal moraine is of similar age, and behind this are more or less concentric loops from later advances.

5. The next prominent lateral ridges on the eastern side are dated at 1605–1655 and there are prominent terminal and lateral ridges on the

FIG. 19—Blue Lakes and Tasman latero-terminal moraines. From a surface formed about 1850, looking toward surfaces formed in (6a) mid 17th century, (6b) century, (10) 13th century. (N.B. The number is missing from 13th century moraine, which is the highest long ridge above (8) in the upper right corner.)

western side also from 17th century advances, which appear to have been at least twofold. However, it has not been possible to differentiate early from mid 17th century moraines. Numbers of other small, undated moraine ridges are present among the 15th, 16th and 17th century moraines. Meltwater stream at times flowed on the eastern side of the main mass of terminal moraine and old channels wind beside and through the 15th century recessional moraines.

6. An advance in the 18th century is represented by a somewhat less conspicuous sixth lateral ridge on the eastern side of the galcier, the crest of which lies some 12 m lower than that of the 17th century moraine along much of its length. This ridge is dated at 1725–1750 and, though continuity is broken, the ridge can be projected onto a terminal loop. Little 18th century moraine could be identified on the western side of the glacier, although an undated ridge near the Hayter stream is at about the right altitude and may have been formed at this time.

7. A moraine laid down about A.D. 1890 forms the seventh ridge on the eastern side, but it is also not very prominent and it is about 9 m lower than the 18th century moraine along much of its length between a point about opposite the Hooker Hut and the terminus. At the terminal area this moraine rides up over the 18th century moraine (Fig. 4).

8. Some very minor terminal and lateral ridges yielded dates from the early 20th century, but they probably represent small halts in recession. A

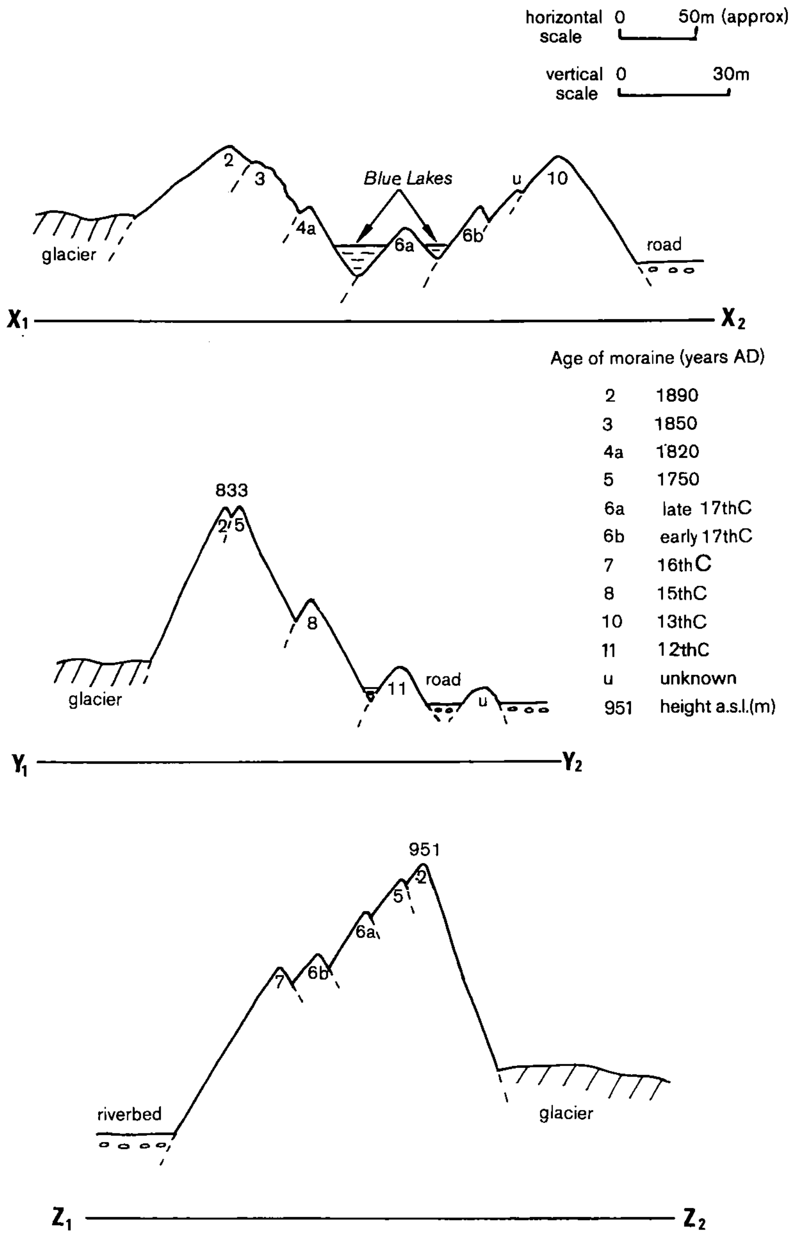

FIG. 20—Tasman moraines, cross-sections showing relative heights of moraine ridges at X_1–X_2, and Y_1–Y_2 (see Fig. 14), and Z_1–Z_2 (Fig. 15).

FIG. 21—Lateral moraines of Hooker Glacier looking from western to eastern side. Surfaces formed (2) about 1890, (5) about 1750, (6) 17th century, (8) 15th century, (10) 13th century. (N.B. The number is missing from 13th century moraine, which is the highest long ridge above (8) in the upper right corner.)

slightly more prominent terminal ridge which may be projected onto some lateral ridges is dated at A.D. 1930. Since 1890 the glacier has lost amounts of ice from its surface varying from about 15 m, vertically, near the terminus to over 30 m near Hooker Hut. In the last decade there has been collapse of much of the ice near the terminus. The trunk appears to be stagnant and is moraine-covered from about the Hooker Hut downward. The terminus proper has only retreated some 136 m from its 1890 position, however.

Near Hooker Hut there has been considerable collapse of the lateral moraines, affecting ridges formed in the 15th century and later. It seems likely from this that the recent period of glacier recession is the most profound which has occurred since these moraines were formed.

Figure 22 shows a section across the lateral moraines on the east side of the glacier, (cf. McKellar 1955) and a section through the terminal moraines.

EUGENIE GLACIER

A small glacier, the Eugenie, reconstituted from ice-avalanche debris, fallen from its high, hanging limb, has extended down to meet the western lateral moraines of the Hooker Glacier at times during the last 800 years. At present the Eugenie is solely a hanging glacier, with its terminus at about 1360 m altitude, above a cliff some 150 m in height (Fig. 23). Occasional ice avalanches and, in winter, frequent snow avalanches, fall

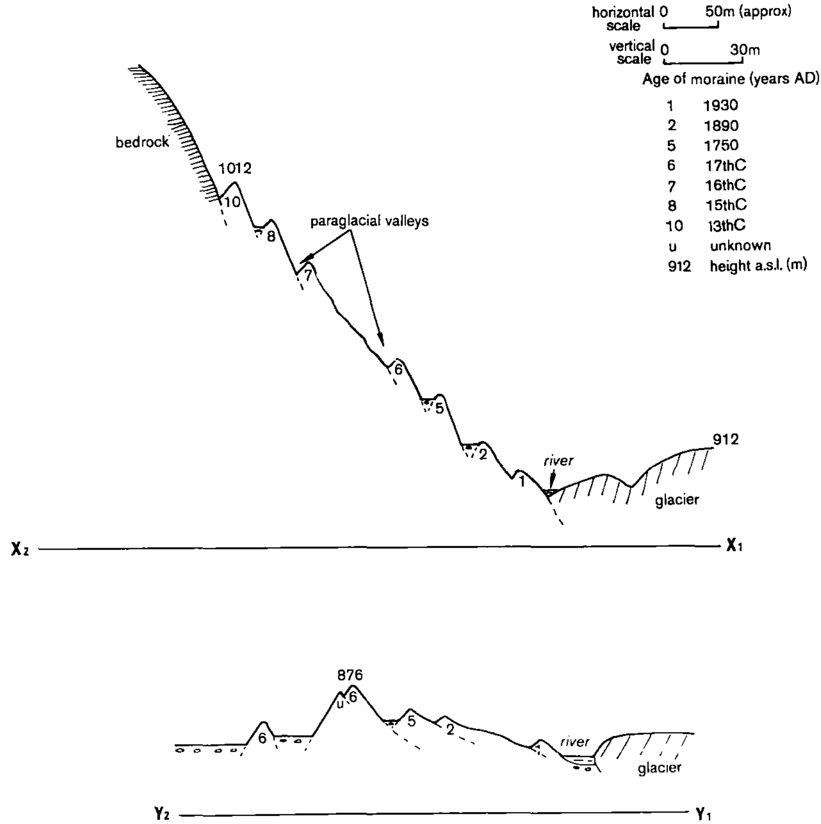

FIG. 22—Hooker moraines, cross-sections at X_1–X_2 and Y_1–Y_2, (see Fig. 16).

over the cliff but the supply of ice is insufficient to reform an active glacier below the cliff at present although some stagnant debris-covered ice appears to be present. Numerous moraine ridges are present, some in the form of almost complete loops.

The form of the Eugenie moraines depends largely on the slope of the surface upon which the glacier lay. The crests of the moraines often slope downward at 25 to 30° from horizontal. Outwash streams have destroyed or buried portions of moraine with debris so that it is difficult to see the limits of some of the older ridges. The oldest moraine which could be dated yielded an age of A.D. 1590 but there are at least two ridges older than this, one of them cutting across and younger than a lateral moraine of the Hooker Glacier formed in the 13th century. The successively younger ridges gave dates between A.D. 1685 and 1900 but it is suspected that in each case the dates may be minimal because lichens are rather sparse on the moraines. The youngest complete loop is assumed to date from the late 19th century and the oldest complete loop from the 17th century.

FIG. 23—The Eugenie Glacier and some of its moraines, from a point above the 19th century moraines of the Hooker Glacier.

DISCUSSION

From Fig. 13, 14, 15, and 16 it may be seen that there are similar chronologies for the glacial expansions which have occurred at Mueller, Tasman, and Hooker glaciers during about the last 700–800 years. As Burrows & Lucas (1967) and Burrows & Orwin (1971) point out, similar dates were often obtained using two different lichen species. The dates younger than about the late 16th century may be accepted with a good deal of confidence. Older dates must be accepted more cautiously, yet several times, similar maximal lichen diameters were measured on different parts of an extensive moraine, and elsewhere very similar dates were obtained on the equivalent moraines of different glaciers. Equivalence was gauged by the relative spatial positions of moraines beginning with the youngest surfaces of known age. There are discrepancies caused by the apparent absence of some surfaces in some places, and by the absence of suitable lichens for measurement in others. As was noted briefly in the text, each glacier has behaved somewhat independently as far as relative magnitudes of expansions at the same times are concerned. This is of considerable general interest and will be discussed in a future paper.

Some of the dates for expansion periods suggest that formation of moraines may have taken place over comparatively short time periods of the order of five to ten years. The possibility that the moraines have resulted from glacier surges, occurring over periods of a year or less, such as are known in some Alaskan glaciers (e.g., Bayrock 1967) was considered. It is unlikely, however, that surges are responsible for the formation of these moraines because surges are destructive events and moraines formed by them are secondary features resulting from displacement of existing moraines (R. P. Goldthwait pers. comm.).

The moraines of the Mount Cook glaciers record a longer history of recent glacier fluctuations than any in other parts of the world except those on the Stubai Alps of Austria (Mayr 1964). The New Zealand record is more detailed than that in Austria, however. As was noted by Burrows & Lucas (1967) there is good agreement between dates for the New Zealand advances and those recorded in various places in the Northern Hemisphere from the late 16th century forward. Mayr (1964) has shown, from recent work in Austria, that within the last 2000 years there is radiocarbon-dated evidence for advances of glaciers in the 1st to 8th centuries A.D., and also in the 12th and 13th centuries A.D. and later. Although there are some older moraine fragments near the present glaciers at Mount Cook, dates earlier than the 12th century have, so far, not been recorded among the more recent moraines. A more detailed analysis of the comparison between the New Zealand glacial record and that elsewhere will be made later; the causative phenomena seem to have operated at about the same times in both hemispheres.

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APPENDIX

LICHEN MEASUREMENTS FOR *Rhizcarpon geographicum* AND *R. candidum*, ON MORAINES OF MOUNT COOK GLACIERS, FROM WHICH DATES WERE OBTAINED.

(Measurements in cm on longest axis of oval thalli.)

Generalised Age of Surface	MUELLER		HOOKER, WEST SIDE		HOOKER, EAST SIDE		TASMAN, WEST SIDE		TASMAN, EAST SIDE		EUGENIE	
	R.geog.	R.cand.	R.geog.	R.cand	R.geog.	R.cand.	R.geog.	R.cand.	R.geog.	R.cand.	R.geog.	R.cand.
1930	2.3•	nl	nl	nl	2.3•	nl	nm	nm	nm	nm		
1915	3.3• 3.3§	nl	nm	nm	nm	nm	nm	nm	nm	nm		
1890	5.1• 4.8† 4.8§	nl	5.1‡	nl	4.6•	nl	4.8•	nl	4.6•	nl	4.1	nl
1850	8.4• 6.8† 7.4‡ 8.6‖	4.3† 5.1‖	nm	nm	nm	nm	7.1•	4.8•	nm	nm		
1820	nm	nm	nm	nm	nm	nm	9.4•		nm	nm		
1770–90	12.2• 10.4† 10.6‡ 9.9‖	7.1• 6.6‖	nm	nm	nm	nm	nm	nm	nm	nm		
1730–50	13.2• 15.2† 13.7‡ 14.2§	8.6† 8.4 8.6‖		10.2‡	14.5†	7.9• 10.2†	14.7•	10.4•	12.9•			
Mid-late 17th C.	19.0‡ 19.3§	12.9§	17.3†	12.2†		15.2• 14.7†	18.0•	12.9•	19.5•	12.9•		11.7
Early 17th C.							18.8•	14.5•		15.0•		
16th C.	23.6‡	17.8‡		19.5†	23.4•	18.8• 17.0†	nm	nm	26.4•			15.7
15th C.		22.1‖ ?	31.7•	20.6• 21.1†	34.3•	21.8• 22.1†		22.1• 23.1†		20.3†		
14th C.		25.9§ ?										
13th C				29.5†		29.2 •	42.7•	28.4•				
12th C.								35.3• 35.6†				
Locality Codes:	•South of first swing-bridge †Between swing-bridges ‡White Horse Hill and Spillover §Kea Point Spill-over ‖North-west of second swingbridge		•Near Hooker Hut †Near Hayter Stream ‡Near Eugenie Stream and terminus		•Near terminus †From opposite Eugenie Stream to opposite Hooker Hut		•Near Blue Lakes and terminus †Near source of Blue Stream		• Novara Corner † South of Murchison bulge			

nl = no lichen present; nm = no moraine present; Blank indicates undated moraines present, or lichens small or diffuse;
? = probably underestimates age of surface