LATE QUATERNARY SNOWLINES AND CIRQUE MORAINES WITHIN THE WAIMAKARIRI WATERSHED

With three separate charts

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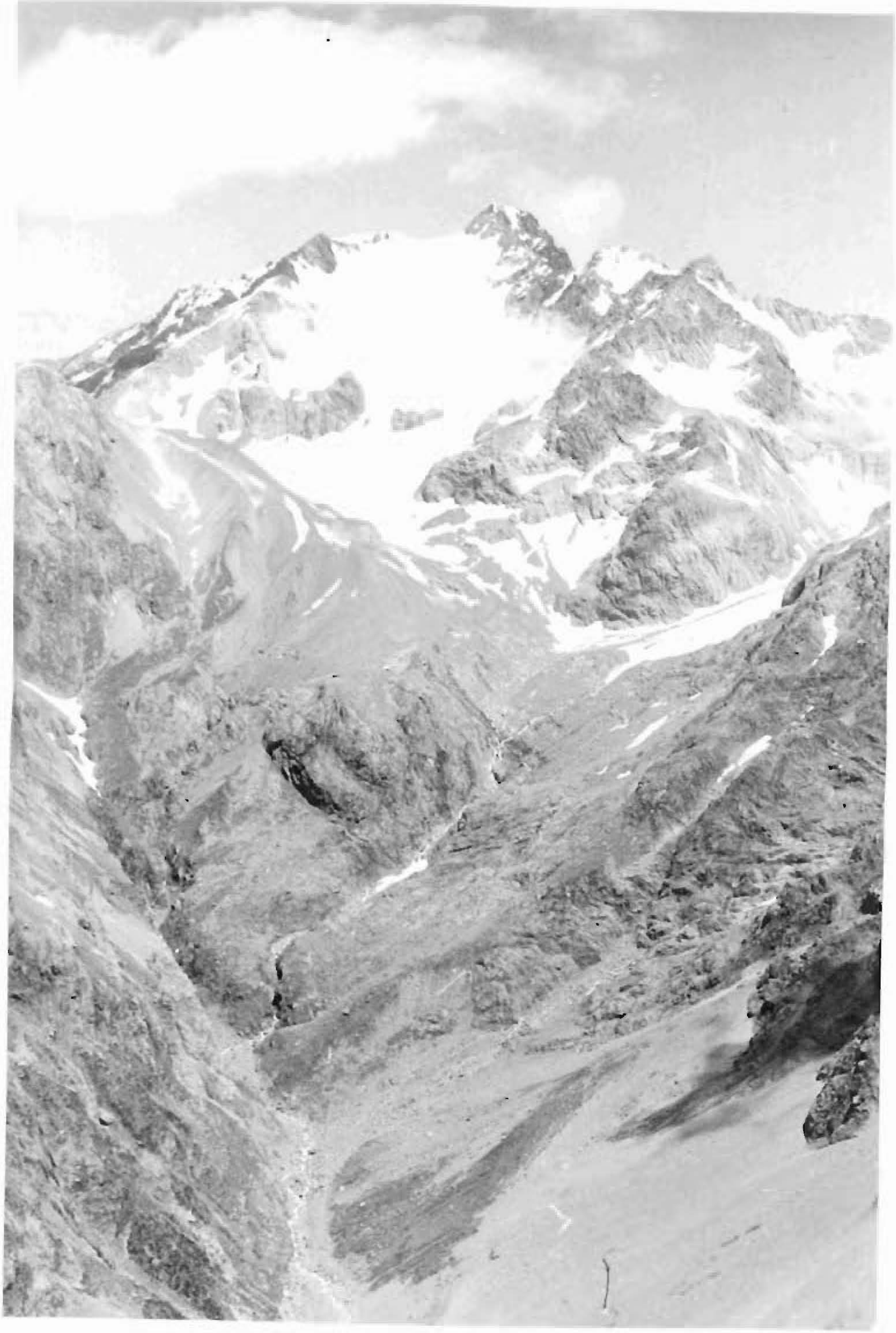

FRONTISPIECE

Mt Murchison (2401m) and the White Glacier.

ABSTRACT

A study of the glacial geology and present and past snowlines of tributaries to the Waimakariri River, South Island, New Zealand, has yielded a glacial chronology from late Pleistocene times up to the present day.

Three advances of the ultimate (Otiran) Pleistocene glaciation were recognized and named the Kowai, Porter and Tims Stream advances. Ice limits were established for an early Holocene (McGrath) advance and for three following Neoglacial ice resurgences, named Arthur's Pass, O'Malley and Barker advances.

Moraine-headwall and area-altitude methods were used to compute past snowline elevations from which snowline surfaces have been constructed. Compared with the present snowline, depressions of up to 970m for the Pleistocene, 480m for the McGrath advance and 400m, 300m and 200m for the Neoglacial events are indicated. Isopleth maps of the snowline surfaces show a steep upward gradient towards the east, with strong topographically-induced irregularities superimposed upon this pattern.

Weathering rind studies on surface boulders of the Holocene deposits showed a systematic increase in thickness with increase in age. Radiocarbon dates with rind thicknesses from landslide deposits provided the basis for a rind thickness growth curve. This curve was used to age and correlate the glacial events.

Parallelism of the different snowline surfaces suggests that climatic patterns remained similar throughout the Holocene. Early Holocene deposits suggest a cool wet period between the Tims Stream and McGrath events, while a number of rock glacier deposits indicate a cool drier climate for the beginning of the Neoglacial advances.

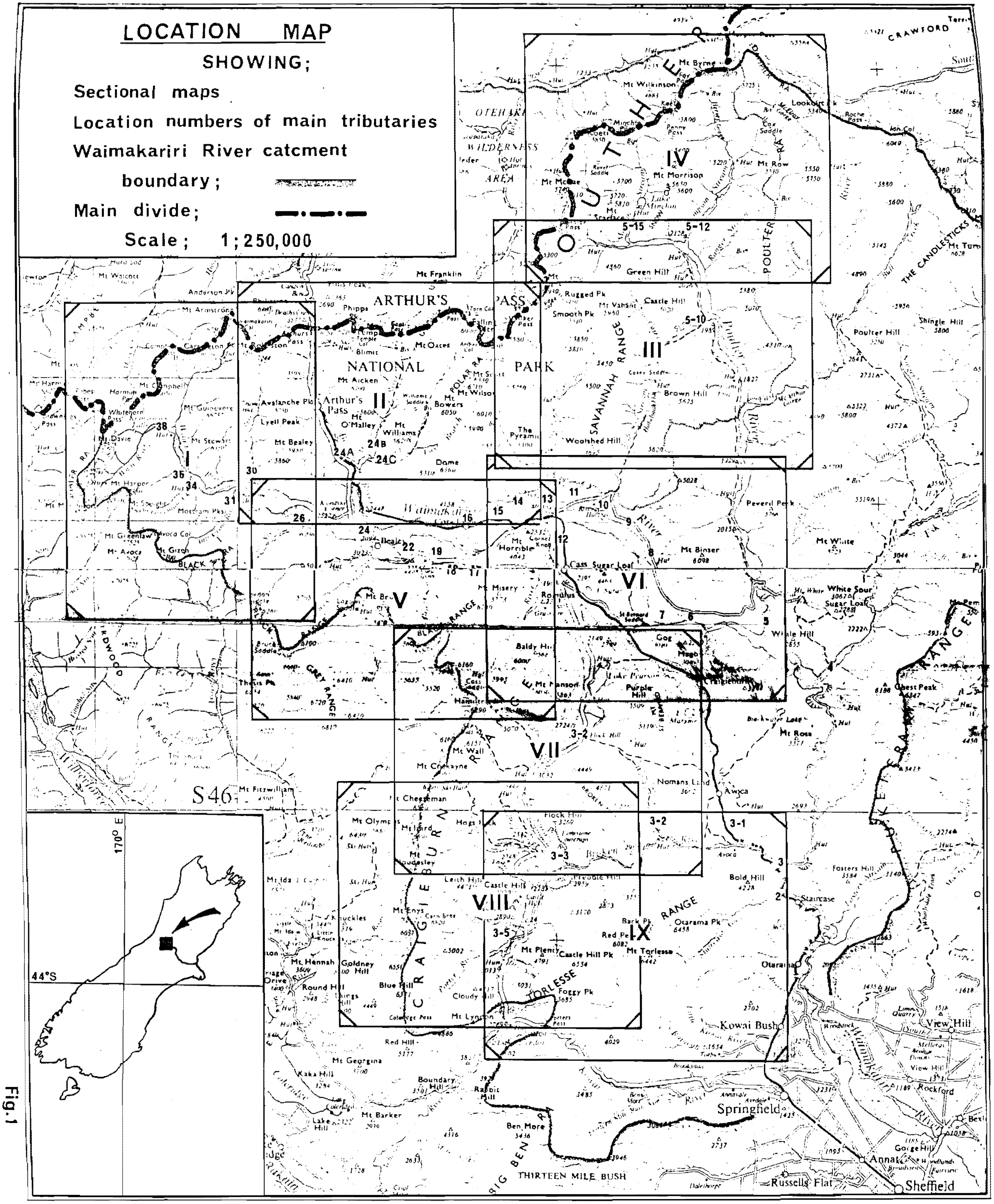
LOCATION MAP
SHOWING;
Sectional maps
Location numbers of main tributaries
Waimakariri River catcment
boundary;
Main divide;
Scale; 1;250,000
ARTHUR'S PASS NATIONAL PARK
I
II
III
IV
V
VI
VII
VIII
IX
Arthur's Pass
Mt Rolleston
Mt Byrne
Mt Wilkinson
Mt Morrison
Green Hill
Castle Hill
Rugged Pk
Smooth Pk
Brown Hill
Woolshed Hill
SAVANNAH RANGE
POULTER
THE CANDLESTICKS
CRAWFORD
Mt White
White Sour Sugar Loaf
Peveril Peak
Mt Binser
Cass
Sugar Loaf
Mt Horrible
Mt Misery
Romulus
Baldy Hill
Mt Hanson
Purple Hill
Lake Pearson
Craigieburn
Goldney Hill
Mt Wall
Mt Cockayne
Mt Cheeseman
Mt Olympus
Castle Hill
Castle Hill Pk
Mt Plenty
Foggy Pk
TORLESSE RANGE
Otarama Pk
Red Pk
Mt Torlesse
Bold Hill
Staircase
Otarama
Awaca
Kowai Bush
Springfield
View Hill
Rockford
Annat
Gorge Hill
Sheffield
Russells Flat
THIRTEEN MILE BUSH
BIG BEN RANGE
Ben More
Rabbit Hill
Boundary Hill
Mt Barker
Mt Georgina
Kaka Hill
Red Hill
Lake Hill
Mt Hennah
Round Hill
Blue Hill
Cloudy Hill
Mt Lyndon
Mt Enys
CRAIGIEBURN RANGE
Mt Fitzwilliam
S46
Mt Aicken
Mt O'Malley
Mt Williams
Mt Bealey
Avalanche Pk
Lyell Peak
Mt Oates
Mt Bowers
Dome
Mt Franklin
Mt Armstrong
Mt Davie
Mt Stewart
Mt Harper
Mt Greenlaw
Mt Avoca
BLACK RANGE
GREY RANGE
Waimakariri
River
Bruce Saddle
Thetis Pk
Hamilton
1
2
3
3-1
3-2
3-3
3-5
5
5-10
5-12
5-15
6
7
8
9
10
11
12
13
14
15
16
17
18
19
22
24
24A
24B
24C
26
30
31
34
35
38
170° E
44°S

Fig.1

CHAPTER I

INTRODUCTION

(1) Description of the Area

This study covers an area of over 2,000 km^2, constituting a greater part of the catchment area of the Waimakariri River, South Island, New Zealand. N.Z.M.S. 1 topographic map series covers the area at a scale of 1:63360, on sheets S58, S59, S66 and S74. The area studied includes part of the Waimakariri River watershed, extending from the foothills up to the main divide south of a boundary formed by the Waimakariri and Poulter Rivers and the Poulter Range. The north-eastern part of the Poulter River watersed, together with the whole of the Esk River watershed, was not included in the study area, because of poor access and the complexity of the glacial deposits there.

The portion of Arthur's Pass National Park lying east of the main divide is included in the study area.

The region is sparsely populated, having only the one township of Arthur's Pass, but good access is afforded by both the Christchurch-Kumara main highway and the Christchurch-Greymouth railway, which pass through the area. Apart from these two means of access, there are few other roads, making foot travel necessary over much of the country.

The highest peaks rise to 2,200m in the north-western sector of the area, and the ranges descend to elevations of 1600m in the northern sector. The present glaciers are restricted to a limited area among the highest peaks. These few dozen small glaciers, glacierets and snow patches are wasting remnants of former, more extensive areas of ice, following the considerable glacial recession which has occurred over the past half century. The largest of the glaciers in the area, the White, Marmaduke Dixon and Crow Glaciers, range in length from 1.1km to 1.7km.

Tributaries from the main divide drain through narrow, glaciated and frequently gorged streams, into the wide, alluvium-filled valleys of the Waimakariri and Poulter Rivers. Below its confluence with the Poulter River, the Waimakariri River is confined by deep gorges as it passes through the foothills between the Torlesse and Puketeraki Ranges, before discharging eastwards onto the Canterbury Plains. The subsidiary Craigieburn and Torlesse Ranges, which reach elevations of up to 1800m, drain through the extensive terraced alluvial fill in Castle Hill Basin before joining the Waimakariri River at its confluence with Broken River.

A continuous cover of beech forest (Nothofagus sp.) clothes the ranges up to the tree line at approximately 1,200m, in an almost continuous cover for some 10km to 15km east of the main divide. Further eastward from this margin the forest cover gives way in discontinuous patches to the tussock grassland, scrub and scree of the remainder of the region.

(2) Present climate

The present climate of the area is governed by the regular procession of anticyclones and troughs of

PLATE 1

Winter aerial photograph of Arthur's Pass area. Mt Rolleston (2271m), centre background and Black Range in the foreground.

PLATE 2

Castle Hill Basin, showing part of the Craigieburn Range and terraced basin floor. Tertiary limestone outcrops in foreground.

low pressure moving on to the country from the Tasman Sea to the west. A strong fohn effect is generated by the Southern Alps' lying across the path of the prevailing westerly winds, thus creating a steep eastward precipitation gradient. There is a rapid decrease in mean annual precipitation from 5,072mm at Otira, west of the main divide, to 3,952mm at Arthur's Pass, 1,275mm at Cass, 912mm in Castle Hill Basin and 700mm on the east coastal margin. Although westerly winds prevail, easterly, and in particular, southerly winds can be important sources of snow in the foothils areas. Rainfall is distributed evenly throughout the year.

(3) Basement rocks

The basement rocks of the area are almost entirely sandstones and siltstones of the Torlesse super-group. This faulted, folded and closely-jointed triassic rock contains occasional inclusions of cherts and igneous rocks. Isolated outliers of infolded and infaulted Cretaceous and Tertiary rocks occur in Castle Hill Basin and in other small areas.

(4) Previous work

Five distinct periods of Pleistocene ice advance in the Waimakariri Valley have been described by Gage (1958), and subsequently by Gage and Suggate (1958), Suggate (1965), where these events have been related to other New Zealand Pleistocene ice advances. Earlier discussions on glacial activity in the area include Haast (1879), Hutton (1884), Gudex (1909) and Speight (1916, 1917, 1935, 1938). These discussions contain little mention of the post-Pleistocene glacial events, apart from noting the presence of Holocene moraines and existing glaciers at the headwaters of the Waimakariri River. An early identification of moraines on the summit of Arthur's Pass was made by Dobson in 1865, and Speight (1938), mapped a small number of moraines in the Waimakariri headwaters.

No systematic studies of past or present snowlines have been made in the area, and the few that have been made elsewhere in the Southern Alps' include the past snowline estimates made by Willett (1950), and Porter (in press). A number of studies of New Zealand Holocene glacial sequences has been made, most of which emphasise the more recent glacial events, and few have been on a sufficiently large regional scale to include a full sequence of Holocene ice advances. The more recent of these studies include those of McGregor (1967), on Ben Ohau Range, Waitaki Catchment; Burrows (1971), Mt Cook area; Wardle (1973), West Coast; Burrows (1973), the Arrowsmith Range and Burrows (in press), Rakaia River headwaters area.

(5) Objectives of the study

The cirques and their associated moraines in the Waimakariri River Catchment offered an opportunity to establish a Holocene glacial sequence for the region which would follow on from the Pleistocene glacial history of the area published by Gage (1958). By studying the past snowlines on a regional scale, on the evidence from cirques and moraines, snowline trend surfaces may be established for each glacial episode. By extension of this approach to include Pleistocene ice-occupied cirques, composite snowlines may be found for this period.

(6) Acknowledgements

Grateful acknowledgement is made to the Ministry of Works and Development, for the opportunity to undertake this course of study and to the University of Canterbury Geology Department, for assistance and supervision. The Arthur's Pass National Park Board gave generous assistance during the course of the fieldwork, and useful criticisms were made by Professor S.C. Porter, Dr C.J. Burrows and Dr I. Brooks. Valuable criticism and assistance in the field was given by Dr M. Kelly.

CHAPTER II

FIELD EVIDENCE

I FIELD METHODS

Field work was carried out over the summer periods of 1972-73 and 1973-74, to avoid winter snow cover. Most of the area was studied during the first summer period, the remaining areas were visited during the second summer, together with a number of critical localities which were revisited to gain more detailed verification. The field excursions took the form of circuits made on foot and of about a week's duration. They covered either main valleys or ranges, depending upon the location of the more important features.

A special visit to Section I was made in early April 1973, to study the present snowline. April is normally the time of the highest retreat of the snowlines, when the glacial equilibrium line elevations are displayed on the glaciers as the bare ice - firn boundary. The area was flown in a fixed wing aircraft to gain oblique aerial photographs of the more important features, and of some hitherto undetermined features.

(1) Preparation

Comparatively few of the mountains and streams of the area are named, and this has made it necessary to develop an arbitrary numbering system, giving reference numbers to individual streams and their headwater basins. Each tributary of the Waimakariri River, arising from areas of present or inferred past glacial activity, was numbered consecutively in an upstream direction, beginning at the upper limit of the Canterbury Plains. The branches of these tributaries were then numbered consecutively in an upstream direction until all the first order streams were numbered. One departure was made from this system, where three third order streams are confluent at nearly the same point; the Bealey, Mingha and Edwards Rivers. To avoid cumbersome reference numbers, these rivers were numbered 24A, 24B, and 24C respectively.

As an example of this tributary identification system, the upper Temple Basin ski-field is numbered 24-24A-12, which is arrived at from the following:-

24 - the 24th tributary of the Waimakariri.
24A - defines which tributary of stream number 24.
12 - the 12th tributary of stream number 24A.

The study area covers over 2000km^2, and a single map on an adequate scale to show the wealth of small detail would therefore be unduly large and cumbersome. To simplify references to particular locations, the area was divided into the nine sections given on the location map, (figure 1).

A set of vertical aerial photographs, taken in 1959 and in 1960, was obtained for use in the field, and the centres of these were plotted by inspection on the 1:63,360 scale base maps for location reference.

Before field work was begun, a study of the aerial photographs was made, using a mirror stereoscope, with the aim of locating features of interest to be visited in the field. As field work progressed, it was found that this early perusal had picked up very few of the relevant features, and that a large proportion of those features noted had, in fact, been misinterpreted. With experience in the field and on the stereoscope some skill in aerial photograph interpretation was acquired, but the danger of misinterpretation was always present.

(2) Field work

(a) Early field work: The earlier field work consisted of a general reconnaisance of cirque basins, their moraines and other associated features, aimed at establishing a classification of forms rather than a glacial chronology. As sequences of glacial advances began to be recognised, emphasis was shifted towards the development of a glacial chronology and criteria for recognising and ageing tills and moraines.

(b) Later field work: To provide a more accurate basis for plotting features and for the calculation of past snowlines, one set of the nine sectional maps was enlarged photographically from a scale of 1:63,360 to a scale of 1:31,680 (1 inch to ½ mile).

The procedure of plotting details directly onto aerial photographs in the field and later transferring these data onto these enlarged base maps proved satisfactory. All moraines and tills were plotted, along with the occurrence of outwash terraces, debris falls, rock glaciers, surviving Pleistocene ice-eroded surfaces and fluvial dissection limits. In particular, for the present snowline study the position and elevations of the firn lines of existing glaciers were noted, and for past snowlines the positions and elevations of past glacier terminals were determined as accurately as evidence permitted. As a pattern began to appear in the mapped moraines, it became possible to predict successfully the positions of some glacial advance limits, and then to plan field traverses to confirm these locations.

The two main problems encountered in the field were:-

1. Identification of tills or moraines.
2. Ageing of deposits.

The correct identification of tills was particularly important when attempting to distinguish moraines from landslides with similar surface topography. (See Appendix II). The older moraines were normally dissected, and some occurred along with landslides and other diamicton deposits. It was therefore assumed that a deposit was not of glacial origin unless there was independent confirmation.

II GLACIAL AND PERIGLACIAL FEATURES

(1) Erosional features

(a) General: Although the features resulting from glacial erosion are conspicuous throughout the whole of the study area, there is a significant difference between the types associated with smaller individual Pleistocene glaciers of the eastern Torlesse and Craigieburn Ranges; compared with those of the western ranges which were the source of the main Pleistocene ice streams. Erosional features of the

PLATE 3

Extensive scree development typical of the study area. View north-east across Sudden Valley, tributary 13-1.

PLATE 4

Stereoscopic pair of upper Greenlaw Creek, (tributary 34-2), showing advanced fluvial dissection and remnant glaciated surfaces, R.

smaller of the eastern ranges are confined within local glacial basins and cirques where few of the Pleistocene ice-sculptured surfaces have survived without modification. Areas abraded by later glacial episodes are also fragmentary and survive only where they have not been dissected by stream action or overwhelmed by the extensive scree development of the area.

The higher ranges towards the west display the features associated with intensive glaciation, including "U" shaped valleys with ice-scoured surfaces and assymetrical cross-section on bends, truncated and overriden spurs, etc. Few glacial features survive on the main valley floors which have been over-deepened and subsequently covered with valley train alluvium and large alluvial fans. Thus on the main valley floor roches moutonnees are rare and glacial stairways non-existent. Surviving glaciated valley floors occur at higher elevations towards the heads of tributary valleys, especially where the valley heads at a low pass (e.g., the Edwards River, number 24C). The streams in these higher valleys are usually deeply incised below their ice-trimmed valley floors.

(b) <u>Fluvial dissection and remnant surfaces</u>: Steep, actively eroding slopes and gullies occur between the alluvium-filled valley floors and higher level ice-worn surfaces. The well-defined upper limit of fluvial dissection, shown on the features maps (figures 22 to 30), constitutes a boundary below which glacial deposits are unlikely to have survived. Extensive areas

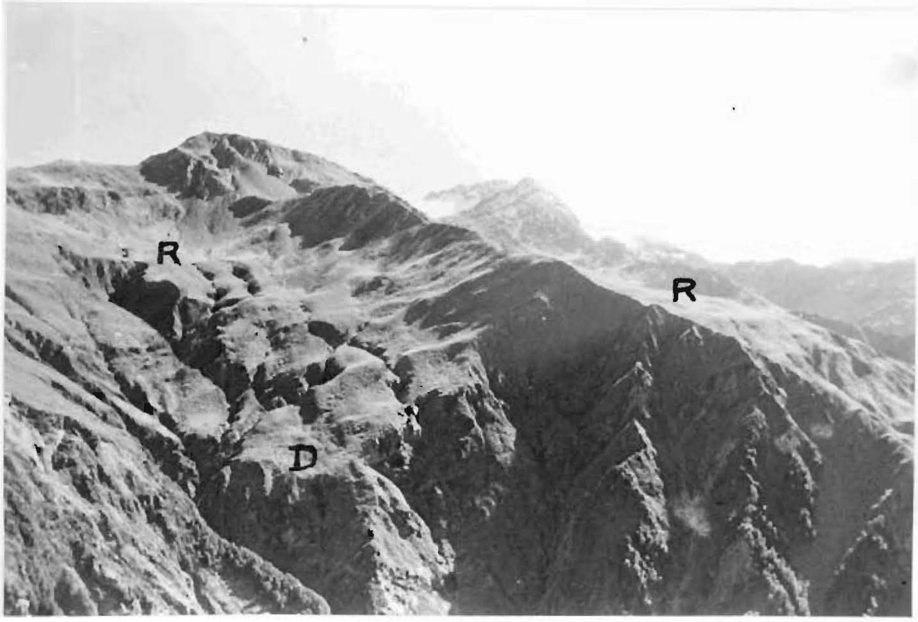

PLATE 5

The upper fluvial dissection limit (D), where remnant glaciated surfaces (R), are intersected by steep dissected faces, Mt Avalanche, Arthur's Pass.

of ice-eroded landscape survive above this limit, the dominant forms being alp surfaces and cirque basins. The bulk of the *"Neoglacial" deposits are found in these areas of cirque and alp surface which have as yet escaped destruction by fluvial erosion. The alp surfaces are widespread throughout the western part of the study area (plates 4 and 5), and frequently extend for considerable distances along the ranges between subsidiary ridges or cirques, indicating the existence of extensive areas of neve-sheathed slopes between tributary ice streams during Pleistocene times.

(c) Cirques: The cirque basins range in extent of development from incipient hollows to mature cirques containing tarns, and are almost invariably discordant with the main valleys. Those cirques at higher levels that have been occupied by later glacial advances are noticeably better developed. Higher level cirque basins developed at the heads of the large Pleistocene tributary ice streams by rotational ice flow W.V. Lewis (1960), Flint (1971), appear to have undergone little modification during the subsequent Holocene glacial advances. Evidence for the relatively minor amount of Holocene glacial erosion is seen in both the terminal positions and the volume of debris left by the Holocene glaciers. The positions of the moraines show that the Holocene glaciers were generally incompatible with the cirque morphology. Moraines either spill over the cirque lips, or are confined within the lower limits of the basins. The volumes of the moraines is small compared to the volume of material

*See Chapter IV, Proposed Glacial Chronology, for a definition of Neoglacial.

removed to form the basin, suggesting that there has been limited modification of the basins since their formation by Pleistocene ice erosion.

The smaller Pleistocene glaciers, isolated from the large ice streams, occupy well-developed basins now enclosed by massive moraines. Level cirque floors, where they occur, are attributed to the erosional effects of composite Pleistocene snowlines of the Otiran Glaciation, because the floors rarely coincide with the snowline elevations calculated for the Pleistocene advances. There is also a frequent disparity of size between the cirque and the inferred extent of the ice formerly occupying it, for example at Tims Stream (tributary 3-3-3-1), and Porter River (tributary 3-7), where the termini of even the later Pleistocene advances have advanced beyond the limits of the valleys, to spread out into piedmont lobes, while in other cases, the termini have been contained within the valley limits.

(2) Glacial deposits

(a) Extent: Moraines, tills and fluvioglacial outwash deposits in varying states of preservation occur throughout the area where there is significant relief. Pleistocene moraines and outwash deposits occur on the valley floors and extend downstream to the upper limits of the Canterbury plains, Gage (1958), while moraines younger than Pleistocene age do not extend further than the base of the main ranges. In the Graigieburn and Torlesse areas, Pleistocene moraines occur close to the base of the ranges.

In the headwaters of the Waimakariri, where the highest peaks occur, (up to 2,200m), the early Holocene moraines of the larger valleys are found at valley floor level. As summit elevations decrease along the main divide towards the north-east, the level of these moraines gradually rises until in the Poulter River headwaters, Holocene moraines rarely descend as low as the main valley floors.

Later Holocene (or Neoglacial) moraine sequences are displayed up-valley from the early Holocene moraines in all of the higher ranges of the main divide area. In the north-east these sequences extend only into mid-Neoglacial times, while in the west they include recent moraines of existing glaciers. Close behind the youngest Pleistocene moraines of the eastern ranges are the early Holocene moraines extending rarely into early and mid-Neoglacial moraines.

(b) State of preservation: The preservation of the glacial deposits is very fragmentary. No traces remain of many of the older deposits, while few of those occurring even in favourable sites have escaped at least some degree of modification. The degree of erosion and dissection of the moraines was found generally to increase with increasing age and increasing gradient of the valley sides and floors.

In the higher basins and cirques, at the upper limit of fluvial dissection, many of the former glaciers appear to have terminated in ice-avalanches at the foot of which debris accumulated to form amorphous talus cones, Luckman (1971). Because of the glacial origin of

"Spilled Till" (ST), in the upper Anti Crow River (tributary 31-4). Early Holocene morianes (M), and late Holocene moraines (B), also evident.

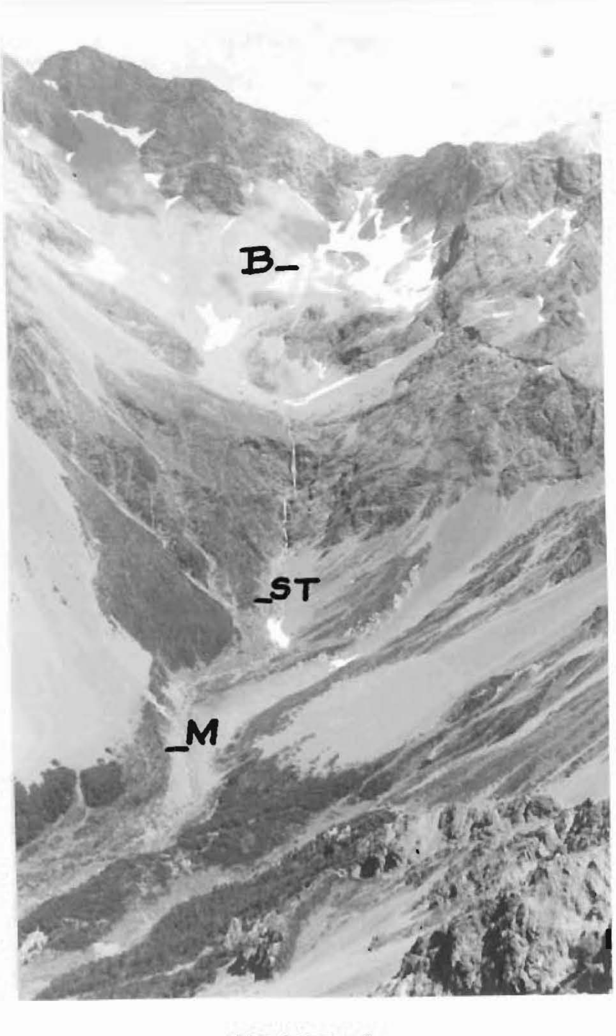

PLATE 6

the material in these deposits, they have been termed "spilled tills", (plate 6). Many of these "spilled tills" have been extensively modified by avalanches and frequently show no reliable form from which glacial outlines may be interpreted, (plate 36). It was found that even in areas of recent glacial activity, the debris from winter snow avalanches very quickly modifies moranic forms into scree cones.

Above the fluvial dissection limit, where gradients are more gentle, better-preserved moraines afford the most reliable evidence of the later glacial successions. These moraines tend to be of mid to late Neoglacial age in the highest ranges, and progressively become older with the low summit heights towards the north-east. A small number of cirques contains no moraines at all, but useful, "negative" results for glacial extents may be gained by ageing, by weathering rind thickness, rock pavements of cirque floors. For example, the cirque floor at Waimakariri Falls (tributaries 46 to 48) was aged at between mid and late Neoglacial time by this method.

(3) Recognition of moraines

Problems in moraine recognition arise mainly from similarity with other widely-distributed deposits of non-glacial origin resembling glacial deposits in both form and composition. Till mantles spread over undulating bedrock surface can be mistaken for terminal moraines. As seen on aerial photographs, bedrock features, such as bedding and lithological contrasts, minor surface faults and slump scarps can take forms remarkably similar to those of moraines. Large scale slumping in a few instances has deformed local areas to the extent that the moraines are unrecognisable. On the upper western slopes of Dome (tributary 24C-1), for example, is displayed a complex of small sub-parallel scarps of sufficient extent to suggest that the crest of this whole range is slumping. Consequently although moraines may be present, none were mapped from this area.

Forest cover normally obscures all but the largest moraines on aerial photographs, and makes them difficult to discern even in the field.

The moraines were recognised in the first instance by their form, usually in the shape of one or more concentrically situated loops, breached by a meltwater stream. Where fluvial dissection has been active, the terminal moraines have usually been reduced or destroyed, leaving only lateral moraines or fragments from which to construct the former glacier outline. Older Holocene ablation moraine dumps on valley floors are sometimes detected on the aerial photographs as swampy clearings in the forest cover, attributable to the impervious nature of the till. Not all tills encountered were impervious, however, as cases of streams flowing through moraine ridges were noted, for example the moraine-dammed pond on the summit of Arthur's Pass.

In localities where glacial deposits have been completely or partially removed, fragmentary, indirect evidence sometimes gives a clue to the extent of the former glacier. Irregularities in the form of double ridged spur ends and offset valley side-streams may for example suggest ice-margin modification of stream patterns where a tributary flowing directly into the main valley was deflected by the glacier to flow parallel to the ice margin. Following the retreat of the ice, moraine ridges and fluvial incision can permanently superimpose a new stream pattern that may persist even after part or all of the glacial deposits have been removed. This type of evidence for ice limits was used with care, and preferably not without independent supporting evidence. In the Kowai River (tributaries 1-5 to 1-7), an area which shows recent tectonic activity, somewhat similar morphologic irregularities have been identified as structural stream control because of the absence of other evidence in support of an ice margin origin.

(4) Tills

The majority of the tills encountered in this study were the deposits of small glaciers that had travelled over relatively short distances. These deposits show some differences in character when compared with those of the major valley glaciers of the area. The tills occur mainly in the form of lateral and terminal moraines, with rare examples of ablation moraines and basal till deposits. Because of the relatively short distances over which these tills have been transported, boulders tend to be more augular, and ice striae much rarer than those from the tills of the major valley glaciers. Water-worn clasts were found in all of the tills examined, emphasising the high proportion of rainfall in the total precipitation onto these glaciers. (Gage 1958, Anderton and Chinn, 1973). Because most of the tills studied were lateral or terminal deposits of small glaciers, compaction was not an important factor.

The occurrence of many formless fragments of the glacial deposits amongst moraine-like deposits of non-glacial origin made it essential to verify in the field the source of deposits by seeking exposures from which the composition could be studied. Tills were identified by their angular clasts, and typically unstratified, unsorted, homogeneous composition. When distinguishing moraines from landslides and other slope deposits the inclusion of odd water-worn pebbles within the deposit gave credence to a glacial origin. Exceptions occurred where landslides had crossed or otherwise incorporated alluvium.

(5) Outwash

Outwash terraces and valley trains are associated only with the older and more extensive glacial advances. No outwash terraces younger than the *McGrath advance age were found, that could be directly associated with a particular glacial advance.

The Pleistocene moraines of the Craigieburn and Torlesse Ranges mark the upper limits of some very extensive terrace complexes. The Kowai River (tributary No. 1-7), drains through a set of terraces, comprising

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*See Chapter IV, Proposed glacial chronology.

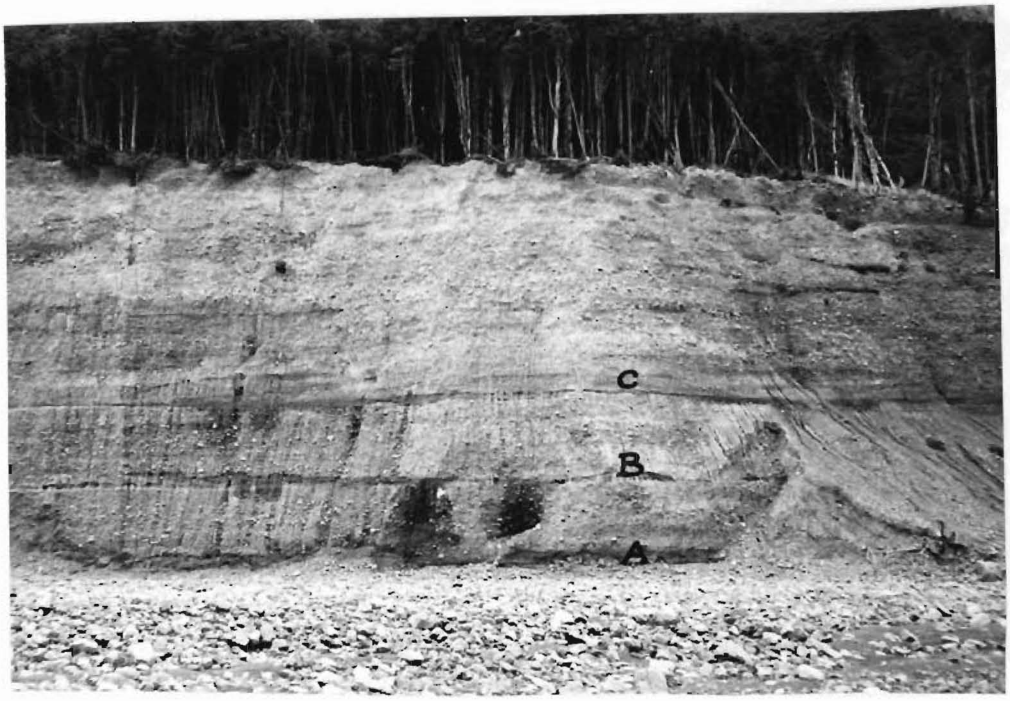
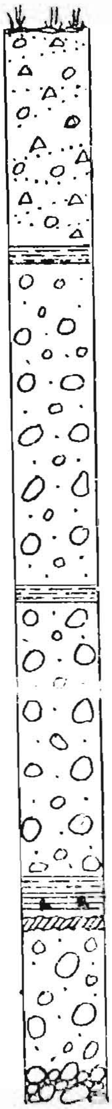


PLATE 7

Outwash terrace exposure near tributary 5-14, Poulter River.

Descriptive section



9.5m	Lensed sub-angular fan gravels.
Bed 'C'	40-50cm silty clay, with wood fragments. Iron stained top and bottom.
3.5m	Loosely compacted river gravels, lightly weathered.
Bed 'B'	30cm weathered silts.
3.5m	River gravels.
Bed 'A'	(35-40cm red-yellow silt.
	(35-40cm blue clay containing tree stumps.
	Iron pan.
	Well weathered river gravels.
	Present riverbed.

see p.114)

PLATE 8

Active solifluction lobes at 1850m on the Polar Range.

PLATE 9

Deep, complex slope deposits at 1100m on the Craigieburn Range, exposed at a skifield access road cutting.

two main constructional surfaces and one main degradational surface. With some difficulty the constructional surfaces may be traced back to their respective Porter and Tims Stream advance moraines, (plate 19). There is also a suggestion of a high level terrace trace which may be associated with the Kowai advance, but as this trace follows the Porter's Pass fault zone, its outwash origin is questionable. The terrace sets of the Castle Hill Basin (plate 2), have been studied in detail by Breed (1960).

The Poulter River has the greatest extent and thickness of terrace development encountered in the study, all apparently associated with the recession from the final Pleistocene ice advance. One terrace of McGrath age, which has been radiocarbon dated from a wood sample obtained near tributary 5-14 occurs in branches of the upper Poulter River, (plate 7).

In other parts of the region outwash terraces of McGrath age may be traced to their associated moraines in the Mingha, Bealey and Waimakariri Rivers. The mouths of the White, Harper and Greenlaw Valleys have similar terrace formations, assumed to be of a similar age. These latter terraces have slightly steeper gradients than that of the present riverbed, suggesting that any down-valley extensions of these terraces will be buried beneath the extensive alluvial flats and fans of the present Waimakariri River bed.

(6) Rock glaciers

(a) Characteristics: Rock glaciers are

characteristically deep deposits having corrugated surfaces of transverse and longitudinal ridges terminating in steep frontal slopes, (Wahrhaftig and Cox, 1969: Potter, 1972: White, 1971: Dingwall, 1973). Definitions and descriptions of rock glaciers do not draw any precise distinctions between rock glaciers and debris-covered glaciers, but indicate that there is a gradation from "ice-cemented" rock glaciers, "ice-cored" rock glaciers through to debris laden glaciers, Barsch (1971), Dingwall (1973). Rock glaciers are periglacial phenomena which owe their existence to a unique combination of circumstances that includes a relatively low accumulation of snow and a large supply of debris, in a cool climate environment (Potter, 1972: Dingwall, 1973).

They uniquely have a very low ratio of accumulation area to ablation area, of as much as 1:7 found by Potter (1972), which allows the tongue to descend to much lower elevations than do those of ordinary glaciers in a corresponding position. For this reason, these features must not be used when making snowline elevation computations.

(b) Extent: A number of deposits, occurring between the 1680m to 1880m levels along the extent of the Craigieburn Range have been identified as rock glaciers. These deposits occur in an environment of active talus (scree) slopes running from exposed rounded ridge crests down to the valley floors, with only rare rocky outcrops. In most cases, the talus cones have overwhelmed the lateral margins of the rock glaciers.

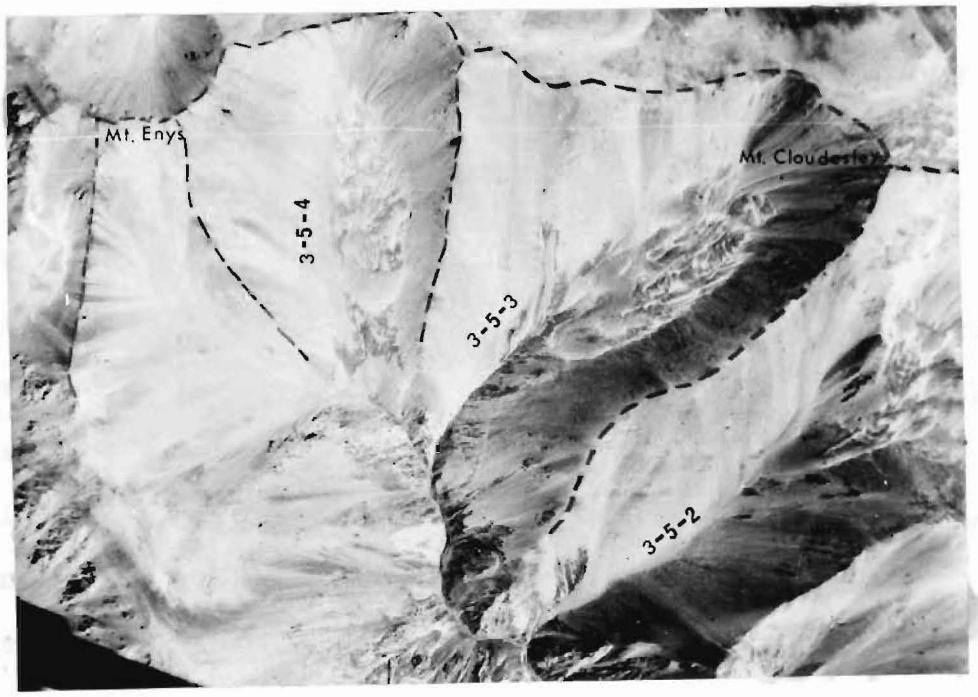


PLATE 10

Vertical aerial photograph (2747/30)
showing three rock glacier deposits of the Craigieburn
Range. Ridge crests dashed.

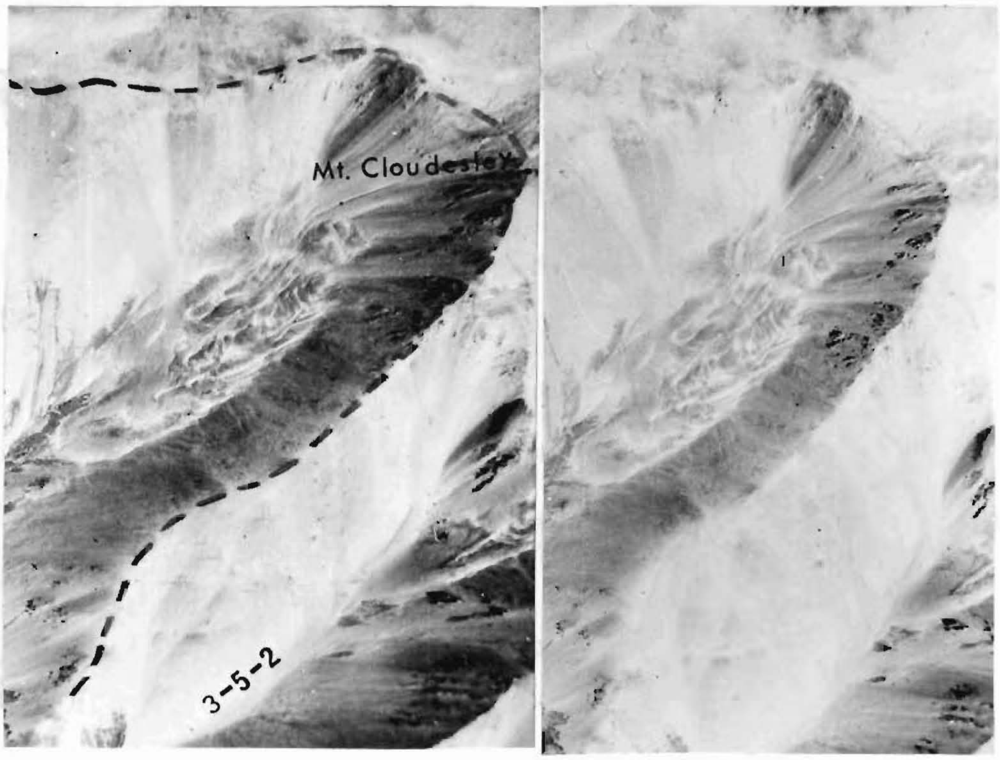


PLATE 11

Stereoscopic pair showing surface details of
Rock glacier deposit 3-5-3, under Mt Cloudesley.

Further to the west, on Mt Binser (tributary 7), and in the Hawdon Valley (tributary 13-5), two large rock glaciers were at first identified from their surface composition and form. However, for various reasons (see Chapter IV), these features are not now regarded as true rock glaciers, but rather as the result of massive landslides falling on to already existing glaciers, causing reduced ablation, and the consequent extension of these glacier snouts to exageratedly lower levels.

(c) Deposits: Identification of the deposits has been based primarily on their unusual thickness and steep frontal slopes, supported by the occurrence of microrelief characteristic of rock glaciers, (plates 10 and 11).

For the majority of the features, there is little doubt that they are rock glacier deposits. In one or two cases, however, towards the western end of the range, the features mapped as rock glaciers (figure 29, tributaries 3-2-4 and 3-2-5) show characteristics of both glacial and rock glacier deposits. In these cases, transverse ridges may be interpreted as concentric glacial moraines, and it is suggested that these deposits are those of an "intermediate" type of glacier, lying between true glaciers and rock glaciers.

The rock glaciers encountered in this study occur in unison with a steep upward trend of the past snowlines (figure 9) which is the result, at least in part, of reduced precipitation. This trend is in good agreement with one of the required conditions of reduced precipitation for the formation of a rock glacier.

(d) Conclusion: From their position in the glacial sequences of the area, the rock glaciers appear to be all of the same age, and belong to the Arthur's Pass advance. Presumably the advances before this time had sufficient vigour to clear the debris as it accumulated. Later advances, following the period of rock glaciers, must have either had snowlines sufficiently close to the mountain summits to reduce the source area of frost driven debris to below that required for rock glacier formation; or alternatively, the required steep headwalls may have already degenerated into talus slopes by this time. It is assumed that none of these rock glaciers are active at present because the peaks of the Craigieburn Range are all below the inferred present snowline and many surfaces have a stable vegetation cover (Birkeland, 1973).

CHAPTER III

SNOWLINES

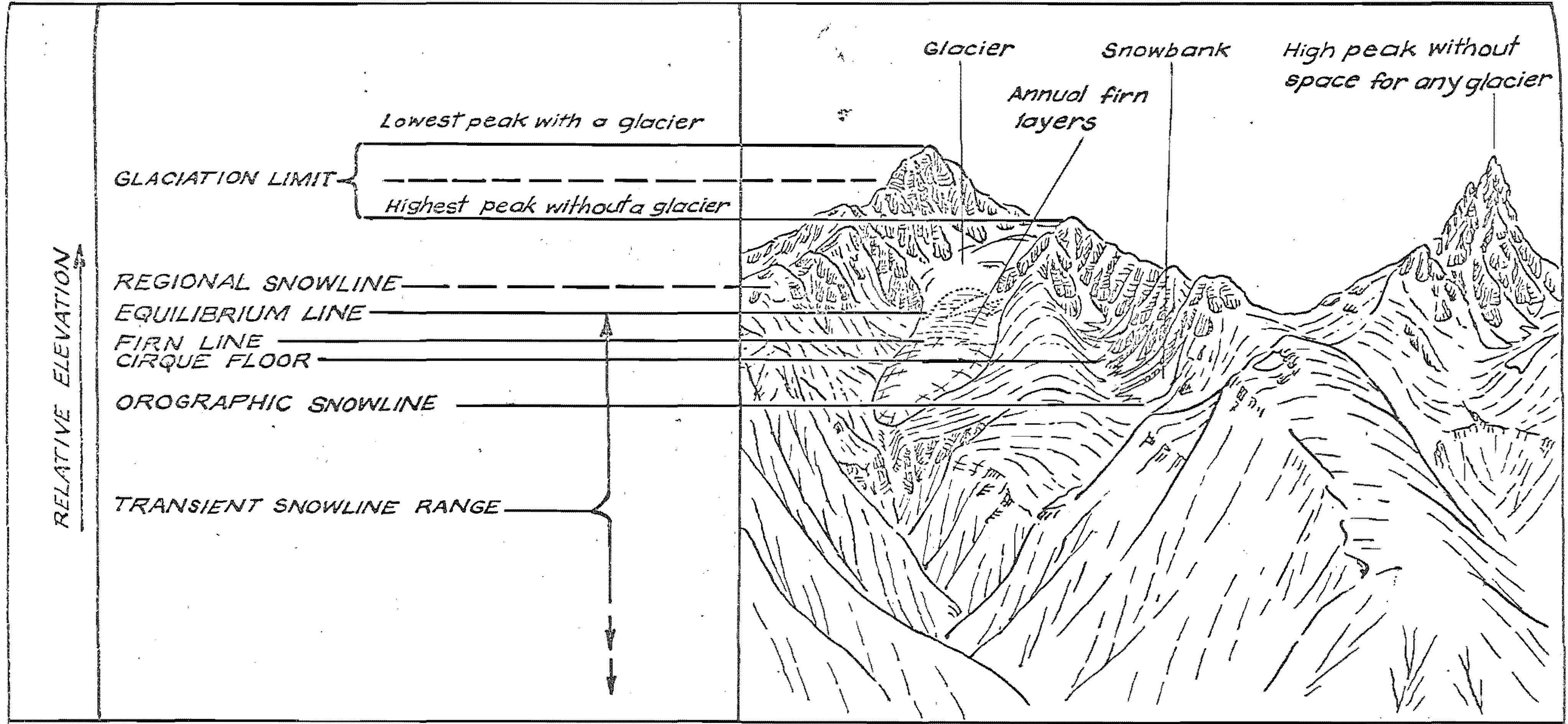
I THE PRESENT SNOWLINE

(1) Definitions

The elevation of the snowline is very difficult to define because in practice the snowline may be defined in a number of different ways, and each definition results in a different elevation, (figure 2). Although the terminology dealing with various kinds of snowlines is confused, most attempts to determine an elevation have defined a snowline as the lower limit of perennial snow, (Hoshiai and Kobayashi, 1957; Mercer, 1961: Østrem, 1966; Porter, 1968: Andrews and Miller, 1972). This definition of a snowline can be visualised as an irregular, abstract surface connecting points on the ground where the preceding winter's snow will just disappear at the end of the summer. Snow patches, snow banks and snowfields will remain above this surface, whereas all snow below it will disappear each summer season. It is impossible to determine a fixed height of the snowline thus defined, because of considerable variations both over short distances and from year to year.

A variety of approaches has been developed to the classification of snowlines, and according to their intended use both the definitions and methods of calculation will vary. The following types of

FIG. 6



SCHEMATIC DIAGRAM OF RELATIONSHIP BETWEEN TOPOGRAPHY AND ICE AND SNOW BODIES, AND THE RELATIVE POSITIONS OF THE DIFFERENT SNOWLINES

snowlines are included in most classifications:

(a) Orographic snowline: A surface drawn through the lower limits of all perennial snow patches, regardless of their origin. This surface shows large variations in altitude owing to the local effects of topography, drifting, avalanching, etc.

(b) Climatic snowline: Many attempts have been made to construct a snowline in such a way that local influences are eliminated. This snowline may be generalised as the lower limit of perennial snow on a smooth hypothetical surface, unmodified by any topographical effects. It is one of the most important climatological factors when dealing with glaciers, but as such hypothetical surfaces do not naturally occur, the climatic snowline cannot be measured directly.

Various indirect methods for determining its altitude have been applied, but none of them is entirely satisfactory because of the large number of meteorological variables involved. The usual method has been to establish the height of an appropriate "summer isotherm" coincident with the snowline. Hoshiai and Kobayashi, (1957) examined this method in detail and have shown that estimating a snowline from the 0°C summer isotherm is both complex and subject to a number of errors. The level of the snowline is controlled by the balance between the total snow accumulation and the ablation losses. The ablation losses are a function of the incoming radiation, outgoing longwave radiation, condensation of water vapour and sub-surface heat transfer. Values of all of these variables and of precipitation are essential for snowline calculations based on the $0^{\circ}C$ summer isotherm, particularly if the calculations are based on free air data, which can differ significantly from the regional climate in mountainous areas. However, by the use of standard lapse rates, with careful selection of the "summer" period, this method can give useful results.

(c) Regional snowline: A derivative from the orographic snowline, in which the irregularities have been smoothed out on a regional scale.

(d) Equilibrium line: An abstract line on a glacier surface, connecting places where the mass balance equals zero, or alternatively connecting the highest positions of retreat of the previous winter's snow. This line shows annual variations in altitude, depending on whether the mass balance was positive or negative for the previous glacial balance year, and must be averaged over a number of years for an accurate value, (Meier, 1962: Paterson, 1969: Østrem a Stanley, 1969).

The distinction between the equilibrium line and firn line (below) is particularly important in this study because the equilibrium line altitudes have been used as the snowlines for the past glaciers, while firn lines have been used for the present snowline. The present glaciers are undergoing a period of marked recession and are not in a state of equilibrium. This negative mass balance means that the equilibrium lines have retreated to higher elevations well above the firn lines.

(e) Firn line: The firn line is defined as the boundary on a glacier between ice and firn (compacted snow at least two years old) at the end of summer. This line, like the equilibrium line, varies with changes in the glacier mass balance, but at a much reduced rate. It equals the equilibrium line at times when the mass balance is zero, Meier (1962), Østrem and Stanley (1969).

As the firn line is the highest level on a glacier to which snow cover recedes during the ablation season, the firn line may be used to determine the height of the snowline. Due to the cooling effect of the glacier, the firn line will not coincide with the snowline on the bare ground, but will be slightly below this level. This vertical separation is supposed to be approximately 100m, Klebelsberg (1948).

(f) Glaciation limit: The lowest altitude at which glaciers can now form. In presently glaciated regions it can be determined in any area where it is possible to compare the elevations of the highest peaks without glaciers and the lowest peaks with glaciers, Andrews and Miller (1972), Østrem (1966).

(g) Transient snowline: The line separating areas with more than 50% snow cover at any time of the year from those with less than 50% cover.

(2) Snowlines of the Waimakariri watershed

There are comparatively few glaciers in the study area, and only a few of these are suitable for snowline determination. All of the glaciers, excepting one on Mt Rolleston, occur within Section I, in the

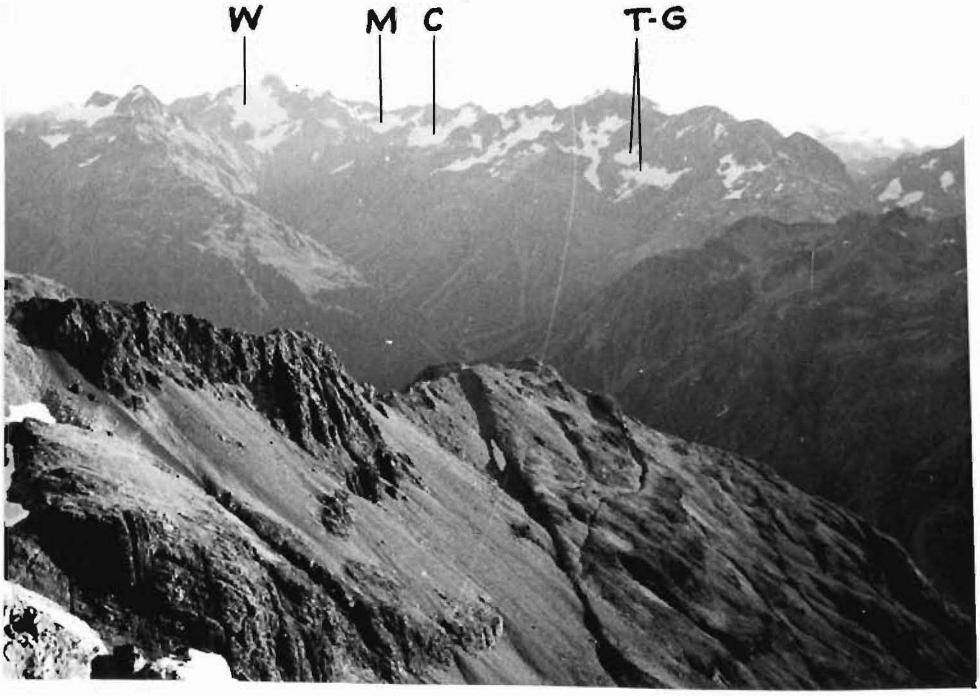


PLATE 12

Glaciers of the White River used in establishing the present snowline. T-G, "tiered glaciers". W, White Glacier; C, Cahill Glacier; M, Marmaduke-Dixon Glacier.

PLATE 13

Cahill Glacier, positions of present snowline arrowed.

north-western corner of the study area. All of the glaciers, at the time of the study, were in a state of strong negative balance which had persisted for several previous years. All firn lines were therefore below the equilibrium lines and many of the smaller glaciers were in an advanced state of thinning to the point of collapse, for example the glaciers at tributary 30-10-2 on Mt Carrington. Glacier beds were exposed through ice in many places and the extent of ice cover was much reduced since 1969 and 1960, when the aerial photographs had been taken. Some small glaciers had lost all of the previous winter's snow, i.e. their equilibrium lines had retreated beyond the upper limit of the glacier, leaving none of the previous winter's snow to nourish the glacier. There were also some cases of "tiered snowlines" where two disconnected glaciers were arranged with a vertical separation, each having its respective firn line but with the snout of one terminating above the upper limit of the other, (plate 12). Snowlines determined from such glaciers would obviously be misleading.

This state of negative balance was inferred to have prevailed for a number of years, and to have led to the presence of relict glaciers and snow-patches. Snowlines determined from these bodies can be climatically misleading unless the period over which the snowline applies is specified. Under conditions of an ascending snowline, the equilibrium line altitude (hereinafter referred to as the ELA), will give a snowline value for the past year, while the firn line altitude gives an integrated snowline value for the past few years. By employing the glaciation limit method (see below), the presence of relict glaciers will give a lower composite snowline estimate for the past tens of years. To estimate the present snowline over the past couple of years encompassed by this study, the firn line has been used in preference to the annually variable ELA. The following ELA data (table 1), from recent studies made on the Tasman and Ivory glaciers (Anderton and Chinn, 1973), situated respectively 115km and 60km SW of the Waimakariri watershed, indicate the recent trends in snowline migration. All of the years included were years of negative balance for both glaciers.

TABLE I

RECENT EQUILIBRIUM LINE ALTITUDES FOR TWO N.Z. GLACIERS

YEAR	TASMAN GLACIER	IVORY GLACIER	
	ELA (M)	ELA (M)	SPECIFIC BALANCE (M WATER EQUIVALENT)
1965-66	1730	-	-
1966-67	1970	-	-
1967-68	1630	-	-
1968-69	1690	-	-
1969-70	2200	*1650	+ -2.11
1970-71	1930	*1650	+ -1.66
1971-72	1850	*1650	-1.66
1972-73	1900	*1600	-1.73

* Strictly the altitude of change from net negative to net positive.

\+ Not full year.

(3) Calculation of the present snowline

The present snowline elevation was estimated by two different methods, using both the firn line elevations and the glaciation limit, to give a comparison and to allow a check of the reliability of the results.

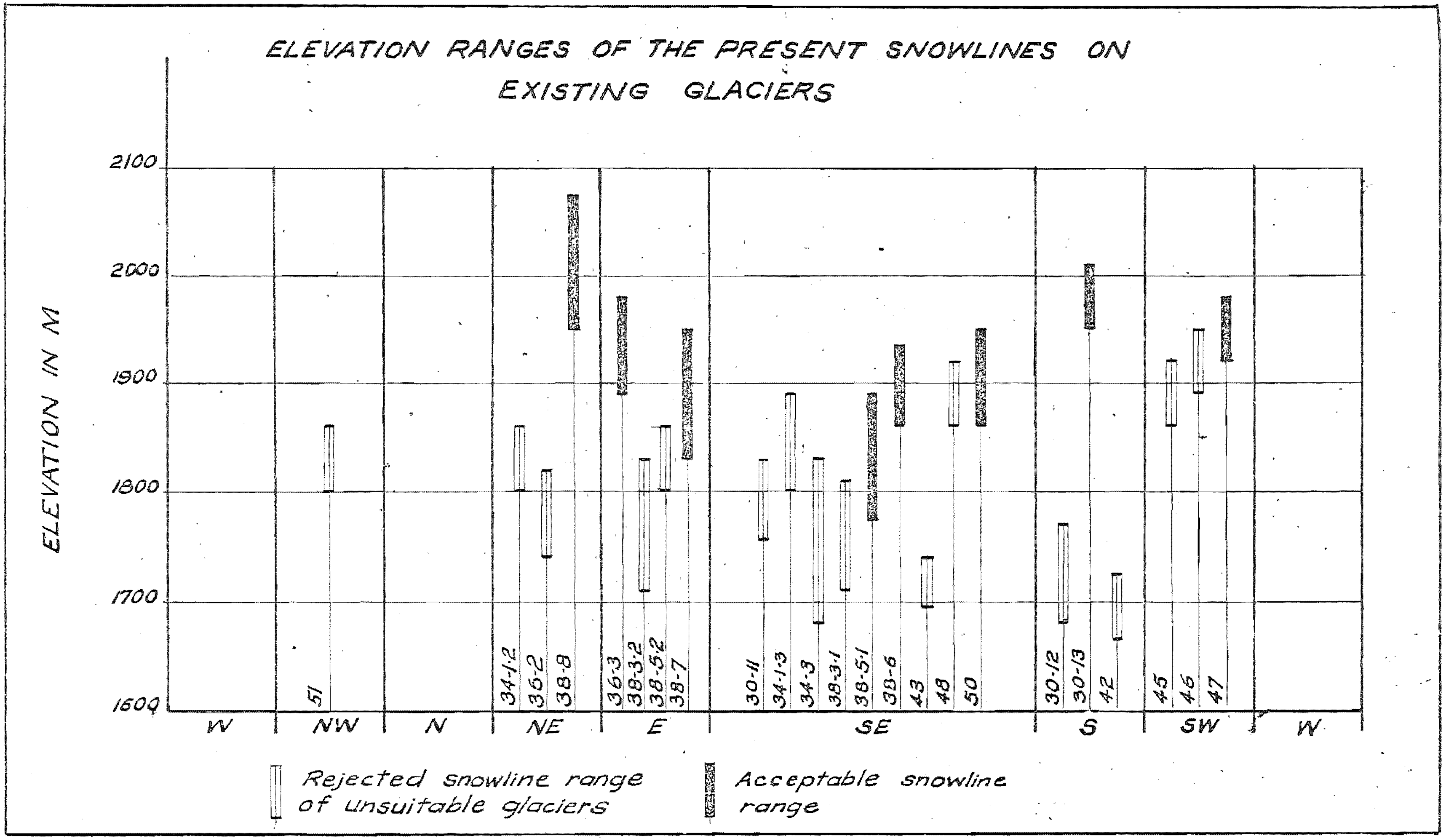
(a) Firn line elevations

At the end of summer the firn lines of the present glaciers, seen as the boundary between the firn and bare ice, were drawn on aerial photographs in the field. These were later transferred as accurately as possible onto the contoured topographic maps for the estimation of mean altitudes. Almost every glacier in the area was seen during the late summer period in the course of field work and the firn lines noted. Glaciers of every aspect were included, to obtain values for the variation of firn line elevations with aspect.

To establish the aspect-elevation differences of table 2, the data were separated into eight directional aspect groups and the elevation ranges of the firn line estimates were plotted on a diagram (figure 3). The data were then examined for quality by objectively assessing the reliability of each glacier for firn line elevation estimation. The criterion used to assess the reliability of the firn line data was that, the closer the topography of a glacier approached to a smooth, gently-sloping surface similar to the theoretical surface of the "climatic snowline" above, then the more reliable would be the firn line data. Thus, those glaciers having steep gradients, high headwalls, icefalls or breaks in slope near the firn line and glacierettes of small size which may be subject to "protalus" processes, etc., were considered to provide ureliable firn line data.

From a set of 23 firn line values, 15 were rejected on the above grounds and the remainder were used to establish the present snowline and the snowline aspect differences. An examination of the data showed no consistent trend in the snowline surface, presumably because the glaciers studied are confined to a limited area with insufficient regional coverage to indicate any regional trends. The eight accepted snowline (firn line) elevation ranges were plotted against aspects on figure 4, and smoothed by applying a partial sinusoidal curve. This curve gives a value of 1900m for the elevation of the present southerly aspect snowline. Because there are relatively few northward-facing glaciers in the area studied, this snowline curve is incomplete, covering only the directions from north-east to south-west. The minimum value is displaced slightly from the expected south direction to the south-south-east.

Since direct field evidence failed to give snowline elevation values for glaciers whose aspect was between west and north, it was necessary to compute values for these directions. The assumption was made that, since elevation differences related to aspect arise primarily from incident solar radiation and since the amount of incident solar radiation is



ELEVATION RANGES OF THE PRESENT SNOWLINES ON EXISTING GLACIERS

FIG. 3

PARTIAL SNOWLINE ELEVATION~ASPECT CURVE FROM THE ACCEPTED SNOWLINE RANGES OF FIGURE

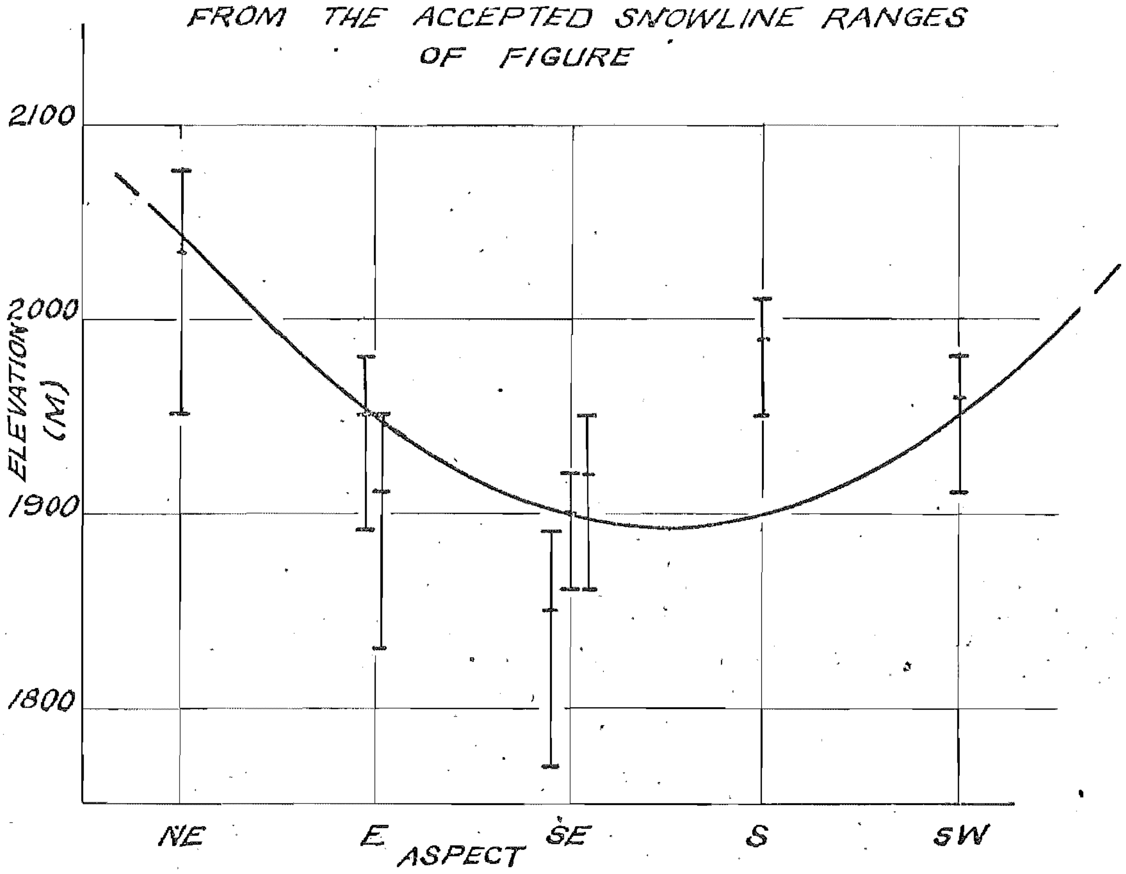
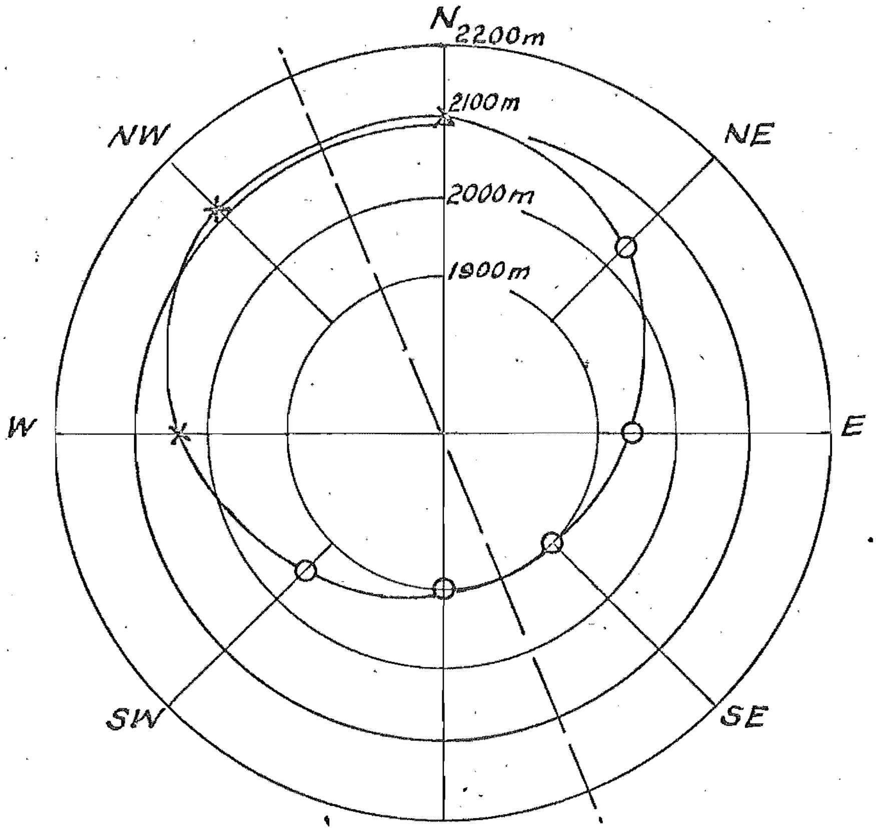


FIG. 4



FULL SNOWLINE ELEVATION~ASPECT DIAGRAM DEVELOPED ABOUT A NNE.- SSE AXIS OF SYMMETRY

O Field data from fig.
X Points calculated

FIG. 5

symmetrical about a north-south axis, then snowline elevation aspect differences should also be symmetrical about a north-south axis. It is possible for wind or strong topographic trends to distort this symmetry. No evidence was seen in the field to suggest that topographic distortion of this symmetry does occur and the prevailing wind direction, being from the north-west, is close to being parallel to this axis of symmetry, thus providing conditions for minimal distortion.

By assuming that snowline elevation aspect differences are symmetrical about an axis, the snowlines for the aspects lacking direct field data were calculated from the snowline elevation - aspect diagram of figure 5. The axis of symmetry for this figure, having been derived from the snowline elevation-aspect curve (figure 4), also lies along a NNW-SSE axis. It is suggested that this small deviation from a N-S axis is due to the combined effects of daily air temperatures and shading. Lower morning air temperatures tend to result in no ablation in shaded areas, whereas high temperatures in the afternoon tend to allow ablation to continue in shadow. The SW-facing glacier is in greater morning shadow than an equivalent SE-facing glacier and consequently suffers little morning ablation compared with a SE-facing one. Under the influence of higher afternoon temperatures the SE glacier continues to ablate, although it then has the greater coverage of shadow. From figure 5, the present mean snowline elevations of the study area were derived for each of eight directional aspects. These snowline elevations, derived from the 1972-73 end of summer firn lines, are tabled below:-

TABLE 2

PRESENT SNOWLINE ELEVATIONS, VARIATIONS WITH ASPECT

	N	NE	E	SE	S	SW	W	NW
m	2120	2040	1950	1900	1900	1950	2040	2120
ft	6910	6650	6400	6240	6240	6400	6650	6910

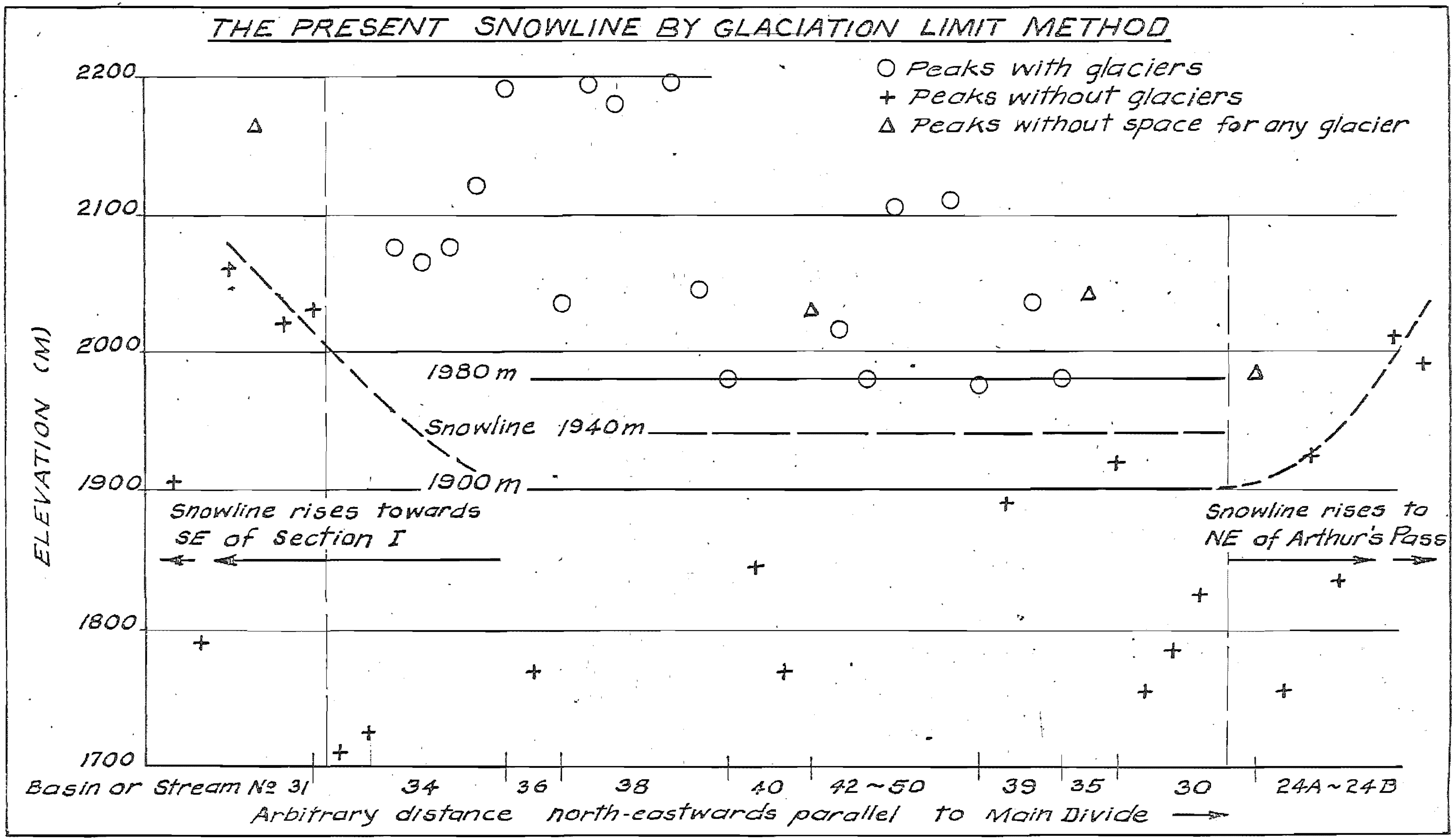
The error of the plotted snowlines is estimated to be less than ± 50m, while the accuracy of the calculated points is estimated to be within ± 100m. Any error arising from the assumed symmetry of the snowline elevation aspect distribution will have limited significance in the following past-snowline computations, because in studies of both the present and the past snowlines, the main bulk of the data is from basins having a southerly sector aspect.

Most authors working on snowlines have considered one aspect only, Porter (1964), so that data on aspect differences are meagre, however, Waharftig and Cox (1959), found the difference to be 580m to 610m (1900 ft - 2000 ft) at latitude 64°N, in the Alaskan ranges, compared with 220m (710 ft) found for latitude 43°S in this study. Because the differences between snowline elevations of differing aspects arise primarily from the differing amounts of incident solar radiation received, these elevation differences will vary with the maxium angle of elevation reached by the sun. Aspect differences should, therefore, be zero at the equator and should increase, along with increasing latitude, towards the poles.

(b) Glaciation limit: An alternative assessment of the present snowline was made by the glaciation limit method, where the altitudes were plotted of both the highest peaks not supporting glaciers and of the lowest peaks with glaciers, Østrem (1966), Andrews and Miller (1972). The glaciation limit is then the mean of the two values thus obtained, (figure 6). This method tends to give values which are slightly higher than those for the climatic snowline. Østrem (1966) suggested that the glaciation limit values were approximately 100m higher than those of the climatic snowline and 200m above the ELA (equilibrium line altitude). He also found that the difference between the two sets of peak heights used in the glaciation limit method is normally about 60m. This method compares glaciers of all aspects and as most of the glaciers in the study area have a southerly aspect, the snowline computed should be compared with only the southerly aspect results of the ELA method described previously.

The results of the glacier limit method give a snowline elevation of 1940m compared with 1900m found by the ELA method, and an elevation difference of 80m between the two sets of peak heights. The difference of 40m between the glaciation limit and ELA snowlines is lower than the 100m suggested by Østrem (1966). Part of the reason for this lower value will be because

FIG. 6



THE PRESENT SNOWLINE BY GLACIATION LIMIT METHOD equilibrium lines in the Southern Alps at least, are shown by the number of wasting glaciers to be currently rising. This current imbalance between glaciers and climate causes the ELA to rise detectably long before the glaciers themselves have readjusted to the new regime. Thus, the presence of wasting "relict" glaciers has tended to lower the value of the glaciation limit snowline, bringing it closer to the value obtained by the ELA method.

(4) Causes of local snowline variations

When snowline data from some 23 glaciers and glacierettes of the area were plotted, numerous inconsistencies appeared which could not be explained by aspect alone, but which were rather a result of the variety of topographic influences. Of the more important factors leading to variation in snowline elevations, only wind deflation of the snowpack produces anomalously high elevations. Other factors tend to produce values below the true snowline value. Consequently, abnormalities in snowline elevations tend to be in the direction of a depressed snowline.

Basin morphology features which are chiefly responsible for the majority of abnormally depressed snowlines are:

(i) Overdeepened, well-developed cirques, which tend to collect avalanche and wind-drifted snow to depths greater than the normal winter snowpack.

(ii) Very steep headwalls, which favour drift and avalanche accumulation, thus producing a deeper snowpack at lower levels.

(iii) A combination of a deep, enclosed basin and a steep headwall, which invariably has a strongly depressed snowline.

(iv) Steeply sloping glacier surfaces which increase the frequency of snow avalanches, giving a thicker snowpack at lower levels.

(v) High, steep headwalls, oriented so as to reduce the radiation on south-facing glaciers, which tend to lower the snowline further.

The effects of many of the above snowline variations are evident on any one glacier where the end of summer snowline shows altitude variations over many tens of metres, (plate 13).

II COMPILATION PROCEDURE

(1) Computation of past snowline elevations

(a) General: When a glacier is in a steady state of mass balance, the altitude of the firn line, snowline and equilibrium line will be approximately equal. Past snowlines may therefore be estimated as equilibrium line altitudes (ELA's) of past glaciers by using geologic data on the position and altitudes of the past glacier margins.

Numerous methods of varying degrees of complexity have been employed to determine the ELA's of past glaciers as estimates of past snowline elevations. Less accurate but simpler methods have been described by a number of authors including Richmond (1965a), while Pewe and Reger (1972), give the following three simplified methods of obtaining the ELA of a past glacier:-

(i) The visually-positioned boundary midway between accumulation and ablation areas on a contoured reconstruction of the glacier.

(ii) The line separating the accumulation and ablation areas at a position separating a percentage (25%:75%) of the lower part of the glacier from the upper part, or

(iii) The mean elevation, between the moraine and the headwall of a reconstructed glacier.

The first method was employed in this study to begin with, but was found to give quite unacceptable results. The reason for this could have been a personal bias arising from the author's familiarity with modern glaciers in a state of recession, which have ELA's at a greater height than those of glaciers in an equilibrium state. Use of the moraine headwall method considerably improved the consistency of results.

(b) The moraine headwall method: This method is based on data from present glaciers which, when in a steady state of mass balance equilibrium, have an ELA close to the mean elevation of the upper and lower altitude limits of the glacier (Meier and Post, 1962; Andrews and Miller, 1972; Paterson 1969).

To calculate the ELA the inferred position of the reconstructed glacier boundary was drawn on a contoured base map, and the elevation of the upper limit of the glacier itself, distinct from the back-ridge altitude, was estimated. The elevation of the terminus was read from the plotted position of moraine on the base map. The arithmetic means of these two elevations were taken to give the ELA. An error range of ± 15% (Porter, pers. comm.) was assumed and applied to the snowline figures. The value of this error increases with increasing altitude range of a glacier, which is in turn roughly proportional to the glacier length. Hence the shorter the glacier, the more accurately is the snowline defined.

It must be appreciated that this method tends to give a snowline altitude a little above the true altitude, because it assumes an accumulation area ratio of 0.5, rather than the value of 0.6 more often found for present glaciers, Porter (1970).

This error is compensated to some extent, because virtually all of the errors due to topography tend to be negative in sign. Best results are obtained from glaciers of uniform gradient which have no sharp breaks in slope and which do not expand at the snout.

(c) The area-altitude ratio (AAR) method: This method is the most accurate and employs the distribution of area with altitude for the glacier. The area-altitude ratio (AAR), is the ratio of the area above the equilibrium line (the accumulation area) to the total area of the glacier. Because the equilibrium line marks the lower boundary of the accumulation area, its altitude can be determined approximately on a glacier whose AAR and area-altitude distribution are known. AAR values are not directly measurable for former glaciers, and arbitrary values have to be adopted from measurements made on modern glaciers, and preferably from those in the same area. In New Zealand, however, the present glaciers have not been in a steady state of balance, so that any AAR values derived from these glaciers will not be suitable for computing the ELA's of past glaciers under a balanced regime. Results of many glacier balance studies indicate that most glaciers under balanced regimes will have AAR's greater than 0.5 and generally they will be in the range of 0.5 to 0.8, with the majority of the values lying close to 0.6, (Meir and Post, 1962; Porter 1968; Paterson 1969). For the purpose of this study, an AAR value of 0.6 ± 0.1 assumed by Porter (1970), and Porter (pers comm.), is used in this study to derive steady ELA's from area-altitude curves.

The method employed was to construct the outline of the past glacier on a contoured base map, together with reconstructed ice surface contours, and an area-altitude curve is made by cumulative planimetery of the glacier contours. From this curve the snowline was read from an AAR value of 0.6, together with an error range of ± 0.1. The slope and shape of the cumulative area curve influence the range of error, so that the lower the gradient of the curve the smaller the range of error.

The accuracy of this method is greater than that of the moraine-headwall method, especially for the larger of the former glaciers, as the error range of the moraine-headwall method increases markedly with increasing glacier size. The limiting factor for the AAR method is the smallest glacier that may be measured by planimeter on the scale of the base map used.

(2) Data quality

In the foregoing discussions it has been established that the elevations of both present and former snowlines may vary considerably in any one area. These variations are unavoidable with the method used to establish the snowline, and reflect the numerous climatic and topographic factors locally affecting the snowline. For example, the steeper the former glacier, the greater is the error in the computed snowline likely to be.

The main differences in snowline elevation arise from the varying aspects of individual glaciers. This variation was reduced by applying an aspect correction (derived from the present snowlines) (Chapter III-I) to other than the south-facing former glaciers. During the fieldwork it became apparent that some of the former glaciers would give more reliable computed snowlines than would others. These differences were due mainly to cirque morphology and to the reliability of establishing moraine positions and thus the former glacier outline. An objective appraisal was, therefore, made of all of the snowline data, and each snowline elevation was given an assessment of reliability, detailed below.

(a) Aspect correction: All of the snowline studies encountered in the literature were restricted to cirques with a pole-ward aspect, and very little work was found on comparisons of aspect elevation differences. This important contrast, which is primarily a function of latitude, could not be ignored in this study because a full snowline coverage of the region requires that all basins of all aspects be considered. Consequently, the snowlines were calculated for all basins of all aspects, and corrections were then applied to reduce all of the results to a southerly (pole-ward) aspect. These correction factors were obtained from the study of the present snowline. Although the application of aspect corrections generally brought the snowline elevations into closer groupings, it was not always a simple matter to determine the aspect of some of the more complex and curved reconstructed glaciers, for example tributary 5-15-11. Correct identification of aspect becomes important where the steps between the correction values are at their largest in the NE and NW quadrants. Furthermore, where the glacier trunk is acutely kinked, the relative importance of the neve aspect compared with the trunk aspect has to be considered. The values of the snowline aspect corrections are listed in table 2, and the corrections applied to each former glacier are given in Appendix IV.

(b) Assessment of reliability: Wide

variations in accuracy of reconstructed glacier outlines and terminus positions occur from one basin to another, as well as differences in the suitability of topography for snowline calculations. It is therefore necessary to estimate the degree of reliability of the computed snowline for each reconstructed glacier. Following an objective study of each cirque for which snowlines have been computed, employing field observations and aerial photographs, three categories of reliability are defined. These are tabled in Appendix IV and are also given on the profile plots near their respective snowlines:-

(1) Most accurate, where the basin is of a favourable shape and the position of the glacier snout is well defined.

(2) Accuracy fair, where either the basin shape is unfavourable or the snout position is uncertain.

(3) Least accurate, where both the basin shape is unfavourable and the snout position is uncertain.

The relative sizes of moraines was found to be a useful means of indicating the degree of reliability with which the deposit has been identified, and for correlation. Most large valley floor moraines were found to be of early Holocene age, while large, comparatively fresh, sharp-crested upper cirque moraines were found to have resulted from late Neoglacial events.

The relative sizes of the moraines tabled in Appendix IV are indicated by means of an arbitrary scale, viz:

A = Large (indicated by contours on the 1:63,360 scale maps).

B = Intermediate (readily discernable on vertical aerial photographs).

C = Small (difficult to discern on vertical aerial photographs).

The moraine features are further classified as terminal (T), lateral (L) or fragmentary (F), i.e. eroded remnants of either lateral or terminal moraines.

(c) Ageing controls: When plotting snowline profiles, knowledge of the age of the deposits is required in order to prevent the mis-correlation of snowline profile surfaces between different areas. Local controls are available from the statistical weathering rind studies (Appendix I), which are supplemented by many more widely distributed weathering rind values from samples of a limited number of variables, not included in Appendix I.

A reliable widespread control is available for the McGrath Advance. It has been suggested by Gage (1958), that during the final (Poulter) Pleistocene advance, large ice streams filled the whole of the Upper Waimakariri catchment, and that the recession of this ice was a relatively sudden event, for which no recessional moraines of any significant size are to be found. In consequence, the McGrath moraines are normally easily identified as the first substantial moraines encountered inside the final Pleistocene deposits. In areas outside those contributing to the large branched Pleistocene glaciers, such as in the Craigieburn and Torlesse Ranges, this principle does not hold. In these areas the McGrath deposits are frequently located close behind multiple Pleistocene moraines, making it difficult to differentiate between the two, for example the moraines of tributaries numbered 3-3 and 3-2-3, on figure 28.

In some locations the *Barker advance has overridden the *O'Malley deposits to a greater or lesser degree, resulting in the debris from both episodes being combined or lapped against each other in imbricate fashion to form a single massive deposit. These "combined" features are easily recognised by both their large size and their comparatively fresh Barker surfaces. They can afford good age indications for the younger deposits, and are delineated on the snowline profiles (figures 7 to 9), with both a "c" and the combined colour codes of the Barker and O'Malley advances.

(3) Compilation of snowline surface profiles

Field work and stereoscopic coverage of aerial photographs was concluded with the production of the nine features maps, covering the study area at a scale of 1:63,360 (figures 22 to 30). On these maps are shown all of the recognised glacial features, together with those of related alpine processes.

(a) Computation of past snowlines: Past snowline computations were made directly from the

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*See Chapter IV, Proposed glacial sequence.

enlarged contoured base maps at a scale of 1:31,680, which afforded a greater control of accuracy than would have been the case if the 1:63,360 scale maps had been used. From the features plotted on these base maps during the course of the field work, the lower limits and outlines of past glaciers were reconstructed for locations where sufficient reliable data were available. From this information, the past snowline elevations were computed by either moraine-headwall or area-altitude ratio methods. The latter, more accurate method was preferred where the mapped areas of former glaciers were large enough for planimetering.

The past snowlines were computed from only those cirques which contain the glacial deposits necessary to delineate the lower margin of the reconstructed glaciers and to afford evidence from which the glacial advance may be dated. Cirque floor levels, the observations so often employed to derive snowline elevations, were not used in this study. Apart from there being a notable absence of mature cirques with sufficiently well-developed level floors from which to estimate snowlines, cirque floor levels can be misleading, particularly when dealing with Holocene glaciers. This is because most of the cirques encountered had resulted from the composite erosional effects of a number of Pleistocene ice advances, and in addition it was found that higher basins in the headwaters had been excavated by rotational flow of ice streams tributary to the major Pleistocene glaciers, (Lewis 1960, Paterson 1969).

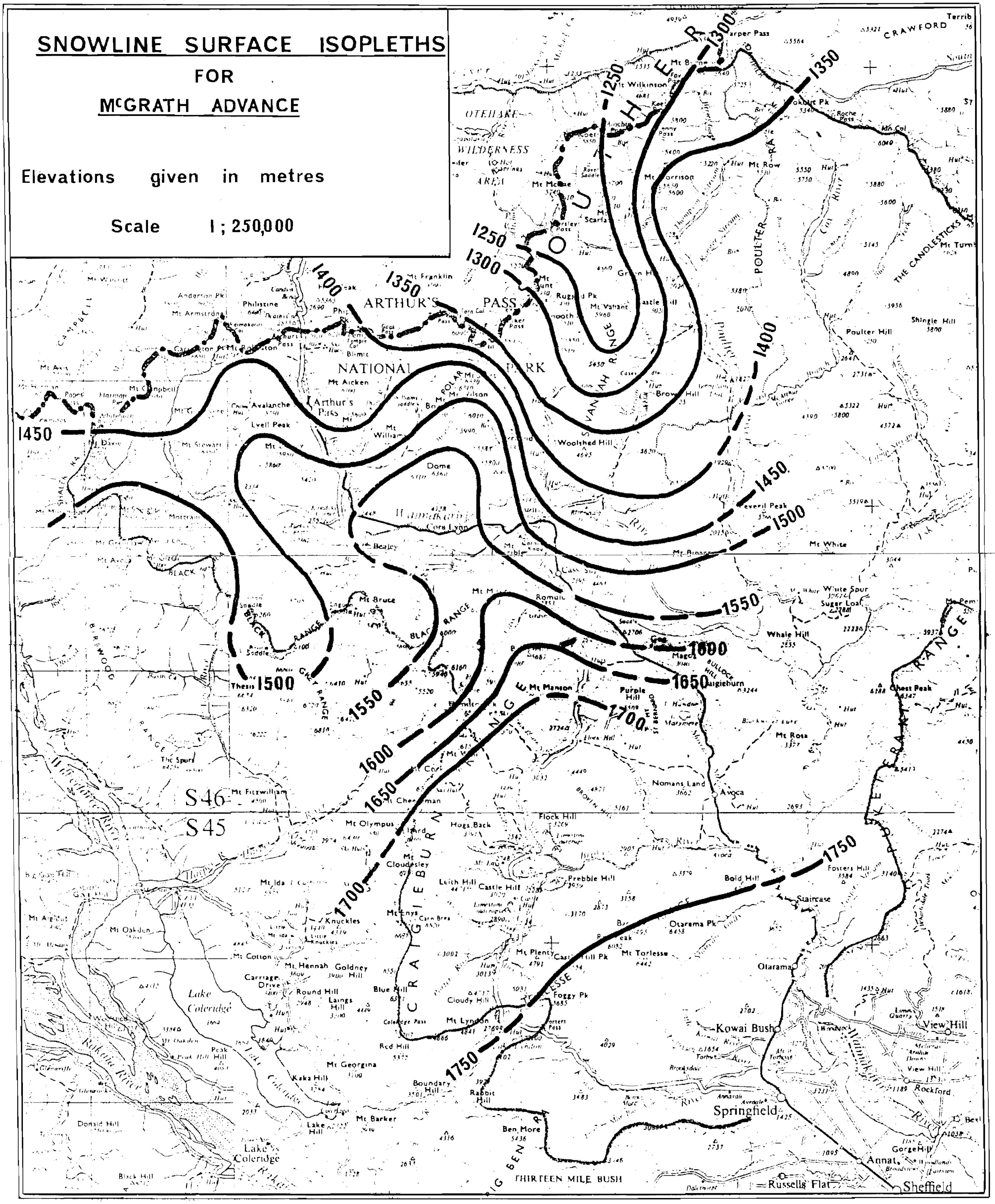
(b) Table of past snowlines: All of the snowline and aspect data are tabled in Appendix IV, II where, because the base maps are contoured at 100 ft. (30m) intervals the elevations given are direct conversions from feet to metres. The rounding-off of these values was accomplished graphically when plotting the profile figures. Meanwhile, the impression is given of a greater accuracy than is actually the case. Reliability of the data and basin-aspect correction factors described above are both given on this table.

(c) Snowline surface profiles: Preliminary investigations using a number of differing approaches failed to show any sets of trend surfaces for the altitudes of the past snowlines. The explanation was later found in that individual snowline variations between glaciers of the same age and the snowline elevation differences between successive glacial advances were of a similar magnitude. The difficulty was accentuated by the fact that most of the glacial advances were multiple events, giving early (lower) and late (higher) sets of snowline elevations. In order to distinguish between the trend surfaces of each advance, the results were plotted on profiles taken along each mountain range, on the assumption that although the individual snowline surfaces may differ markedly in altitude from one range to the next, they change smoothly without any steps along the axis of one range.

The snowline profiles were established by using only the more reliable values (reliability 1, and occasionally 2, of the reliability scale, Chapter III-II (2)(b)) to which a correction for aspect had been applied. In a small number of cases, snowline elevations were available directly from the altitude of the upper limit of uneroded lateral moraines. By use of only the more reliable data (indicated by arrows on figures 7 to 9), the trend surfaces became apparent and they could be plotted on the profiles. Once the snowline surface profiles were established, the remaining less reliable snowline values were plotted on the profiles. It was then possible to assign ages to these snowlines, relative to their respective ages in the Proposed Glacial Chronology, (Chapter IV), from their positions in relation to the snowline profiles. Supporting evidence for ages thus estimated was available by reference to the moraine sequences. The snowline surface profiles are given in figures 7, 8, and 9, together with snowline data from Appendix IV.

(d) Isopleth maps: Isopleth maps (figures 10, and 11) of the trend surfaces of the mean snowline altitudes for two advances, well separated in time, were constructed from the snowline profiles. These maps show the regional trends of the snowline altitudes from which the climatic interpretation in Chapter V have been made. These two maps showed such similar patterns that it was considered unnecessary to construct maps for the other intermediate snowline surfaces.

(e) Snowline elevation variation diagram: The snowline surface elevations from the main divide area



SNOWLINE SURFACE ISOPLETHS
FOR
McGRATH ADVANCE

Elevations given in metres

Scale 1; 250,000

Fig. 10

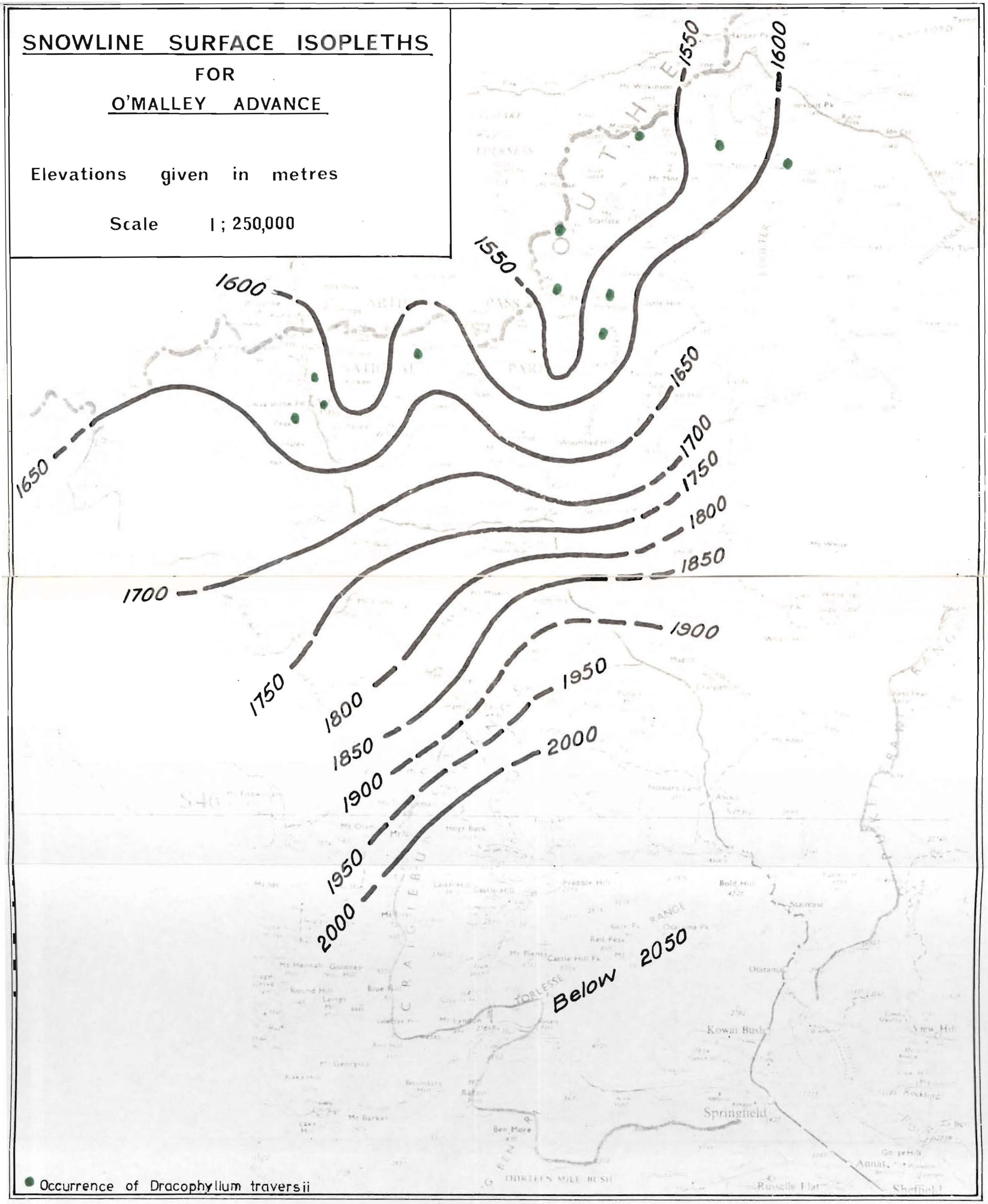
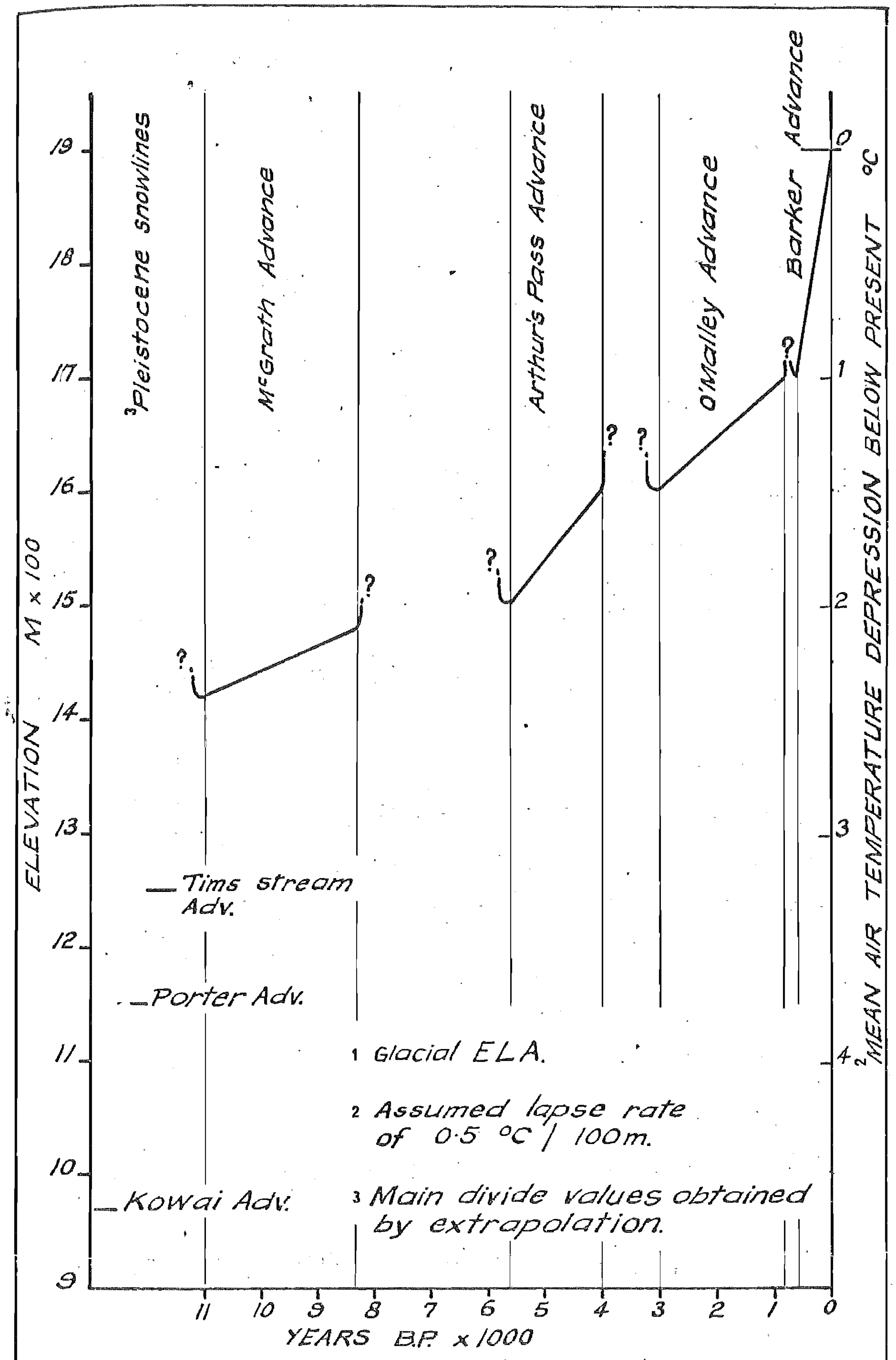

SNOWLINE SURFACE ISOPLETHS
FOR
O'MALLEY ADVANCE
Elevations given in metres
Scale 1 ; 250,000
1550
1600
1550
1600
1650
1650
1700
1750
1800
1850
1900
1700
1750
1800
1850
1900
1950
2000
1950
2000
Below 2050
SOUTHERN
ARTHUR'S PASS NATIONAL PARK
CRAIGIEBURN
TORLESSE RANGE
Kowai Bush
Springfield
THIRTEEN MILE BUSH
Sheffield
● Occurrence of Dracophyllum traversii

Fig. 11



1 Glacial ELA.

2 Assumed lapse rate of 0·5 °C / 100m.

3 Main divide values obtained by extrapolation.

SNOWLINE[1] ELEVATION VARIATIONS

For Main Divide, Arthur's Pass Area

Fig. 12

near Arthur's Pass were combined with the age data derived from the weathering-rind thickness growth curve, (figure 40) to produce this diagram, (figure 12). Given here are the ranges in snowline elevation for each advance, plotted against the approximate duration of each advance.

Because the rind-thickness ageing method gives only approximate results, the accuracy of the ages plotted on this diagram are no greater than ± 10% of the plotted age.

(f) Accuracy: The sources of errors in the process of snowline computation may be divided into (a) topographic errors, (errors inherent in the suitability of the glacier itself, and (b) computation errors.

Topographic errors arise where the shape and/ or the gradient of the basin is unfavourable. Simple basins of gentle gradient afford the most consistent results. "Spilled" moraines (see Chapter II-II(c)), or sharp breaks of slope likely to have produced icefalls generally render a basin unsuitable for snowline determination. Those glaciers with uniform lower gradients, for example, the Pleistocene glaciers of the Craigieburn Range, were deemed to give the most accurate results. Shorter glaciers which cover smaller ranges of altitude have a reduced range of snowline error, and thus give a more accurate definition of the snowline. This accuracy applies only down to a certain limited minimum glacier size. Small steep glaciers and snow patches may have snowlines depressed some hundreds of metres below the true snowline elevation by protalus processes and other effects. Pewe and Reger (1972), suggest such depressions may be as much as 800m.

Computation errors arising from plotting procedures have been estimated in decreasing order of magnitude:-

(i) From plotting moraine (glacier termini) positions, when transferring the features from aerial photographs to contour maps.

(ii) Estimation of the glacier upper limit elevation.

(iii) Accuracy of contours.

The contour interval of 250 ft. (75m) on sheet S58 was found to give results of an unacceptable standard, because the contour interval was of a similar order of magnitude to the snowline altitude differences between successive advances. The contour interval of 100 ft. (30m) on the remainder of the base maps gave good results. Sheet S58 was replaced by compilation sheets having a scale of 1:15,840 and 100 ft. (30m) contour interval. These larger scale maps provided the highest degree of accuracy of all and in addition allowed AAR computations to be made on glaciers of smaller size.

In the AAR calculations, reconstruction of the glacier outline was the main source of error. It was found to be very difficult to estimate the positions of the ice margins to within an elevation error of 100 ft. (30m) especially in the steeper narrow valleys, and to delineate the outline of neve areas of basins with complex ridge systems at their heads. Corrections applied for aspect always brought data into closer agreement, but on a small number of north-facing basins, the correction of 220m appeared to be greater than that required. This is possibly because aspect to prevailing winds also influences the snowlines, as ridges normal to the prevailing wind tend to have lower snowlines due to "snow fence" effect (Paterson and Robinson, 1969).

The compilation of the snowline surfaces by plotted profiles allows for objective consideration of the data for each reconstructed glacier, and for the smoothing of local and individual inconsistencies. Thus any individual misinterpretations or local errors occasioned by the topography are smoothed out, and a close representation of the true snowline surface results. A few of the ages assigned to the more unreliable snowlines, following the establishment of the profile lines, may be in error, especially where multiple deposits occur from each of two or more separate advances. Any errors of interpretation of this type which might have occurred will not effect either the snowline surface elevations or the glacial chronology. To be certain that all age identifications given in figures are correct, each glacial deposit in the study area should be visited in the field.

Short-term climatic fluctuation effects are dampened by both the glacier dynamics (the larger the glacier, the longer its response time), and the time taken for moraines to be deposited. Each single moraine, therefore, represents the meaned result of a period of minor climatic oscillations and the associated short-term glacial fluctuations. Consequently, past snowlines derived from morainic evidence will be the mean snowlines for the time taken to form that moraine, whereas present snowlines derived from the ELA of a glacier will be the snowline for only the year when the observation was made. Because of this, past snowline altitudes will be more consistent than those for the present snowlines, which have been observed only once during a period of relatively rapid glacial recession. This meaning effect also allows the relatively small changes in the snowline, between the beginning and end of each advance, to be computed from the sequence of moraines.

III PAST SNOWLINES

(1) General

A total of 321 snowline calculations were made for this study, 257 were by the moraine-headwall method and 64 by area-altitude computation. The snowline surfaces of each glacial advance plotted from these calculations give a representation of the regional climatic trends arising from weather patterns and topographic influences. The expected easterly rise of snowline elevation following the precipitation gradient is apparent, but an unexpected depression in the snowline surfaces towards the north occurs with each glacial advance. (See Chapter V-II, Climatic Interpretation). Elevation differences between the snowlines of successive advances show a regional consistency with very few cases of convergence or divergence. This consistency is shown in the similarity between the shapes of the snowline surfaces on the Isopleth maps, (figures 10 and 11), for the McGrath and O'Malley advances.

From the snowline profiles (figures 7 to 9) the mean snowline elevations, together with differences, were calculated and are tabled below. Because of the considerable regional variation, these values were calculated for one area only, that being the main divide in the vicinity of Arthur's Pass. To obtain Pleistocene values for this area the snowline elevation differences for the Torlesse and Craigieburn ranges were assumed to apply here, and Pleistocene snowline elevations were obtained simply by subtracting differences from the mean McGrath advance snowline elevation. The table below indicates a snowline elevation rise of 650m from the end of the Pleistocene to the present day, and it is noteworthy that the 200m rise in snowline from the Barker Advance to the present day is the greatest amplitude recorded in any single event on this table.

TABLE 3

PAST SNOWLINE ELEVATIONS (M)

Glacial Advance	Snowline Elevation	Rise
Present Day	1900	-
Barker	1700 to 1900	200 0
O'Malley	1600 to 1700	100 0
Arthur's Pass	1500 to 1600	100 20
McGrath	1420 to 1480	60 170
Tims Stream	1250	- 100
Porter	1150	- 180
Kowai	970	-

(2) Snowline irregularities

A small number of inconsistencies occurring in the profiles require explanation. Most occur in areas where field work was minimal, for example in Section VI, and most may be explained as misinterpretation of features where the interpretations have been made from aerial photographs only.

Section I, (figure 22), includes two sets of moraines which have abnormally-positioned snowlines. The Arthur's Pass advance moraines on Arthur's Pass itself have derived snowlines which plot up to 300m below the expected level for this advance, placing them below the snowlines of the earlier McGrath Advance. A possible explanation for this anomaly is that the Otira Valley is particularly unsuited to snowline calculations, with its broad steep neve areas parallelling a precipice alongside a narrow, low-gradient valley. In addition, a "coalescing glacier" effect may have occurred where numerous termini of ice falls may have combined to pond ice in the low-gradient valley to such a depth as to bury the precipice and to raise the ice level sufficiently to increase the effective neve area. This effect would give a large impetus to the glacier snout, in a manner similar to that discussed by Cooper (1937) in "The Problem of Glacier Bay".

Another inconsistency in Section I occurs on Mt Bealey (plate 14) where, on tributary 30-1, two moraines have been aged by weathering rind thickness (samples E and F figure 32) and both show evidence of a McGrath advance age, from both the rind thicknesses and the volume and surface appearance. Yet the snowlines for these two deposits plot some 140m above the expected elevation for this area. Meanwhile, located just within the proximal margin of this McGrath moraine, is a fresh, blocky moranic deposit which exhibits the weathering characteristics of Barker advance age (sample U, figure 34). The snowline derived for this deposit plots some 60m below the regional snowline elevation. This depressed Barker advance snowline may be explained as an extreme case of a low protalus deposit, while the anomalously high position of the former McGrath age moraine awaits explanation.

In Section II (figure 23) a feature on tributary 24C-2-1 was identified in the field as a moraine, together with a landslide deposit below it in the

PLATE 14

Barker moraine, B, and McGrath moraine, M, occurring in anomalously close proximity on Mt Bealey. Figure for scale.

East Edwards riverbed. The snowline elevation calculated for this feature suggests that it is more likely to be a dissected remnant of a landslide than a glacial deposit.

Section IV (figure 25) on tributary 5-12-5 has a well-preserved,double-ridged morainic deposit under forest cover, which was identified as a moraine both in the field and on aerial photographs. However, a snowline computed for this feature lies some 150m below the McGrath advance snowline profiles for this vicinity. Despite its apparent morainic form, the feature is tentatively identified as a landslide deposit, both on the snowline evidence and because other nearby landslides indicate instability in this area.

A number of features in Section VI, seen only on aerial photographs, are shown on figure 27 as indeterminate moraines. Computed snowlines for these features lie so far below the regional snowlines for the area that a glacial origin is most unlikely. The complex features on Mt Binser are treated separately in Chapter IV-II.

Two well-developed cirques which contain a comprehensive but obscure sequence of moraines and tills occur on a peak above Lagoon Saddle (tributary 22-2), in Section V. Cursory rind thickness data from these moraines suggests that the deposits of these cirques cover the complete age sequence from Pleistocene to Barker Advance. However, the derived snowlines are of such unusually low values that to plot the profile lines through these points would introduce a deep trough into all of the snowline surfaces of this area, for which there is no apparent explanation. Only a limited number of rinds was examined on these moraines, and as the till was mainly of fine material, the anomalously youthful ages are attributed to disturbance of the surface by solifluction processes. A fresh, angular, blocky moraine of Barker age at the top of this sequence, however, cannot be explained in this manner, although it may be in part a protalus deposit. In the absence of further field evidence, this set of snowlines has not been used in the profile plots.

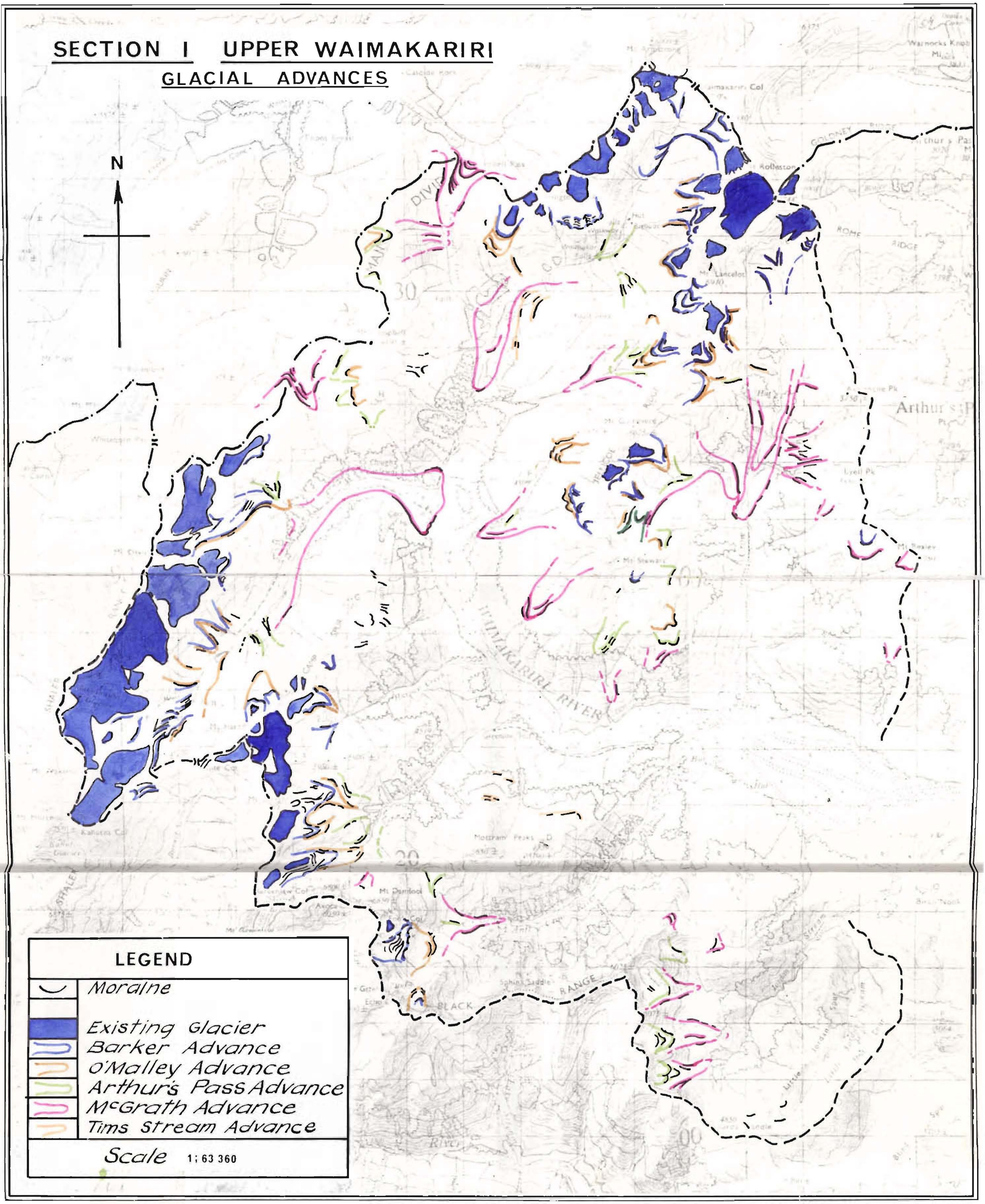

SECTION I UPPER WAIMAKARIRI
GLACIAL ADVANCES
N
LEGEND
Moraine
Existing Glacier
Barker Advance
O'Malley Advance
Arthur's Pass Advance
McGrath Advance
Tims Stream Advance
Scale 1; 63 360
Waimakariri Col
Goldney Ridge
Rolleston
Rome Ridge
Mt Lancelot
Arthur's Pass
Lyell Pk
Mt Stewart
Waimakariri River
Mottram Peaks
Mt Damfool
Black Range
Sphinx Saddle
Kahutea Col
Shaler
Warnocks Knob
Birch Nook
30
20
10
00

Fig. 13

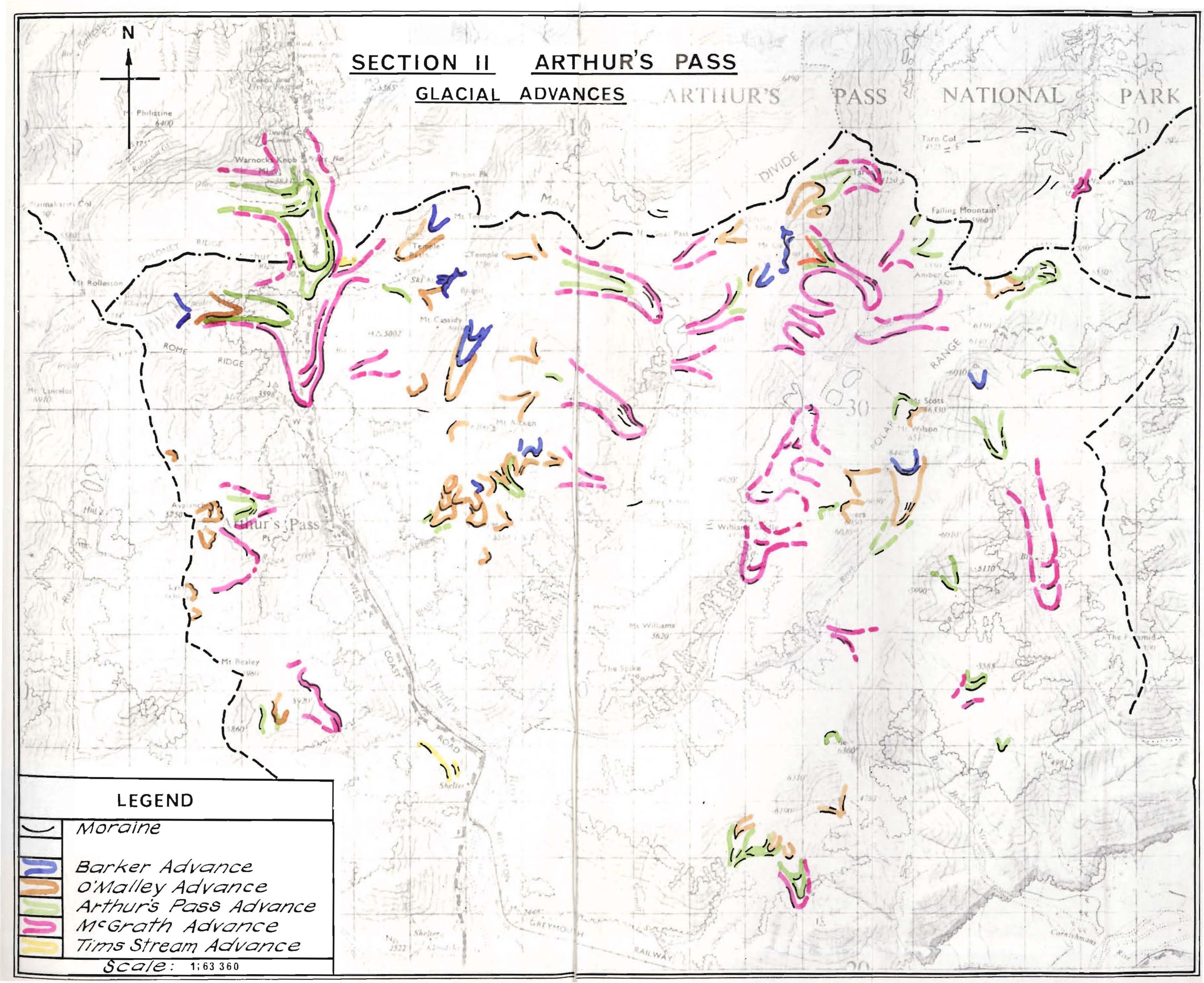

N
SECTION II ARTHUR'S PASS
GLACIAL ADVANCES
ARTHUR'S PASS NATIONAL PARK
Mt Philistine
Warnocks Knob
Mt Rolleston
GOLDNEY RIDGE
ROME RIDGE
Mt Temple
Temple Basin
Mt Cassidy
Mt Aicken
Arthur's Pass
Avalanche
Mt Bealey
MAIN DIVIDE
Tarn Col
Falling Mountain
Amber Col
POLAR RANGE
Mt Scott
Mt Wilson
Mt Williams
The Spike
WEST COAST ROAD
GREYMOUTH RAILWAY
Shelter
LEGEND
Moraine
Barker Advance
O'Malley Advance
Arthur's Pass Advance
McGrath Advance
Tims Stream Advance
Scale: 1:63 360

Fig. 14

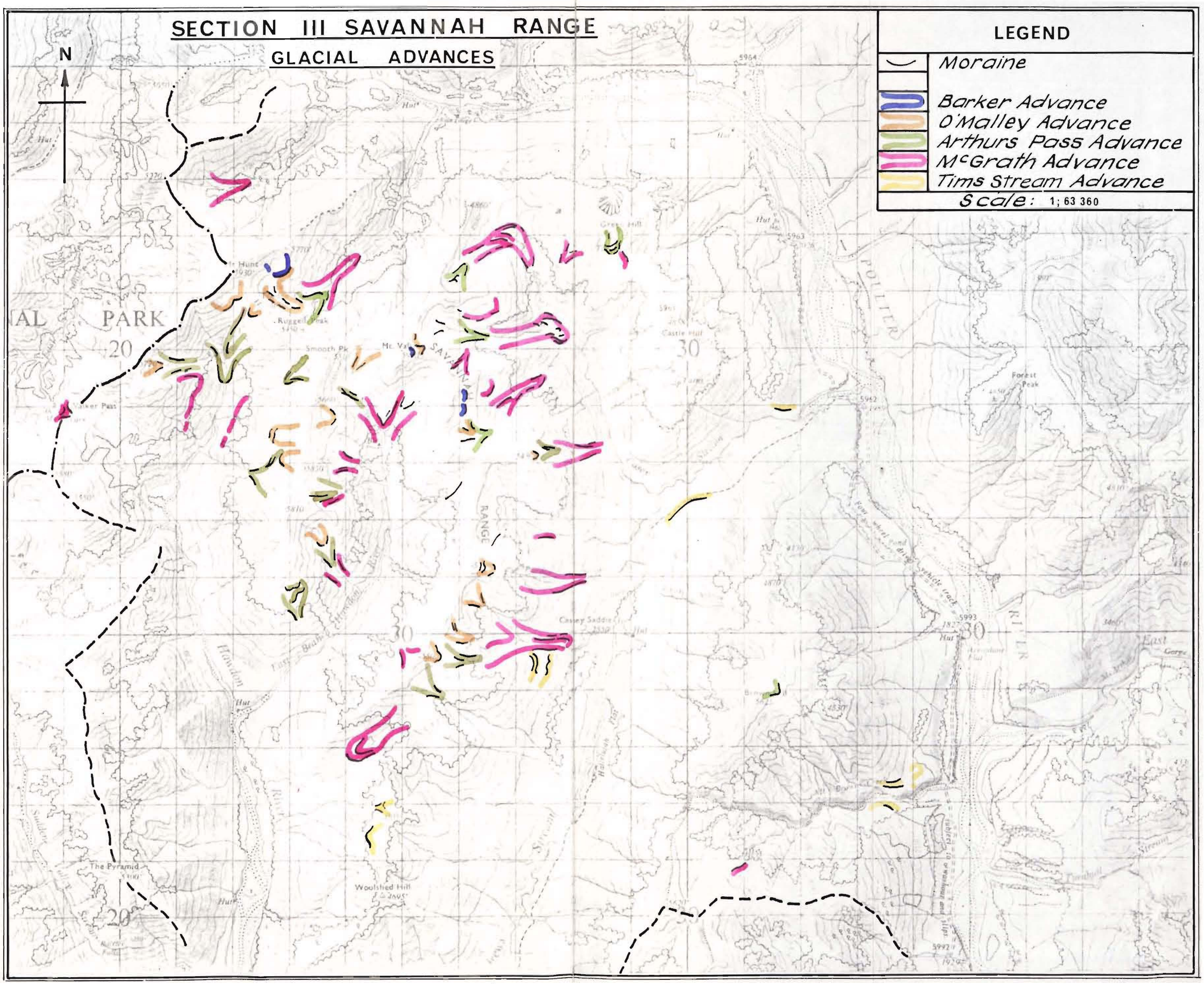

SECTION III SAVANNAH RANGE
GLACIAL ADVANCES
N
LEGEND
Moraine
Barker Advance
O'Malley Advance
Arthurs Pass Advance
McGrath Advance
Tims Stream Advance
Scale: 1; 63 360
PARK
Rugged Peak
Smooth Pk
Castle Hill
Forest Peak
Casey Saddle
Woolshed Hill
The Pyramid
POULTER
RIVER
RANGE
SAVANNAH

Fig. 15

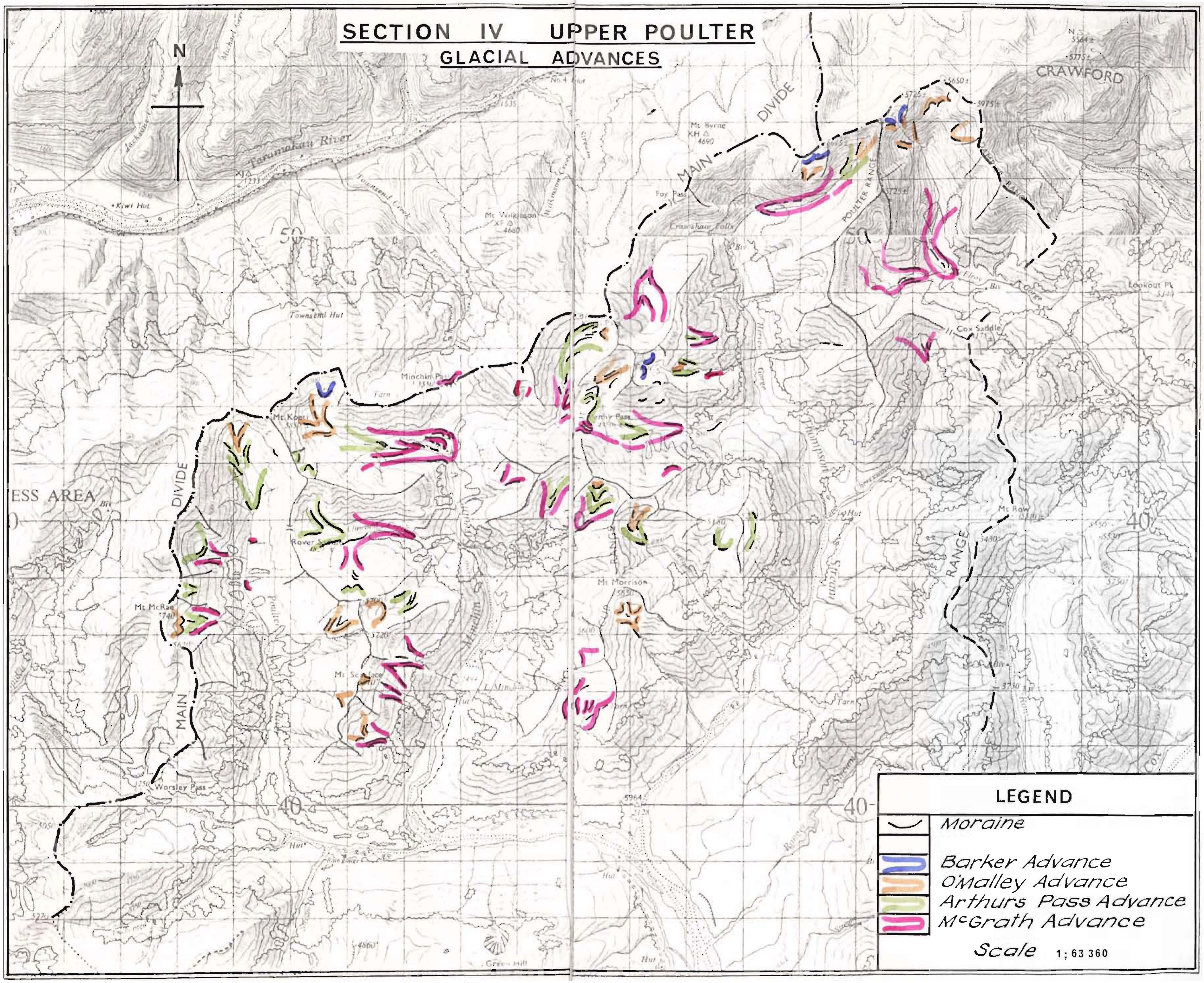

SECTION IV UPPER POULTER
GLACIAL ADVANCES
N
Taramakau River
Kiwi Hut
Townsend Creek
Mt Wilkinson
Mt Byrne
MAIN DIVIDE
Foy Pass
Crawshaw Falls
POULTER RANGE
CRAWFORD
Lookout Pk
Cox Saddle
Townsend Hut
Minchin Pass
Mt Koeti
Jenny Pass
DIVIDE
ESS AREA
Rover Saddle
Mt McRae
Mt Scott
Mt Morrison
Thompson Stream
Mt Row
RANGE
MAIN
Worsley Pass
L. Minchin
Green Hill
LEGEND
Moraine
Barker Advance
O'Malley Advance
Arthurs Pass Advance
McGrath Advance
Scale 1; 63 360

Fig. 16

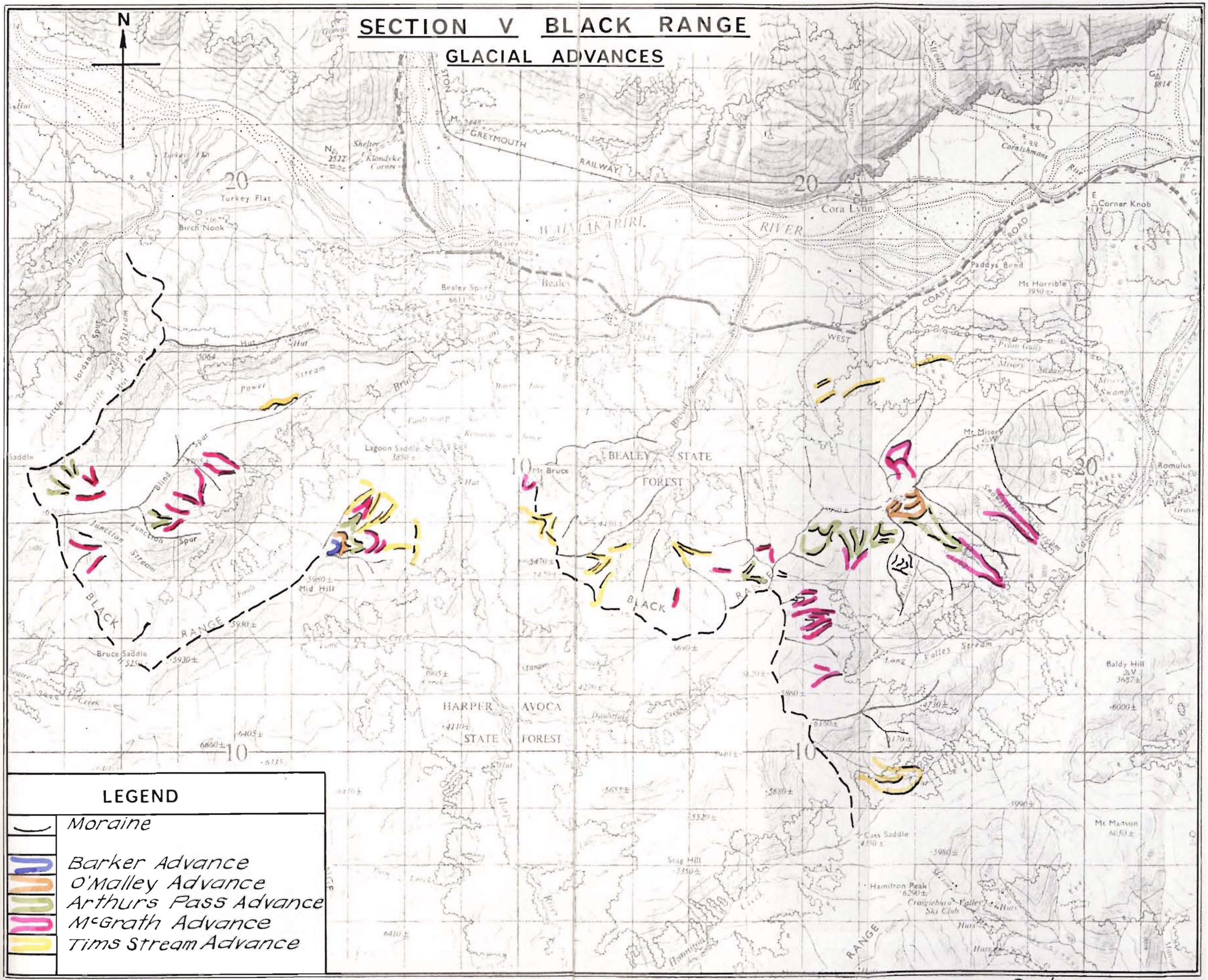


Fig. 17

Scale 1 ; 63 360

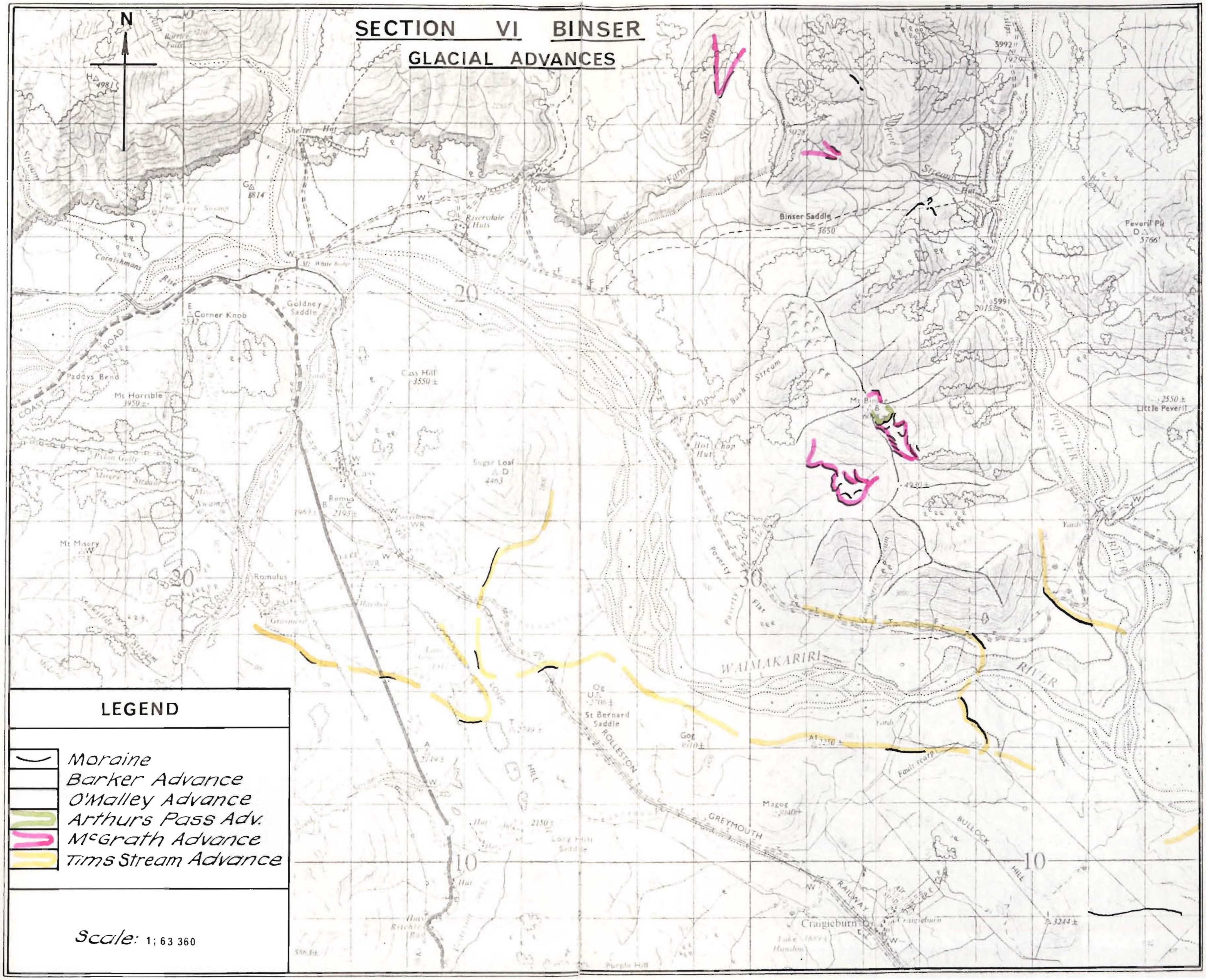

SECTION VI BINSER
GLACIAL ADVANCES
N
LEGEND
Moraine
Barker Advance
O'Malley Advance
Arthurs Pass Adv.
McGrath Advance
Tims Stream Advance
Scale: 1; 63 360
Shelter Hut
Riversdale Huts
Cornishmans
Mt White Bridge
Goldney Saddle
Corner Knob
COAST ROAD
Paddys Bend
Mt Horrible 3950
Cass Hill 3550 ±
Sugar Loaf 4463
Cass
Remus 2193
Romulus
Mt Misery
Grasmere
LONG HILL
ROLLESTON
St Bernard Saddle
Gog
Magog
GREYMOUTH
RAILWAY
BULLOCK HILL
Craigieburn
Purple Hill
Farm Stream
Binser Saddle 3650
Bush Stream
Hut
Mt Binser
Poverty Flat
WAIMAKARIRI RIVER
Fault scarp
Peveril Pk 5766'
Little Peveril 2550 ±
POULTER
5992
5991
4930 ±
20
30
10

Fig. 18

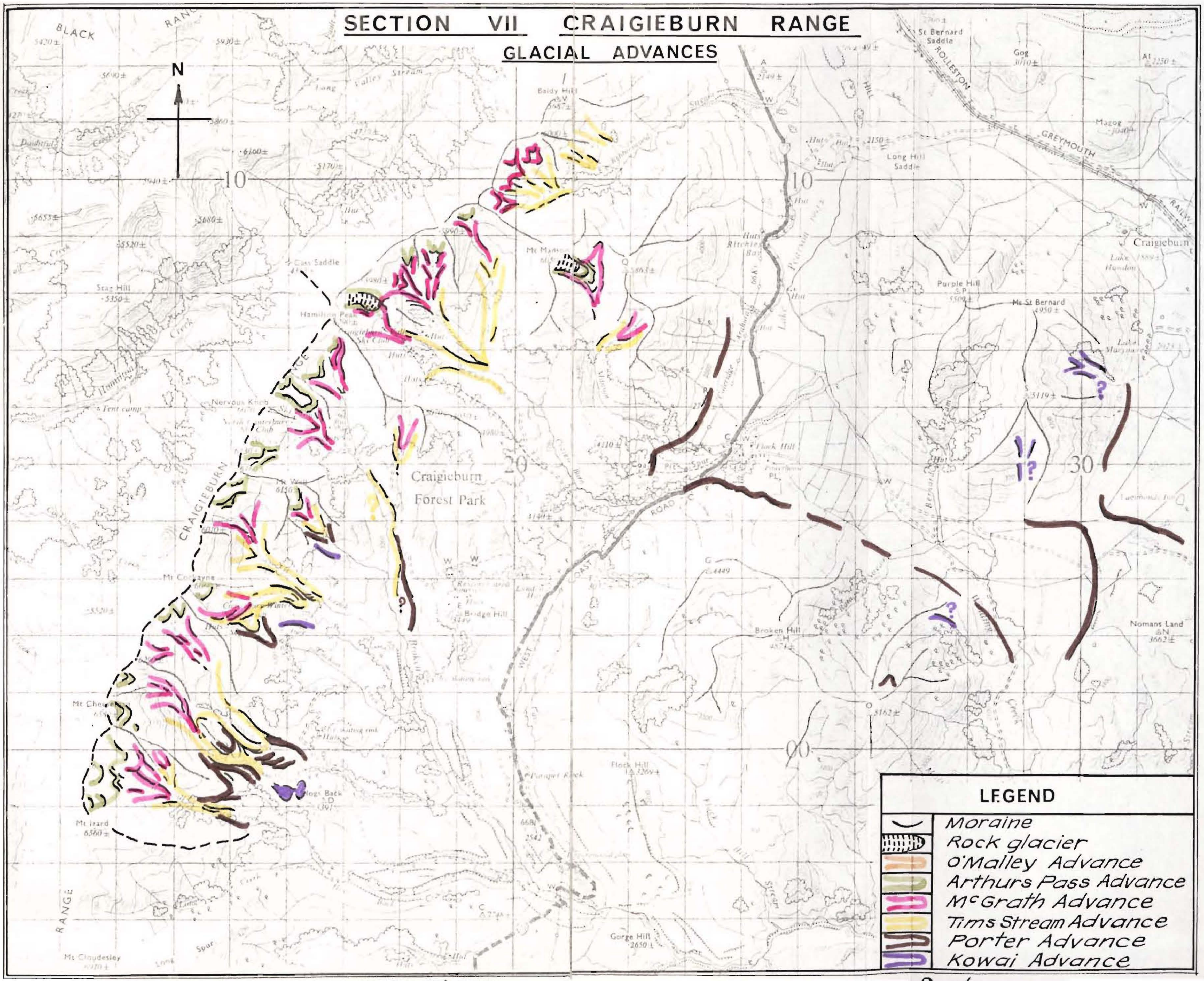


Fig. 19

Scale: 1; 63 360

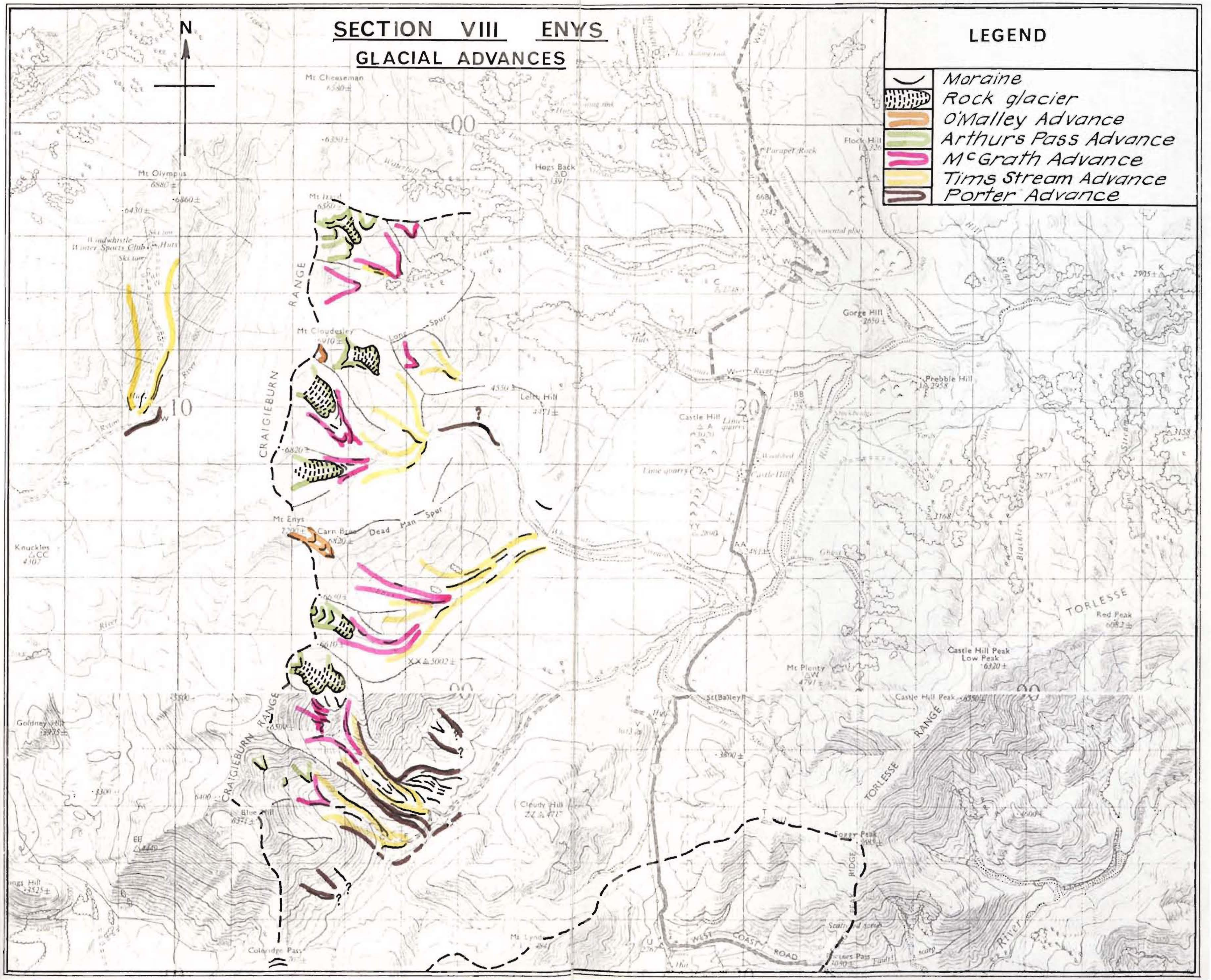
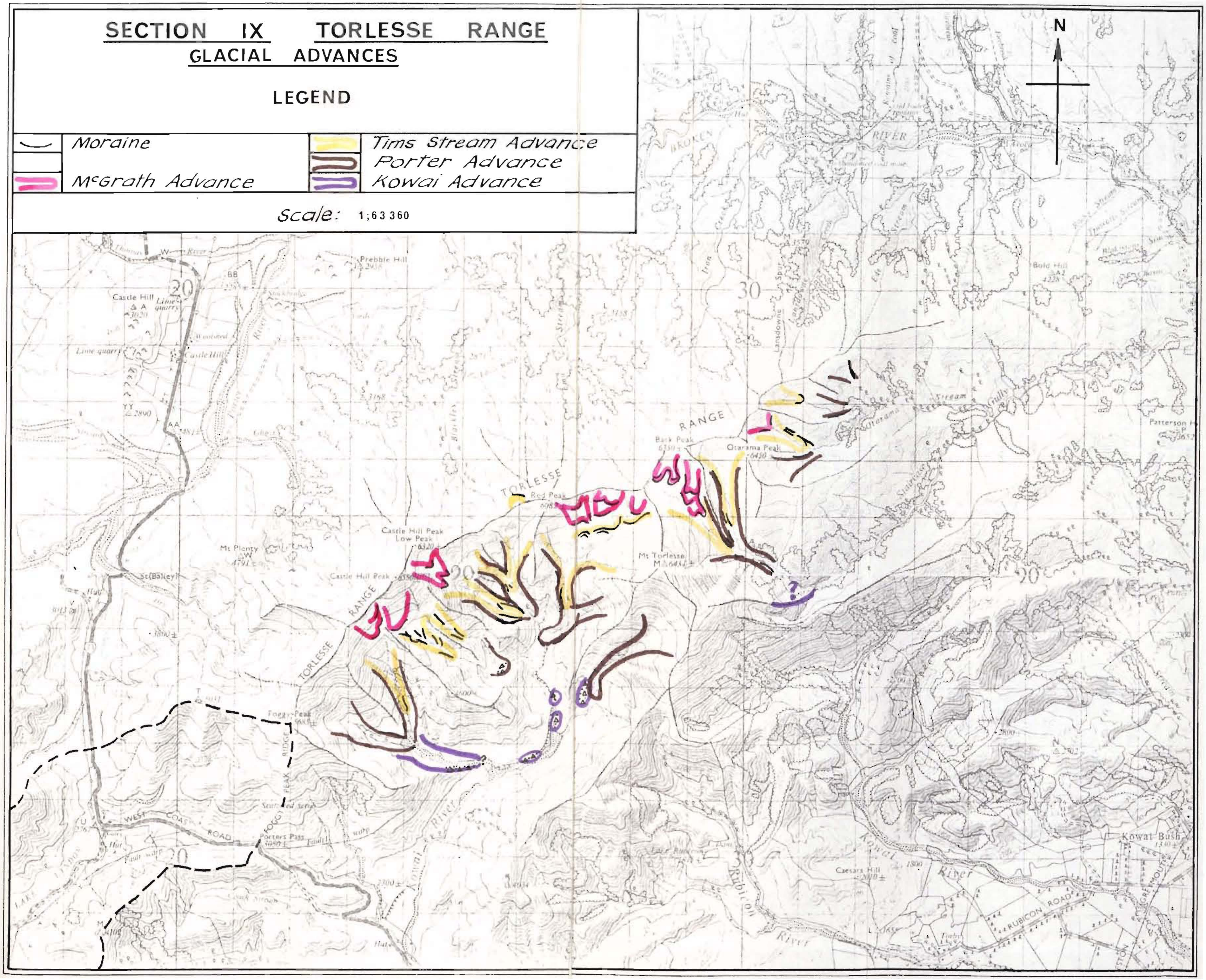


Fig. 20

Scale 1;63 360



SECTION IX TORLESSE RANGE

GLACIAL ADVANCES

LEGEND

Fig. 21

CHAPTER IV

I PROPOSED GLACIAL SEQUENCE

(1) Proposed Chronology

On the evidence from moraines of smaller past glaciers and cirques, a sequence of glacial events has been established from late Pleistocene times to the present. This chronology rests on correlations made throughout the study area because no single valley contains a full sequence of deposits. The correlations were made mainly by comparing the weathering-rind thickness of surface boulders, but a number of additional methods was employed and these are discussed in Chapter III.

Three separate Pleistocene advances are recognised, the earliest evidenced only by isolated till exposures which retain no surface morainic forms. The deposits of the two later advances are normally found as well-defined moraines in close proximity to one another. The Holocene moraines may be separated into four stades, the earliest of which occurred shortly after the commencement of the Holocene period. The remaining stades are contained within the period named Neoglaciation by Porter and Denton (1967), and defined as the "period of glacier expansion subsequent to maximal Hypsithermal shrinkage". No direct evidence, however, was found during the study in support of this warmer period.

The proposed chronology is outlined below, where for convenient reference the Neoglaciation has been subdivided into early, mid, and late Neoglacial periods:-

Present glaciers		Holocene
Barker Advance	Late Neoglacial	
O'Malley Advance	Mid Neoglacial	
Arthur's Pass Advance	Early Neoglacial	
McGrath Advance		
Tims Stream Advance		Pleistocene
Porter Advance		
Kowai Advance		

II PLEISTOCENE ADVANCES

(1) Kowai Advance

The most extensive exposures of the oldest tills and moraine remnants seen during the study are found in the headwaters of the Kowai River, tributary 1-5, on the south-eastern slopes of the Torlesse Range.

(a) Extent: At the foot of the eastern slopes of the Torlesse Range, the banks of the upper Kowai River show till exposures capped by more recent terrace gravels, indicating that the ice of this advance from tributaries 1-7 to 1-10 (figure 30), combined to extend a glacial trunk at least as far as downstream as tributary 1-6. No evidence upon which to estimate a terminal position for this glacier was forthcoming. Near the confluence of stream 1-6, with the Kowai River, large morainic boulders up to 1.5m in diameter were found some 50m above the present stream bed, on the upstream side of a small bedrock ridge obstructing the lower end of the valley. Although no exposures were available, the nature and position of the deposit indicates deposition in close proximity to an ice margin. On this, admittedly sketchy evidence, a snowline elevation value was calculated for this advance.

In Castle Hill Basin, evidence of early glacial activity is available at a number of locations, but none of these deposits give any indication of ice margin positions from which former snowlines may be estimated. Exposures on the Canterbury Winter Sports Club skifield road between Cuckoo Creek (3-3-4) and Wall Creek (3-3-5) show weathered till deposits at an altitude of 1,200m (plate 15). Poorly exposed cappings of coarse gravels on Long Spur and on the spur between Broken River and Cave Stream are considered to have glacial origins, Speight, (1935); Gage (1958); Breed (1960); together with 2m to 3m surface boulders behind Hogs Back. There is insufficient immediate evidence to decide whether these deposits result from one or many glacial episodes. From a study of the terraces of the area, Breed (1960), has shown that these deposits result from two different Pleistocene advances. The deposits indicate that for both of these advances the ice extended beyond the foot of the ranges to one or a number of piedmont glaciers. On the Canterbury Winter Sports Club road, the till exposure occurs at a break in slope of the ridge where the steeply-descending ridge flattens considerably in gradient. Further ridges of a similar shape, with breaks in slope at equivalent altitudes, occur northwards towards Broken River, but a lack of suitable exposures combined with a thick blanket of slope debris leaves a possible glacial origin for these ridges unconfirmed.

(b) Deposits: The tills of the Kowai advance show a much greater degree of weathering and compaction than do the deposits of subsequent advances. Where the surfaces have not been overlain by other deposits, they have been extensively eroded and reworked by solifluction or slope processes. The Kowai River in a small gorge above tributary 1-7, affords some good exposures of till in contact with bedrock and overlain by outwash gravels. The bedrock is shattered and closely jointed. In an exposure in a small gorge of the Kowai River above stream 1-7, the following sequence is shown:-

20cm	Soil and loess cover.
5m	Well stratified fresh grey cobble gravels.
1m to 2m	Boulder gravels.
5m	Compacted unstratified till, sub-rounded to angular clasts up to boulder size. Material superficially weathered to dull brown with weathering of all clast joints.
Bedrock	Shattered and closely jointed, with slight weathering along joint planes.

PLATE 15

Kowai (?) till exposed at
a cutting on the road to Canterbury
Winter Sports Club skifield, above
tributary 3-3-9.

Downstream of stream 1-7 confluence, further till exposures occur along a terrace face above the present riverbed. Here the upper surface of the till is marked by a weep line of subsurface drainage from the overlying terrace gravels. Immediately upstream of the gorge and exposures (above), at the mouth of a small side stream there is exposed a very complex interfingering set of beds of soils, slope and till deposits on bedrock. The till here appears to be slightly less weathered and may be younger than that described above. Other surviving Kowai deposits occur as weathered boulder surfaces on a terrace south-east of stream 1-9 and 1-10 confluence, and on the summit and downstream side of a small ridge entering the lower reaches of stream 1-7 basin.

(2) Porter advance

This glacial episode has been named from an extensive moraine sequence displayed below cirque 3-7 in the upper Porter River, (plate 16).

(a) Extent: Throughout the Torlesse and Craigieburn Ranges, Porter advance ice limits are frequently well-defined by distinctively broad moraines constructed near the toe of the mountain slopes. Ice extents on the eastern slopes of the Torlesse Range, in the Kowai River valley, were generally contained within the smaller tributaries and never reached as far as the main valley. The remainder of this face of the range displays only indeterminate vestiges of moraines, giving little reliable evidence of ice extents.

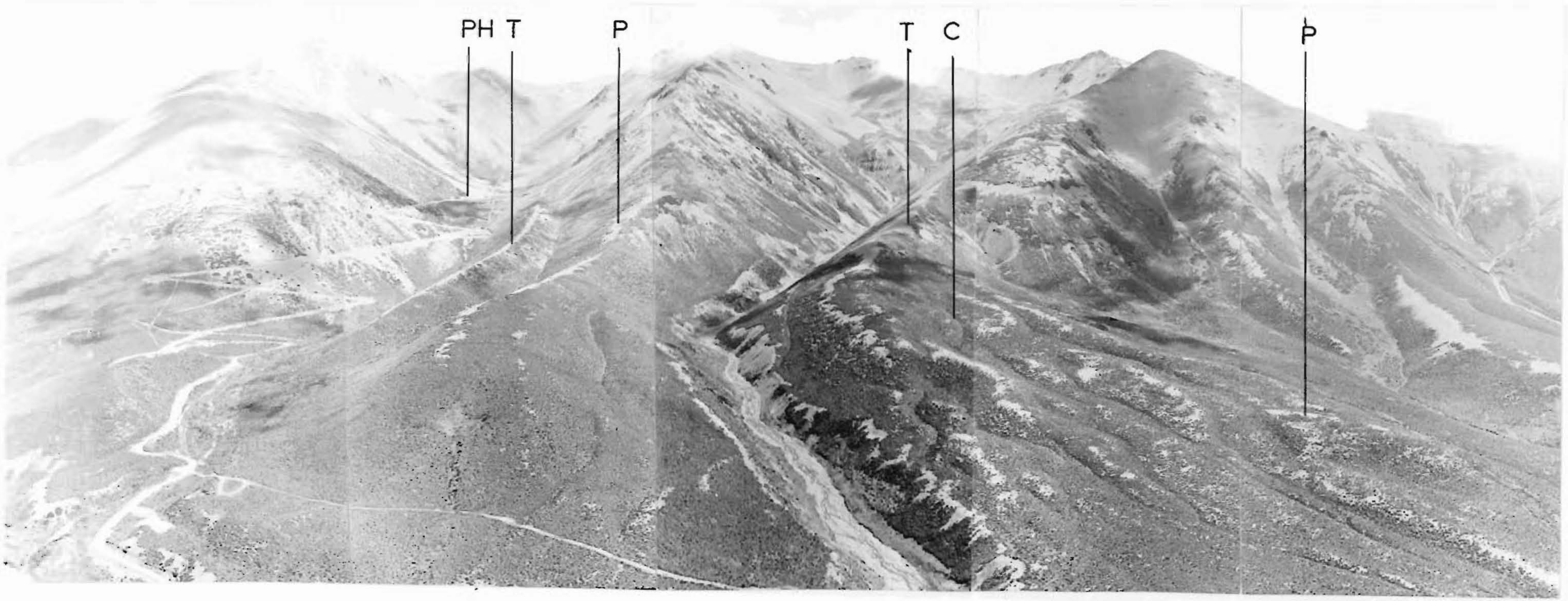


PLATE 16

Porter moraines of basin 3-7 and 3-8 of the Porter River.
P, Porter moraines, T, Tims Stream moraines, C, assumed line of contact between the two. PH, Porter Heights Skifield.

Glaciers during Porter time undoubtedly existed on the northern Torlesse Range slopes, but tectonic deformation and extensive erosion have rendered any remaining traces of ice extents unreliable.

Throughout the Craigieburn Range, glaciers reached the Castle Hill Basin floor from all of the larger valleys, and a number of the glaciers developed laterally-expanded termini. In few if any instances did the glaciers coalesce to form a piedmont glacier. Towards the north-eastern end of the range, Porter moraines become more discontinuous and undefined, making the demarcation of former ice limits very indistinct. No Porter advance deposits were found northward of Mt Manson (stream 3-2-4), beyond which all tributaries flowed into a Blackwater advance distributary (Gage, 1958) of the Waimakariri Glacier.

East of Castle Hill Basin, Mt St Bernard and Broken Hill have features of morainic form alongside streams 3-1 and 3-2-1 which have been tentatively attributed to this advance. Possible Porter deposits on the northern slopes of the Torlesse Range are masked by extensive erosion, landslide and tectonic activity, so that no estimates of ice extent have been made from this locality.

(b) Deposits: Many Porter advance deposits occur as distinctive massive lateral moraines, found near the valley floors of both the Craigieburn and Torlesse Ranges. Torlesse terminal positions are poorly defined in the narrow valleys, although many large dissected lateral moraines survive, which

PLATE 17

Porter moraine exposure in branch 1-6-1 of the Kowai River, Torlesse Range.

constitute complete spur ends in some instances. (Plate 19). The moraine surfaces are mantled by a thick cover of loess, and surface boulders are rare. Exposures are limited because Porter moraines tend to have been protected from stream erosion by enclosed moraine loops of subsequent glacial resurgences. The few exposures show a light weathering discolouration of the till matrix which varies with depth of burial and with insignificant weathering of the clasts (plate 17).

Distinctively large Porter advance moraines have been constructed in the Kowai River tributaries 1-6, 1-8, 1-9, in tributaries 3-7 and 3-8 to the Porter River and in Tims Stream, 3-3-3. A further massive moraine, some 80m in height occurs outside the area near the headwaters of the Ryton River. This feature has been included in the study (figure 28) because its form provides a reliable snowline for comparison purposes.

The moraines of both the Porter River and Tims Stream both record multiple ice advance events, (plates 16 and 18), beginning with an extensive ice expansion which in some cases spread beyond the confines of the valleys. Between the small outermost deposits and the inner Tims Stream moraines, a series of moraine ridges are spread in a sequence, covering the whole area. These features indicate that the initial ice stand was of short duration and was followed by a long and gradual recession wherein small pulses or standstills occurred.

In the smaller basins of the ranges, Porter moraines are frequently to be found at higher elevations, but because of the higher gradients of the slopes, these moraines have suffered a greater degree of erosion and modification.

(3) Tims Stream advance

The final Pleistocene advance is named from distinctively massive lateral moraines in Tims Stream, 3-3-3, superposed behind the Porter Moraines.

(a) Extent: Separate Tims Stream glaciers left deposits throughout the Torlesse and Craigieburn Ranges and towards the eastern end of the Black Range. Outside these ranges evidence shows that few individual small glaciers existed, and that almost all of the small basins were tributary to the "Waimakariri Glacier".

Ice extents on the eastern Torlesse Range of this stade did not quite reach the valley floors, but occupied the narrower valleys within and close to the limits of the Porter advance, (plate 19 and figure 30). Although the extent of the glaciers was close to that of the Porter advance, the ice tongues had a much reduced thickness. Along the Craigieburn Range the ice reached the margins of Castle Hill Basin, but as with the Porter advance, towards the north-eastern end of the range, the ice limits are poorly defined. Separate Tims Stream glaciers existed in Ribbonwood Stream, 3-2-3, and tributaries to Cass River 12, where traces of the previous Porter advance have been removed by erosion. Inland from the Cass River area, no further Tims Stream terminal moraines were found, supporting the probability that glaciers of the northern flanks of the Black Range were joined with the Waimakariri ice trunk.

The farthest westward evidence found of an isolated Tims Stream glacier is a well-defined moraine at a small, low-gradient basin on Woolshed Hill, at tributary 13-4. Little evidence remains of the margins of the main "Waimakariri Glacier" from which to estimate ice profiles. Along the northern slopes of the Black Range intermittent segments of kame terraces and lateral moraines are to be found, but no ice-margin stream channels were seen. Rare recessional moraine traces from lower ice levels are to be found along parts of the upper Black Range, near the Bealey-Edwards confluence, 24A and 24B and well up the Waimakariri River opposite tributary 42, figures 17, 14 and 13. On the valley floor the only deposits found of this advance were thin till coverings on roche mountonnes.

At Lagoon Saddle, (22-2) lateral moraines of two well-formed cirques on the peak near Mid Hill, descend towards the saddle but are truncated at approximately 1450m without any suggestion of an ice terminal. Another moraine at a similar altitude has been constructed on a saddle at the headwaters of Broad Stream (19-2). These two features, together with a barely-perceptible vegetation "trimline" suggest an ice level of 1450m for Lagoon Saddle,

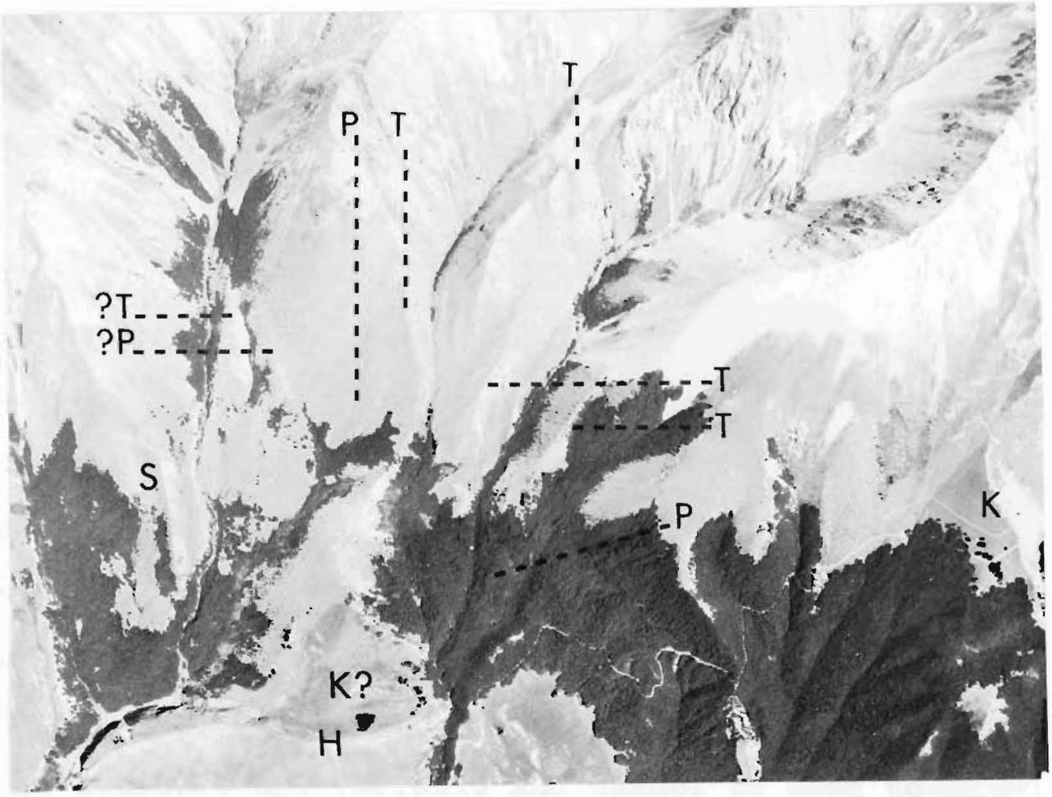


PLATE 18

Part of vertical Aerial Photograph 2748/24,
of Tims Stream, centre, and Waterfall Creek, left.

T : Tims Stream moraines.

P : Porter moraines.

K : Probable Kowai till.

S : Scarp.

H : Hogs Back Hill.

which implies a 200m depth of an ice distributary from the Waimakariri.

(b) Deposits: There is little difference in surface appearance and weathering, upon which to distinguish between the Tims Stream and Porter deposits. Surfaces of Tims Stream moraines are barely detectably fresher and less subdued than those of the Porter moraines. Loess deposits cover the moraines and surface boulders. These are not plentiful, although in some instances seen in the Torlesse area, the loess cover is minimal. Rind thicknesses of the surface boulders are variable and cannot be used to estimate age as these deposits are beyond the range of this method. (See Appendix I). Tims Stream moraines are typically large in volume and appear to override those of the preceding stade, (plates 16 and 18). The spread of terminal moraine positions is limited, indicating a reduced amplitude of fluctuations for this stade. Good exposures are limited, but are more plentiful than those for the Porter advance as a result of the tendency for Tims Stream moraines to occur as a barrier against stream erosion between Porter moraines and the present streams. The degree of weathering of the tills is very variable, depending on the depth of burial. Tills near the surface have a light yellow oxidised matrix, weathered joints of the clasts, but no perceptible weathering of clast surfaces, while deeply-buried tills show little discolouration. The only difference in degree of weathering between the Porter and Tims

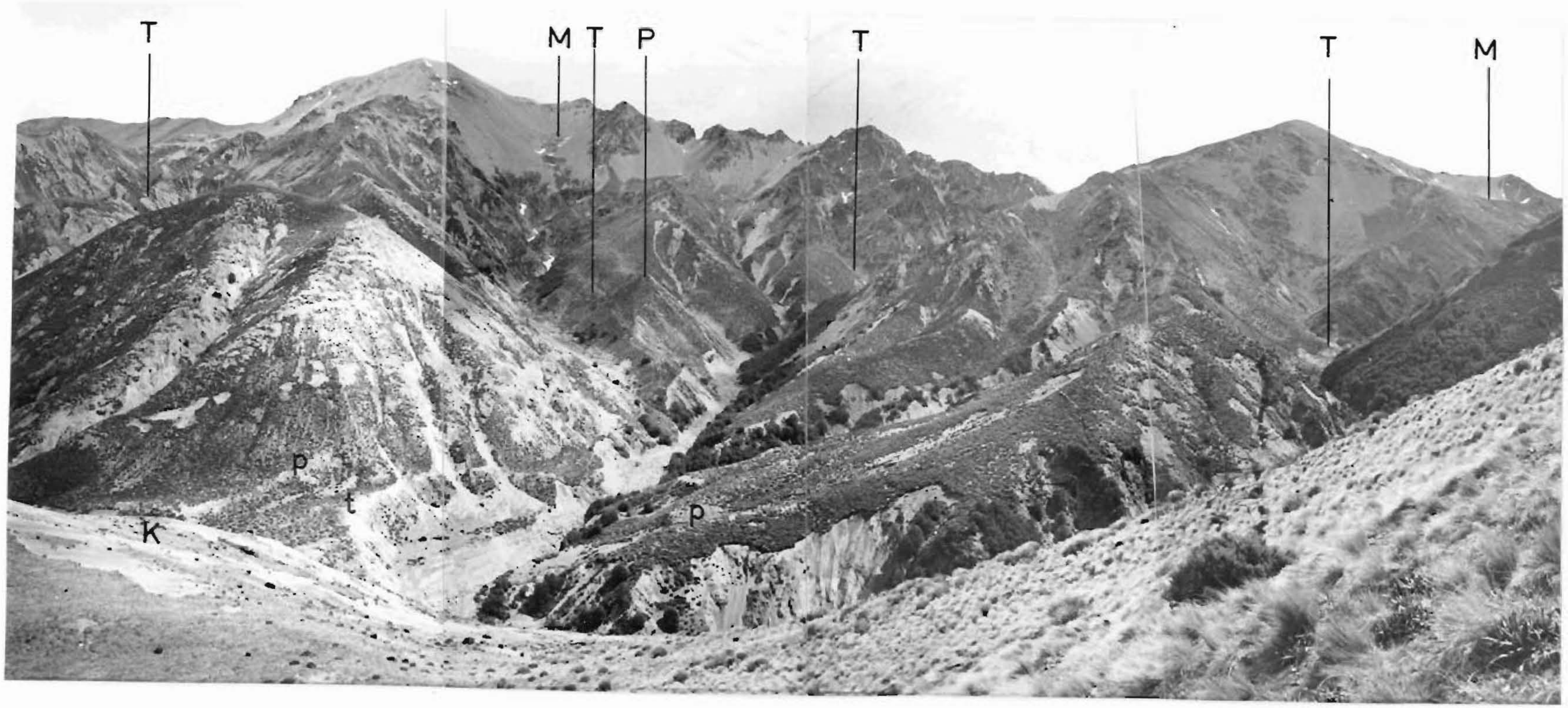


PLATE 19

Headwaters of the Kowai River in the Torlesse Range.
P, Porter moraines. T, Tims Stream moraines. M, McGrath moraines. K, boulders of possible Kowai till, p and t, out wash terraces having closest relationship to P, and T, moraines respectively.

Stream advances appears to be the depth to which weathering has penetrated, and without suitable deep exposures this criterion is of little assistance in distinguishing between the two events.

II THE PLEISTOCENE-HOLOCENE BOUNDARY

(1) General

Following close on the recession of the last Pleistocene ice advance, extensive fluvial deposits were deposited in the valleys upstream of the Tims Stream moraines. Ample evidence of this fluvial activity is seen in the massive fan development and valley infilling throughout the area. Alluvial terrace development is less prominent, except in the Poulter River valley. Associated with these alluvial deposits are numerous landslides and geliflually-disturbed surfaces. The time of this period of fluvial activity was established from a number of cases where there is a continuous sequence from glacial deposits to alluvial deposits, some of which deserve special note.

(2) Mt Binser area

(a) Description: From the Waimakariri River to the Mt Binser basin (tributary 7), the following sequence of unusually extensive deposits occurs:-

An alluvial fan 1.8km in length by 3km wide extends out into the Waimakariri riverbed, where the steep toe of the fan is 70m in height, (plate 20). Clearly visible near the toe of this fan are lake shorelines of glacial Lake Speight (Gage, 1958). Exposures at the steep fan toe show steeply-dipping well-stratified beds, considered to be foreset, overlying thick unstratified deposits of till or mudflow material, (plate 21). The surface of the fan is furrowed by old stream channels, and heavily mantled by loess and soil, beneath which there is up to 1m of disturbed, unstratified gravels. The present stable underfit stream bed is incised to approximately 10m, and is bordered by levees containing boulders up to 3m in diameter. The fan debouched from a narrow valley, now completely choked by a massive blocky deposit which fills the valley for some 1.3km. This deposit consists of angular boulders of 10cm to 2m in size, and shows an incipient surface relief of small mounds and longitudinal ridges. The bare rock surface has no cover of loess or soil, and the present streams flow underground throughout the length of the structure, reaching the surface only where the deposit terminates in a steep blocky front near the angle of repose. The rocks of this deposit have a pebbly sandstone composition (Folk, Andrews and Lewis, 1970), which is of notably coarser grain size than occurs elsewhere in the area. The upper limit of this rock glacier type of feature grades quickly from angular boulders into a substantial morainic deposit of mounds, ridges and hollows, composed of unsorted pebble to cobble-sized material with isolated boulders. This deposit supports a full cover of loess and soil, but again the underlying material is permeable, as streams entering

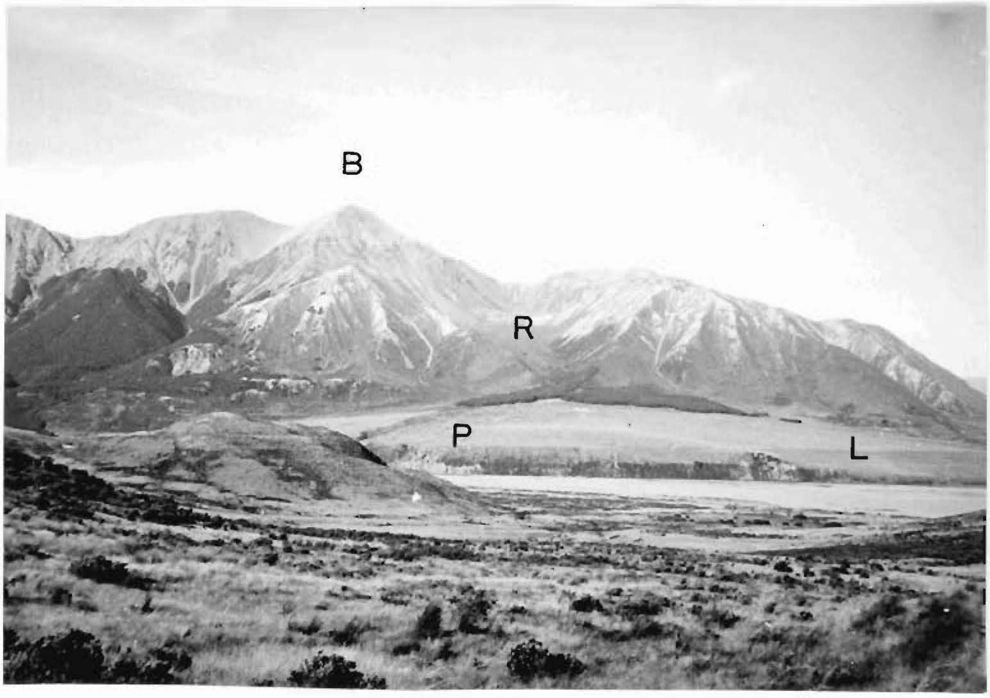


PLATE 20

Extensive alluvial fan developed below Mt Binser (B). R, "rock glacier" deposits. L, lake shorelines. P, location of photograph, plate 21.

PLATE 21

Deposits at the toe of the Mt Binser alluvial fan. A, till and/or mudflow deposits. B, possible foreset beds dipping at 25°, angle of contact 5°.

PLATE 22
Upper Mt Binser valley deposits.

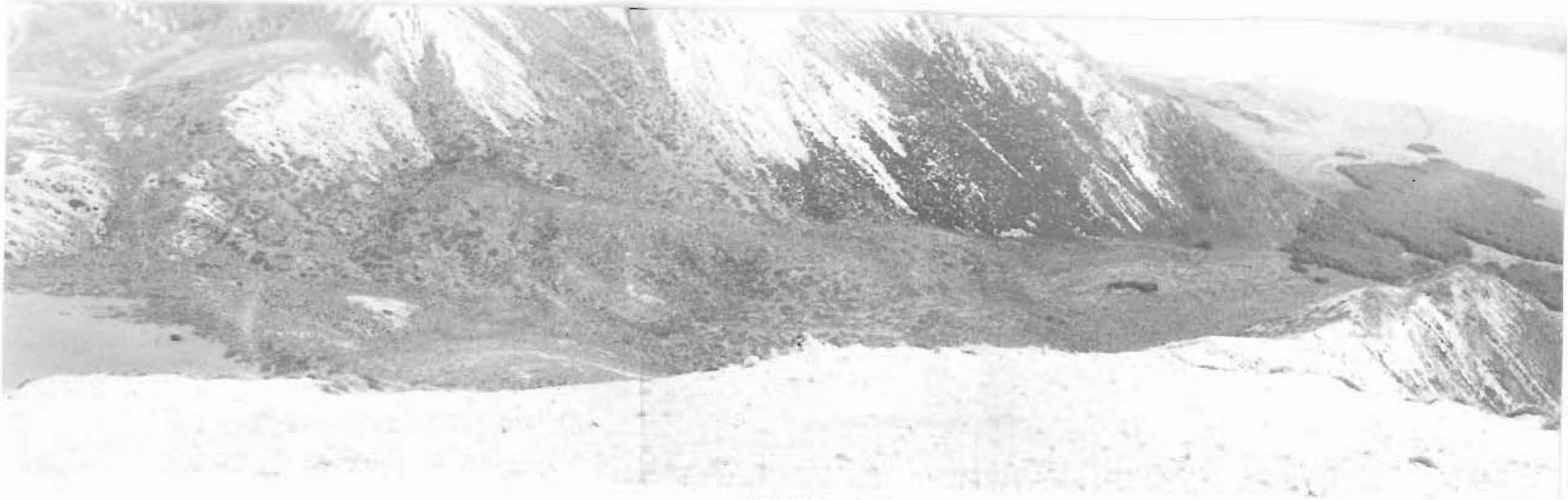


PLATE 23
Lower Mt Binser valley deposits, tributary 7.

hollows at the headwall drain into subsurface channels.

The steep headwall of the cirque basin, rising from immediately behind the upper deposit, takes the form of a flat face, suggesting that the extensive volume of material in this deposit was not removed by a cirque glacier mechanism.

Down-valley from Mt Binser a smaller adjacent valley (tributary 6), displays at its mouth a comparatively large morainic ridge, up to 20m in height and containing boulders up to 2m to 3m in diameter. A lack of good exposures made it impossible to determine whether this deposit had a glacial or a mudflow origin. However, the computed snowline for a glacial origin is far below that of the Pleistocene snowlines for this area, suggesting a mudflow origin.

(b) Interpretation: The following sequence of events is given as an interpretation of the features examined at Mt Binser:-

Contemporaneous with the recession of the Pleistocene glaciers and the formation of the ice-dammed glacial Lake Speight (Gage 1958), the Binser fan was rapidly built out into this lake. The whole of the fan-building process, which had to begin after the maximum ice extent, was completed before the lake disappeared when the moraine and/or ice dam was destroyed. The relatively short time available to build such a large fan indicates extreme instability in the area. The final (surface) deposits on the fan included those of some large mudflows, which placed large boulders in levees beside the stream channel.

It is postulated that the events most likely to have halted the fan-building processes were either a large landslide or a sudden change to a cooler and drier climate. The former is the more likely case, as the change requires the cessation of high streamflows which carried 3m-diameter boulders in mudflows, to a small steady flow, which up to the present has made only a small incision into the alluvial fan. This change must have occurred before the draining of the lake, otherwise there would be some evidence of a large incision and a building of a lower-level fan that would have accompanied the drop of some 70m in base level.

Evidence of a large landslide is available in the large volume and low altitude of 810m, reached by the "rock glacier" feature within the cirque basin, (plates 22 and 23). This feature, however, is not considered to be a true rock glacier because of the very low altitude reached by the deposit. The calculated snowlines for any of the deposits in this basin fall up to 200m below those of any post-Pleistocene snowlines computed for this area, (figure 8). The lowest of these snowlines, when applied to this feature, give an area-altitude ratio of 1:16.5, which is well below that of 1:7 found by Potter (1972) for a rock glacier.

This ratio is considered to be too low to support a true rock glacier by the normal processes. The explanation proposed for this feature is that a large landslide fell onto a small glacier at the valley head, causing an unusually thick rock glacier to form. This "rock glacier" survived until it had moved the landslide material down-valley and re-exposed the neve area, when it would revert to a normal glacier. Subsequent smaller single or multiple landslides then occurred, bringing down finer material of a different lithology. These landslides again possibly covered a small glacier, because distribution and surface morphology of the debris, together with hollows at the foot of the headwall, are best explained by invoking some degree of glacial movement following the landslide.

No glacial acitivity could have existed in the Binser cirque during the period of fan-building, and, because of the relatively low altitude, the next period of glacial activity here after the Pleistocene glaciations concluded, would not be expected before the McGrath advance. If the landslide onto a glacier hypothesis is invoked for the unusual deposits found here, this implies that glacial Lake Speight was still in existence by early McGrath advance time, because the landslide caused the cessation of the fan-building process and the fan displays lake shorelines on its final upper surface.

(3) Poulter Valley

For 30km of its length above the confluence with the Waimakariri River, the Poulter River (tributary 5), contains extensive sets of alluvial terraces between

Slumped alluvial fan at tributary 5-5, Poulter River, assumed to have been the result of deposition over stagnant ice.

PLATE 24

well-developed alluvial fans. One of these fans, opposite tributary 5-5, has a set of two collapse features at its lower end, (plate 24 and figure 26), while another fan of tributary 5-9 has a central collapse-depression now containing a pond mapped on figure 24. Both of these features are interpreted as ice-contact features formed by the collapse of alluvial fans built out over stagnant ice.

(4) Hawdon Valley

Along the eastern side of the lower Hawdon Valley (tributary 13) there is displayed a large set of sloping terraces some 140m above the present riverbed. A number of good sections (plate 25), shows the composition of the deposits to be entirely of sorted and well-stratified fine angular gravels, deposited at an angle of 10° in a direction towards the axis of the Hawdon River. From the surface down to depths of up to 2m, the gravels show a zone of no stratification, presumably as a result of disturbance by geliflual processes.

A downslope projection of the surface of these deposits meets the opposite side of the valley well above present riverbed level, but no vestiges of any matching terraces were found in this locality.

The formation of such substantial high-level deposits, on one side of the valley only, requires control by a temporary high base level situated somewhere near the middle of the present riverbed. It is suggested that these "terraces" are alluvial fans

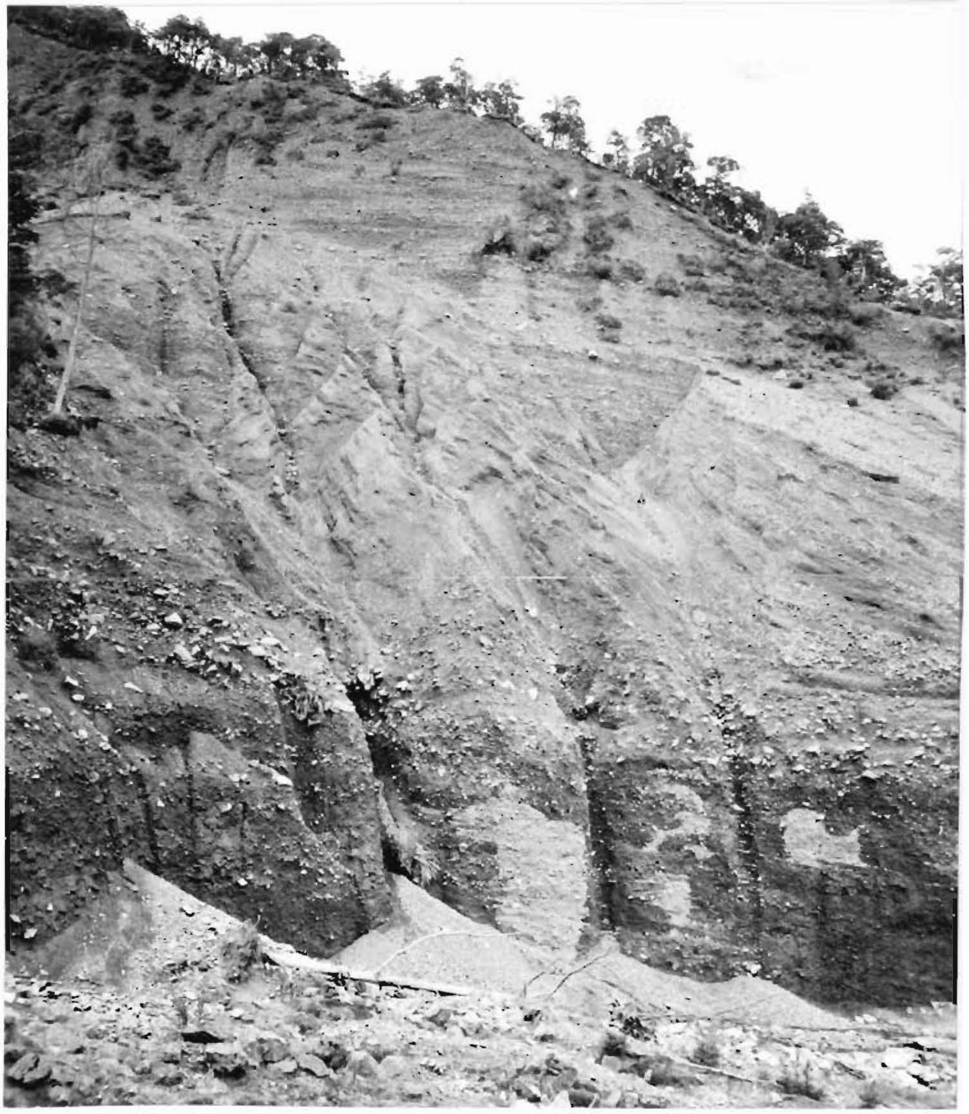


PLATE 25

Deep colluvium deposits in the lower Hawdon valley.

Descriptive section

140m	Top
	2m to 3m unstratified soliflually disturbed gravels. Strongly weathered to 3m to 4m depth.
	(Section partly obscured by dissected scree).
	Coarse, stratified sub-angular gravels dipping at 10°. Boulders to 20cm dia.
7m	Unconformity?
	Fine stratified colluvium. Sub-angular clasts to 15cm. dia. Weathered matrix.
0m	Hawdon riverbed.

washed out against a barrier of stagnant ice.

(5) Hawdon Cirque

Tributary 13-5, which cuts through the upstream end of the "terrace" formations described above, has a maturely-developed cirque situated above an extensive valley fill of blocky material, (figure 24). This stepped, permeable deposit of angular, blocky rock debris extends some 1.3km under forest cover from near the Hawdon River bed, up to the lower boundary of the cirque basin. Here the deposit is spread laterally as a 30m to 50m-high barrier of extensive knob and kettle topography with concentric ridges, enclosing the lower limit of the basin. This depression is drained by subterranean channels, and has no silt deposits to suggest present or past ponding.

This valley has a strikingly similar arrangement of features to those studied at Mt Binser. The excellent state of preservation of the features in both of these valleys may be attributed to the high permeability of the deposits, which permits almost erosion-free sub-surface drainage. Similar deposits may have occurred elsewhere, but if they did not have sub-surface drainage, the chances of sufficient evidence remaining to interpret the sequence of events would be very small. Cherrywood Stream, tributary 5-12-5, may be one such example (see Chapter III).

The sequence of events leading to features of the Hawdon cirque is interpreted in a similar manner to those described for Mt Binser. A massive landslide fell onto an existing glacier, partially or completely burying the ice, thereby creating a temporary rock glacier. The rock glacier phase lasted until the landslide debris was all carried clear of the original glacier site, and the feature then reverted to a normal glacier.

(6) Conclusion

From the above evidence, the following climatic sequence is postulated for the time period between the Tims Stream and McGrath advances.

There was an initial period of rapid warming, causing both a sudden collapse of the Pleistocene ice and extreme slope instability resulting from the sudden change from glacial to fluvial erosion. This was a period of rapid development of many of the major alluvial fans of the region (e.g., the Binser, Hawdon and Poulter alluvial fans), suggesting that there was ample precipitation available for fluvial activity. Following this initial warming, a period of cooler conditions may have followed, to allow large pieces of stagnant Pleistocene ice to survive for the time required to construct the ice-contact features described above. Solifluction disturbance of the surfaces of alluvial deposits may have occurred during this period and culminated during the McGrath Advance. Finally, a marked decrease in fluvial activity with the cooling at the onset of the McGrath advance is suggested, to account for the absence of any evidence of secondary fan-building after the disappearance of ice from the ice contact features, while slope instability continued to be expressed as landslides.

III HOLOCENE ADVANCE

(1) McGrath advance

This early Holocene study has been named after a well-defined set of lateral moraines which terminate near McGrath Stream (tributary 24A-9), Arthur's Pass.

(a) Extent: McGrath glaciers were distributed throughout the study area mainly as small valley glaciers. Their moraines are well separated in distance from the Pleistocene moraines in both the Waimakariri and Poulter river valleys, and are readily recognised as the first significant valley-floor moraines encountered upstream of the Pleistocene ice limits. In the Craigieburn and Torlesse ranges, however, these moraines are closely associated with those of the Pleistocene advances. In the Waimakariri headwaters, ice descended to the valley floors, but glacier lengths became progressively shorter with the decreasing summit elevations towards the north-east along the main divide, until in the headwaters of the Poulter River McGrath ice was confined in the main to cirque glaciers. McGrath cirque glaciers occurred throughout the length of the Black and Craigieburn ranges, and the summits of the Torlesse range just intercepted the McGrath snowline.

The largest McGrath glacier flowed from Mt Murchison down the course of the present White River (tributary 38), for 8km, to terminate at the

White-Waimakariri confluence, a little below the terminal of the glacier from Waimakariri Col (tributary 50). Ice occupied the main tributary valleys of the Crow and Bealey rivers, but the valleys of the Mingha and Edwards rivers were not completely ice-filled. The Edwards valley floor (tributary 24C), has numerous separate till deposits attributed to the termini of a number of separate valley side glaciers. Glaciers of this type frequently form ice-dammed valley-floor lakes, and lake sediments which have been radiocarbon aged at 9120±120 years BP., (Burrows, S59/551), are to be found near Taruahuna Pass. Ice limits of the Sudden Valley (tributary 13-1), and Hawdon (tributary 13), rivers are poorly defined, while morainic forms at the Hawdon-East Hawdon confluence have been attributed to Pleistocene ice recession. Throughout the upper Poulter area, (figure 25), McGrath glaciers were confined mainly to the higher cirques at or above the present fluvial dissection limit, with few cases of ice reaching to the valley floors. The snowline isopleth map (figure 10) shows a depression towards the north-west, indicating that the precipitation divide would have tended to be west of the topographic divide, resulting in increased glacial activity here. Consequently, wherever ice has crossed saddles on the topographic divide, ice flow movement was from west to east. In support of this concept, a number of instances is to be seen where multiple moraine loops on Harman Pass (38-2), Campbell Pass (42-2), Arthur's Pass,

PLATE 26

Coarse McGrath moraines, upper Minchin River (5-15-10).
McGrath I moraines numbered. McGrath II advance indicated.
L, high level landslide deposit. Photograph from outer moraine loop 1.

Walker Pass (13-12), and Minchin Pass (5-15-11), demonstrate ice movement in this direction. McGrath ice occupied all of the higher cirques of the Black and the Craigieburn ranges, and a few small moraines in the highest basins of the Torless range mark the final glacial activity there.

Craigieburn range glaciers terminated close behind the ultimate Pleistocene ice limits, but the McGrath deposits, being on higher gradients, have commonly suffered considerable modification by erosion and slope processes.

(b) Deposits: The McGrath deposits normally exhibit two distinct advances within the study area. Where conditions have been favourable for deposition and survival, the initial advance consists of three to four major concentric moraines together with a number of smaller ridges, for example, Minchin River at tributary 5-15-10, (plate 26) and tributary 24B-6 to the Mingha River. Rind thickness studies made at Arthur's Pass do not demonstrate any age differences between two McGrath I advances and the single McGrath II advance.

McGrath moraines tend to be of a greater volume and to be comprised of coarser material, with larger surface boulders than those of subsequent advances, (plate 27). A number of exceptions does occur where fine material was deposited, for example, the McGrath moraines of tributary 17 near Mt Misery (figure 28) and Green Hill, tributary 5-10-5.

A number of McGrath stade outwash terraces is

PLATE 27

McGrath till exposed on the state highway near McGrath Stream.

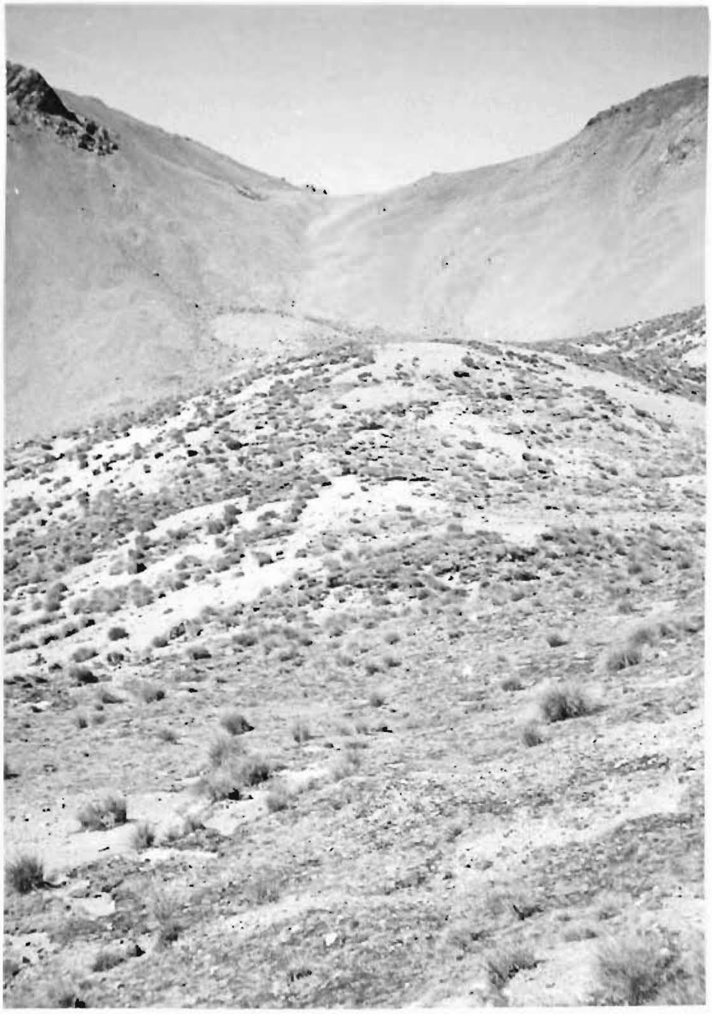


PLATE 28

Fine grained McGrath moraines near Mt Misery, in tributary 17.

to be seen, which in a number of cases may trace directly to their moraine source. A swampy outwash terrace extends downstream from the moraines at Carrington Hut, (tributary 38), and further downstream, above the alluvial fans of Harper Creek (36), and Greenlaw Creek (34), higher level terrace fragments are considered to be of McGrath age. On the right bank of Harper Creek, a beheaded and now dry streambed incised into bedrock, (mapped on figure 22), possibly originated as an ice margin stream. The position of this channel suggests that if Harper Creek ice did not actually reach the Waimakariri river bed, the terminal was very close to it. Outwash terrace fragments follow the Bealey River from the McGrath moraines downstream through the Arthur's Pass township to Rough Creek, where the terrace passes under the Rough Creek alluvial fan and landslide debris. Part of the extensive terrace development of the Poulter River may be attributable to this advance. An excellent exposure of the uppermost reaches of these terraces, at tributary 5-14, shows the sequence given with plate 7.

The surface of the alluvial fan has a gradient of 4° towards the Poulter River, while beds A, B and C dip downstream at a slightly steeper gradient than the 0.5° gradient of the present riverbed. Wood samples taken from beds A and C, for radiocarbon dating yielded the following ages:-

Bed A, No. S59/554	10,100 ± 200 yr BP. (New half-life).

Bed C, No. S59/559 4,110 ± 70 yr BP. (Secular correction applied).

The older basal river gravels must postdate the final Pleistocene glaciation and the next event most likely to have laid down some 6m of alluvium is the McGrath advance. The date for bed A should, therefore, date the commencement of the McGrath stade. The upper date, being so much more recent, apparently marks the commencement of the deposition of the fanglomerate beds. Further dates associated with McGrath advance are given in Appendix IV. Apart from the outwash deposits discussed above, few other fluvioglacial deposits were noted, and all were associated with main divide drainage or the higher peaks.

McGrath advance deposits are frequently associated with landslide deposits and, in addition to those of Mt Binser, (tributary 7), Hawdon River (13-5), and possibly Cherrywood Stream (5-12-5) moraines are also associated with landslide deposits in the Crow River, tributary 30. At this locality, McGrath moraines lie on the upper surface of a deep (some 160m) exposed landslide deposit, testifying to landslide activity prior to, as well as during, the McGrath stade.

(2) Arthur's Pass advance

A well-defined sequence of seven moraines extending across the summit of Arthur's Pass has been employed to name this stade. (Plates 29 and 30).

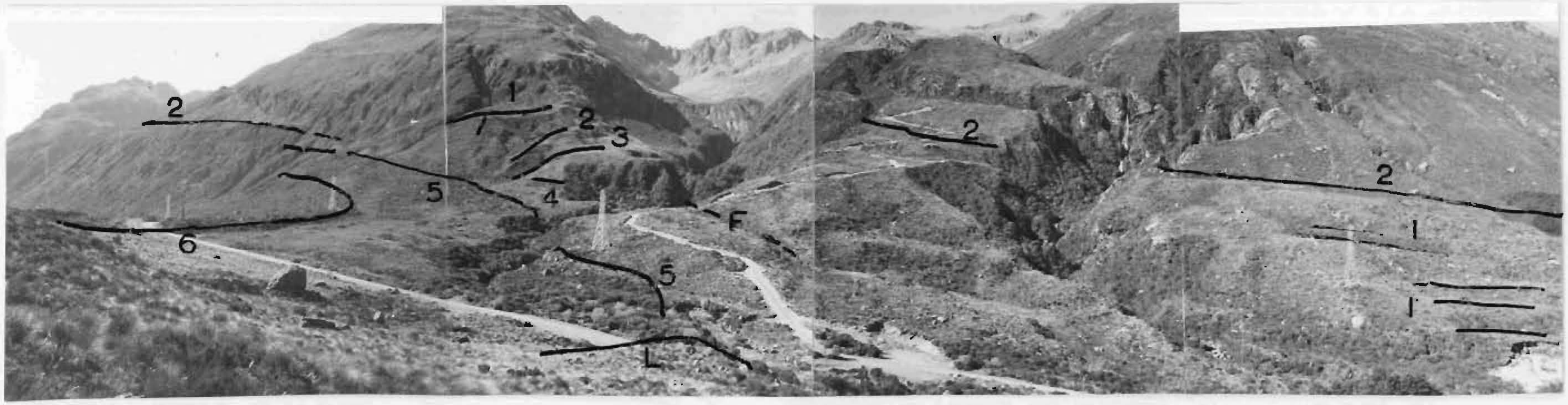


PLATE 29

Moraine sequences at the summit of Arthur's Pass

(1) Late Pleistocene ice-contact gravels.
(2)-(3) McGrath advance moraines.
(4) McGrath recessional moraine trace.
(5)-(6)-(7) Arthur's Pass advance moraines, (continued on plate 30).
F Fault
I McGrath ice-recessional terraces
L Landslide deposit

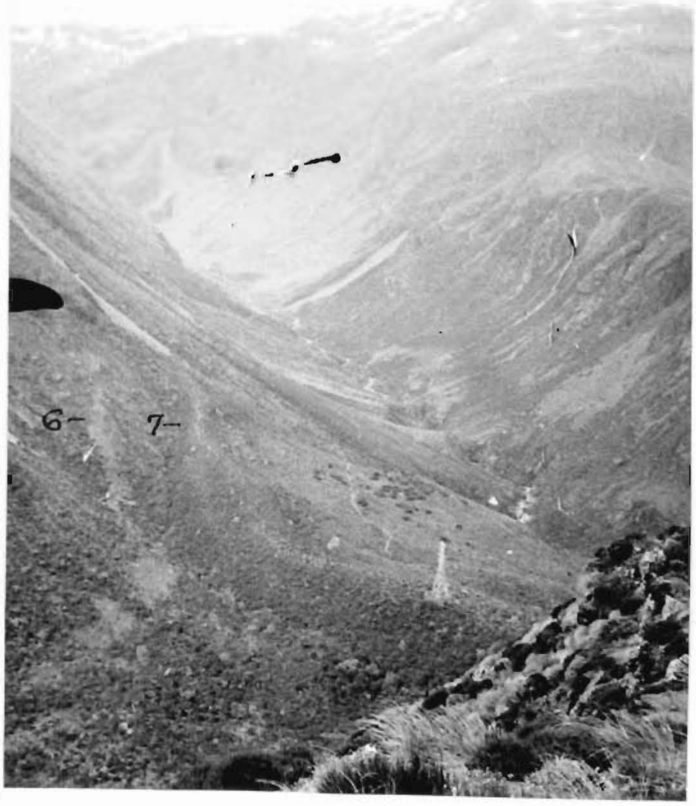


PLATE 30

Upper Otira River, Arthur's Pass moraine sequence continued from plate 29.

PLATE 31

Arthur's Pass advance moraines at 1600m above tributary 15, in a setting typical for the moraines of this advance.

The status of this type area for Arthur's Pass advance has not been fully resolved because of conflicting estimates of the age of the deposits. On the results of weathering rind studies (Appendix I), the exceptionally well-displayed moraine sequence of this area showed a good age correlation with other Arthur's Pass advances and a significant age difference from the nearby McGrath moraines.

A study of peat bog cores from the summit of the Pass made by Dr M. Kelley, however, has yielded a radiocarbon age of 9860 ± 140 years BP. for the deepest peat sample. This age is closer to that of the McGrath stade than the Arthur's Pass stade. Possible explanations for this anomaly include:-

(i) The peat bog was not fully excavated during Arthur's Pass advance. This is unlikely, as no definite hiatus was seen in the core samples. However Karlen (1973), has shown from Baffin Island that overriden moraines may survive the erosive effects of a subsequent advance.

(ii) That the carbon 14 age is incorrect.

(iii) That the weathering rinds can give misleading ages.

Nonetheless, since the weathering rind studies have demonstrated a consistent systematic variation of thickness with increasing age with few anomalies, and since this study is in part one of statistical weathering rind correlations, the use of Arthur's Pass as a type area will be retained in this study.

(a) Extent: The ice extent and number of advances of the Arthur's Pass stade are poorly-defined mainly because of the unique position occupied by these glaciers, plate 31. In the higher ranges, these glaciers tended to terminate in icefalls a little below the break in slope now marked by the fluvial dissection limit, while many of those glaciers occurring near the summits of the lower ranges have had their deposits buried by scree activity. Arthur's Pass deposits may be traced down the Black Range as small cirque glaciers and onto the Craigieburn Range where, with the fall-off in precipitation, the stade was represented by a series of rock glaciers.

Evidently, the Torlesse Range did not intercept the Arthur's Pass snowline, as no deposits of this stade are to be seen here.

(b) Deposits: The deposits of the Arthur's Pass advance are generally of smaller volume and of finer material than those of most other advances. (Plate 31). A possible explanation for the fine material could be that this glaciation was initiated on surfaces covered by scree and slope deposits resulting from a previous warmer erosion phase.

The moraine surfaces are typically subdued, with a loess and soil cover supporting vegetation. No outwash terrace deposits are known.

(3) O'Malley advance

A sequence of three distinct and well-preserved cirque moraines on the south-eastern Mt O'Malley, tributary 24A-4, near Arthur's Pass (plate 32),

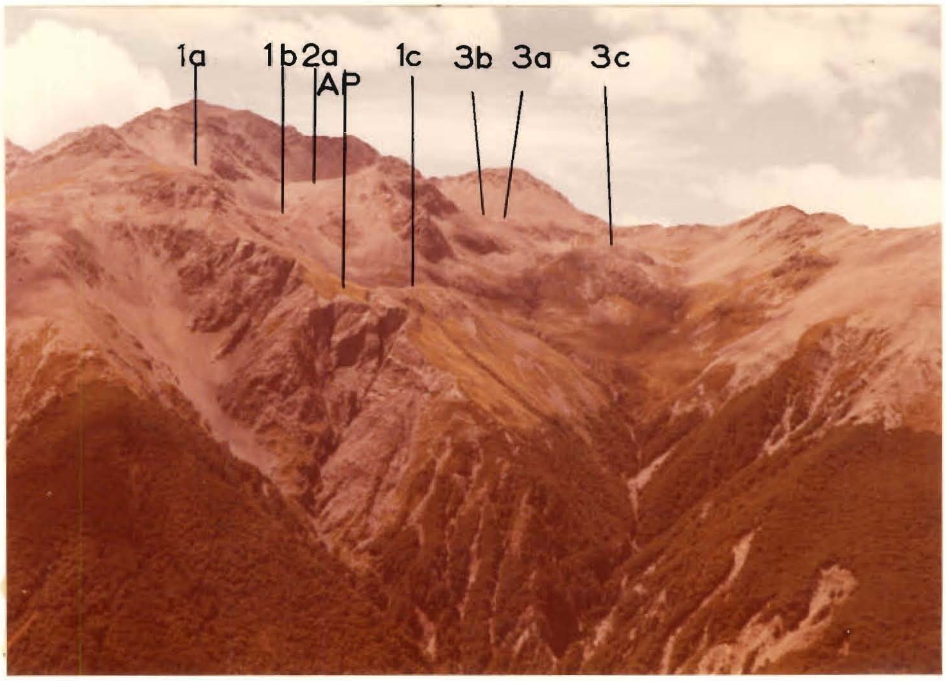


PLATE 32

Mt O'Malley (1690m) from Mt Bealey
showing the O'Malley moraine sequence.

1,2,3 - Separate cirque basins.

a,b,c - Moraine sequence, a, youngest to b, oldest.

AP. - Arthur's Pass moraine.

have been used to name this advance. The details of the relationship between this advance and the following Barker advance have been available from deposits above Greenlaw Creek, (plates 35 and 43).

(a) Extent: O'Malley deposits are frequently poorly preserved because these small glaciers, which had a discordant relationship with their cirques, either spilled till over the cirque lips or left moraines sufficiently close to the headwalls that they have been buried by scree slopes. None of the glaciers extended to the valley floors, yet evidence of these cirque glaciers may be traced north-eastwards along the divide ranges to the headwaters of the Poulter River, and eastwards along the Black Range to the Cass River tributaries. Only the highest peaks of the Craigieburn Range carried O'Malley glaciers, and small moraines are to be found on Mts Cloudesley and Enys.

(b) Deposits: Weathering rind studies show that the O'Malley stade persisted over a comparatively long period of time, figure 12, but produced few large moraines. The deposits are more frequently in the form of small concentric ridges receding back to pass under the subsequent Barker moraines. The youngest O'Malley deposits were not seen, as the initial Barker advance over-ran the O'Malley deposits to greater or lesser degrees.

A great variation of surface appearance is characteristic of the moraines, where the older ridges, normally of finer material, support a full

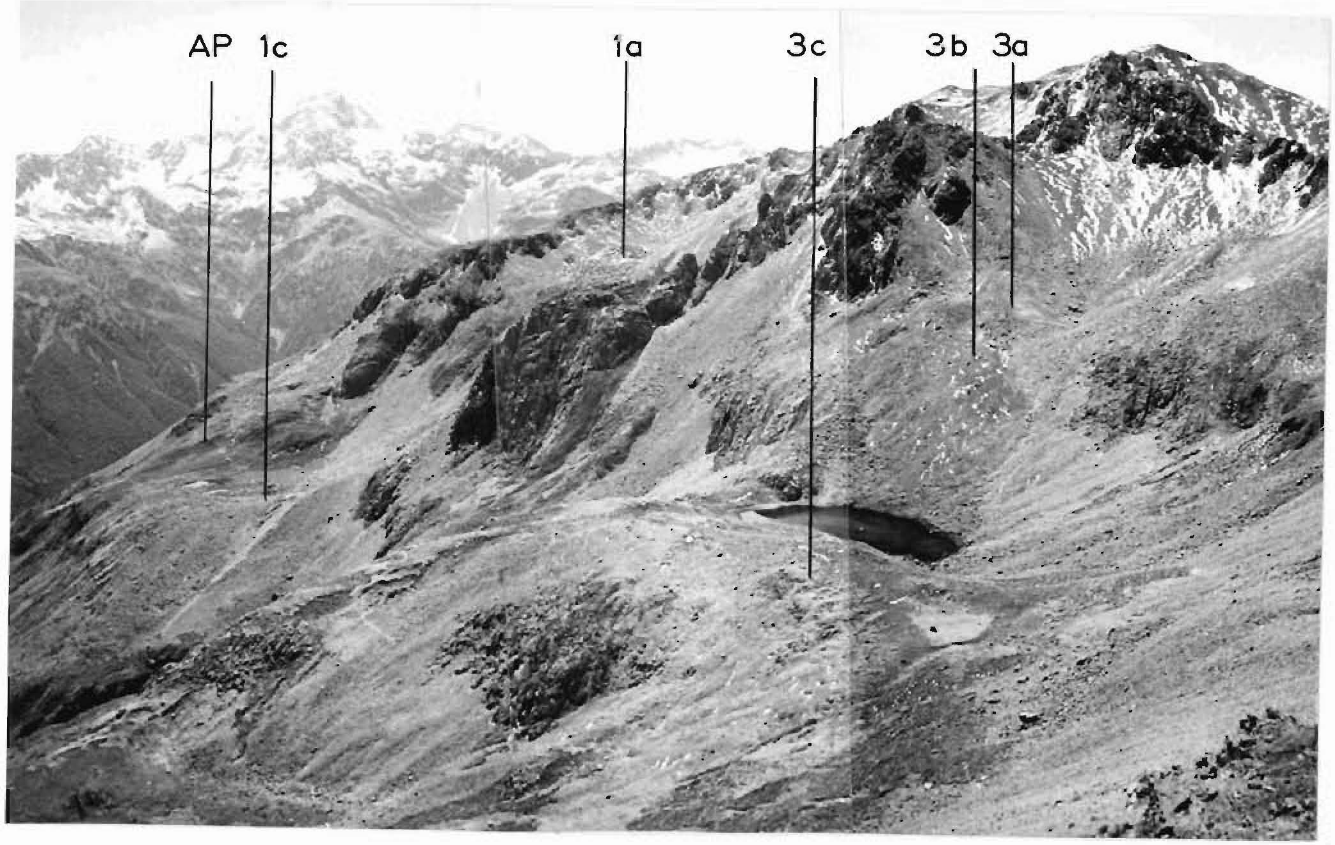


PLATE 33

View across moraines on Mt O'Malley, showing the sequence as distinguished by weathering rind thicknesses: a, youngest, to c, oldest moraines. 1,2,3, separate cirques. AP, Arthur's Pass moraine. Mt Rolleston (2271m) in background. Compare with plate 32.

cover of soil and vegetation. This cover becomes progressively sparser on the younger, more blocky moraines, so that the youngest moraines seen support a sparse vegetation cover, or none at all.

(4) Barker advance

The name is derived from the massive, sharp-crested moraine sequence well-displayed near Barker Hut on Mt Murchison, (see frontispiece).

(a) Extent: This, the most recent stade, began shortly after the final O'Malley phase and continued to the present day. The numerous large and small variations within this advance, occurring both within New Zealand and in overseas correlatives, have received much attention from many authors. Some of the more recent New Zealand studies include those of Lawrence and Lawrence (1965), McGregor (1967), Burrows (1973) and Wardle (1973). Although up to 7 or 8 separate moraine ridges of this advance may be counted near Barker Hut, (plate 34), a detailed subdivision of this stade was not undertaken in this study. The reasons for this are, partly, because the extreme range of the snowline elevation changes over this period is available without the additional work involved, in subdividing the stade; and partly because detailed subdivisions have been studied by other authors. Wherever reasonably complete Barker moraine sequences have been encountered, three significantly larger moraines are normally apparent, indicating three main advances for this stade.

PLATE 34

View down White River showing fresh, sharp crested Barker moraines. B, Barker Hut. (See frontispiece).

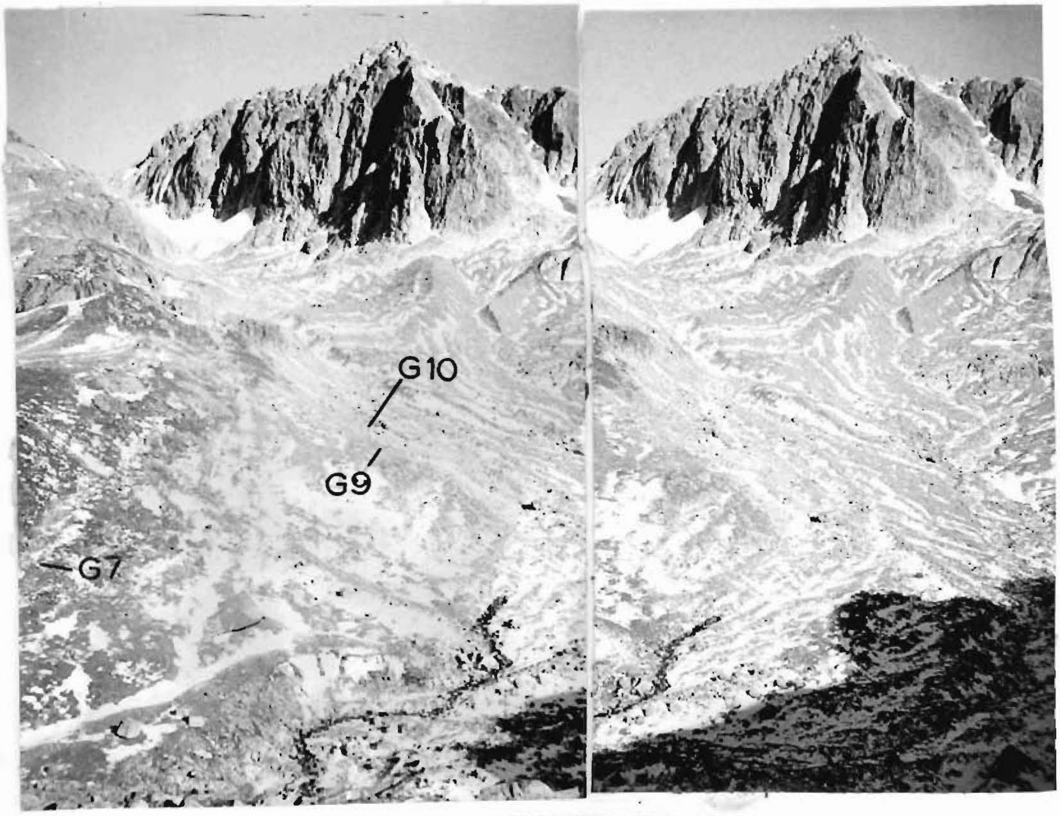


PLATE 35

Stereographic pair of moraines below Mt Speight (2120m), in tributary 34-1, showing relationship between O'Malley and Barker deposits. G7 to G9, O'Malley moraines. G10 and younger, Barker moraines. Compare with plate 43 and figure 35.

All of the Barker glaciers were restricted to the smaller cirque type, the snowline not being depressed sufficiently to generate valley glaciers. These glaciers had a continuous distribution around the peaks of the Waimakariri headwaters, but elsewhere their distribution was discontinuous. North-eastwards of Section I, (figure 22), isolated Barker glaciers were generated on the higher peaks of the majority of the ranges adjacent to the main divide, extending to isolated occurrences of early Barker glaciers in the upper feeders to the Poulter River. The Barker snowline passed above the peaks of the eastern Black Range and the Craigieburn and Torlesse ranges.

(b) Deposits: The Barker deposits are characteristically large, fresh moraines, frequently in the form of sharp-crested ridges. The steep topography has led to the occurrence of "spilled tills" throughout the sequence, (plate 36), although the youngest moraines are commonly well-preserved, where they either enclose existing glaciers or are developed well within the cirques and have yet to be buried by talus development, (plate 35).

The surfaces show a useful range of weathering development, depending upon age and size of material. Where coarse boulders are not prevalent, the oldest moraines support some soils and sparse vegetation cover, while those surfaces of the middle of the stade are characterised by a strong pink oxidation cast of the boulders, seen to be up to 0.5mm in depth during weathering rind studies. The youngest surfaces

"Spilled till" and poorly defined Barker moraines at the head of the Crow River, tributary 30.

1,2,3	Sequence of three main moraines.
R	Mt Rolleston, 2271m.
C	Crow Glacier.
L	Landslide or "protalus" debris obscuring moraine and scree.

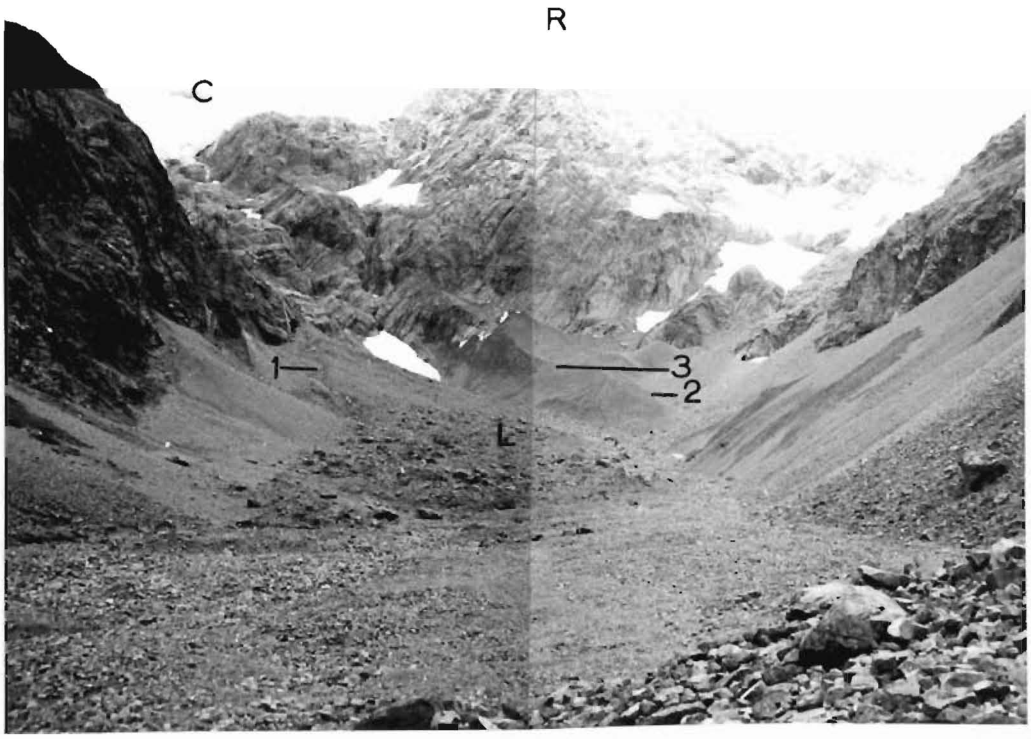


PLATE 36

appear light pink to grey. These three surface types provide a useful estimate of age as they commonly correlate with the three main advances observed. Since lichenometric separation of the various advances was not undertaken, and because weathering rind thicknesses do not have sufficient sensitivity to differentiate between moraines of this age, surface appearance was employed to give rough estimates of age for the main advances. From comparisons with lichenometric dates from the moraines of the Cameron Valley (Burrows pers. comm.) and recent moraine studies (Burrows 1973, Wardle 1973) the following ages are estimated for the main Barker advances:-

Earlier (sparsely vegetated) - 13th to 15th century.

Middle (strong pink cast) - mid 18th century.

Younger (light pink to grey) - AD. 1850 to 1890.

The youngest moraines normally form the most massive ridges, which are frequently sharp-crested, (frontispiece and plate 34). This form may indicate an ice core, but seepage or other evidence was seen to indicate buried ice. This type of ridge may be formed by collapse of the inner slopes following withdrawal of ice support, and may be maintained by stream erosion of the toe of the slopes. The size and volume of these moraines is surprising, considering that the Barker stade was of no exceptional duration. This phenomena is attributed to Barker ice overriding O'Malley deposits and incorporating this material to form massive Barker moraines. Examples of large moraine ridges formed by this process (indicated on figure 7) may be seen at Barker Hut (38-8), the Kilmarnock Glacier (38-3) and along the Jellicoe Ridge.

A cross-section of the lateral moraine beside the White glacier indicates the size of these moraines by the following heights above the glacier margin of the moraine ridges:

HEIGHT ABOVE WHITE GLACIER	MORAINE
10 m	Lowest enclosing moraine (grey).
18 m	Composite moraine, 4 ridges (grey).
58 m	Till-covered bedrock.
55 m	Small moraine ridges.
	Moraine ridge traces.
III 98 m	Sharp crest, largest ridge (grey-light pink).
II 92 m	Wider ridge (pink cast).
82 m	Moraine valley.
I 88 m	Rounded ridge (soils, sparse vegetation).
40 m	Older ridge, (O'Malley advance), overlain by above.

I, II, III main advances.

CHAPTER V

CONCLUSION .

I CORRELATION

(1) Pleistocene events

The three separate Pleistocene ice extensions recognised have been correlated directly with the three stages of the Otiran glaciation described by Gage (1958) for the Waimakariri:

Tims Stream - Poulter
Porter - Blackwater
Kowai - Otarama

These correlations have been made by comparison of the degree of modification and weathering of the moraines, and on position in the sequence. Although no deposits older than Kowai were positively identified, the possibility remains that some of the deposits mapped as belonging to the Kowai stade may be attributable to earlier episodes.

In a study of the terrace formations of Castle Hill Basin, Breed (1960), showed a correlation between these surfaces and the moraines and terraces of the main Waimakariri River. The Cheesman A surface (Blackwater) was traced back to the Porter moraines, but no moraines of a younger age were found to be associated with the younger Cheesman B and C surfaces.

Results of this study indicate that the

moraines of two distinct episodes do occur at the upper limits of these terraces, the younger Tims Stream moraines being superposed on the Porter moraines to a greater or lesser degree. The close association of these moraines, when compared with the 3km to 8km separation between the Blackwater and Poulter correlatives in the Waimakariri, may be understood if area ratios of the past glaciers are considered. The ratio of the total glacier area of the "Blackwater Glacier" to that of the "Poulter Glacier" for the Waimakariri River provides a figure similar to that obtained by taking the ratios between the areas of the Porter and Tims Stream glaciers, even though their respective moraines may show completely different degrees of separation.

Age differences between these multiple moraines are poorly defined, and this fact, combined with little vertical separation between their respective outwash streams, leads to an ambiguous relationship between the moraines and their respective outwash terraces. As a result of these findings, the following correlations with the Castle Hill Basin terraces are suggested:

Tims Stream (Poulter) - Cheesman C surface (Cheesman B degradational terrace)
Porter (Blackwater) - Cheesman A surface
Kowai (Otarama) - Enys surface

(2) Holocene advances

(a) New Zealand correlations: Correlations with other Holocene glacial resurgences described from New Zealand are somewhat indefinite for the earlier Neoglacial deposits, primarily because no one author has described a complete three-fold sequence similar to that described in this study. In addition, a scarcity of radiocarbon dates has led to the use of a number of different ageing methods. A correlation, based on the results of weathering rind studies, with some of the more comprehensive Holocene moraine studies made in this country is given in Table 4.

The McGrath advance shows a good correlation both in sequence and description with other early Holocene moraines, despite the ubiquitous absence of good ageing controls.

Some of the early-and mid-Neoglacial correlations, however, are less clear, such as the comparison with the Cameron Valley sequence. This correlation demonstrates the differences obtained when different ageing methods are employed. The author accompanied Dr Burrows on a field visit to the Cameron Valley, where a rind thickness study was made of the complete moraine sequence. (See Appendix I). The results of this study are compared here with the results obtained by Burrows employing lichenometric and soil profile dating.

TABLE 4

CORRELATION OF N.Z. HOLOCENE GLACIAL EVENTS

Weathering Rinds						
Thick-ness (mm)	Age yrs BP	This Study	Cameron Valley (Burrows)	Mt Cook (Burrows)	Westland (Wardle)	Ben Ohau (McGregor)
"None" to 0	0	BARKER III	ARROWSMITH 1930 to 1950	MT COOK 1930 to 1820	1930's to 1830's	Dun Fiunary
0 to 0.5		II	1750 to 1720	1790 to 1730	1790 to 1730	
0.5	550	I	1650 to Mid 14C	Late 17C to 13C	1690 to 1620	Jacks Stm?
1.0	800	O'MALLEY	Late 11C		(ii) over 2160 yr BP	Part Ferintosh ?
2-2.5	3000					
3.0	4000	ARTHUR'S PASS	Early 9C Early 7C	Several small moraines	(i) over 4730 yr BP	Part Ferintosh ?
			MARQUEE (ii)			
	5600		(i)			
			? LOCHABER	BIRCH HILL	WAIHO LOOP?	BIRCH HILL
5.0	8300	McGRATH II	WILDMAN II			II
6.0	11000	I	I			I

(b) Correlations abroad: Studies of the North American and European Holocene have generally shown a pattern of glacial activity similar to that found in this study, although the number and duration of cycles is not always clearly defined.

In many areas the maximum post-Pleistocene ice extent has been achieved by later Neoglacial ice advances, which have effectively obliterated traces of earlier cyclogenisis.

Early Holocene or late Pleistocene equivalents of the McGrath advance have been described for Baffin Island (Miller 1973), the Colorado Front Range (Benedict 1973), and the Sierra Nevada (Curry 1969). Denton and Porter (1970), Miller (1973), Benedict (1973) and others suggest the occurrence of a hysithermal interval at approximately 6000 yr BP., although Karlen (1973), on evidence from lichen ages, found a glacial advance during this period.

The warm interval accords with the time between the McGrath and Arthur's Pass advances of the Waimakariri, although no direct evidence for a warming was forthcoming during the field work.

A summary of worldwide Neoglaciation by Denton and Porter (1970), shows a three-fold resurgence with which this study shows good agreement.

Neoglacial studies from different localities have been summarised by Benedict (1973, P.597) and here again a 3-fold pattern is apparent. Equivalents of the Arthur's Pass stade are shown by Denton and Porter (1970), Benedict (1973) for the

Colorado Front Range and Taileffer (1973) for the European Alps. Possible correlations with the O'Malley stade are described as two advances from the Colorado Front Range by Benedict (1973), East St Elias Mts, by Denton and Karlen (1973) and from Baffin Island by Miller (1973), while a single O'Malley equivalent has been described from Mt Ranier by Crandell (1969), and from Europe by Taileffer (1973). Curry (1969), describes many distinct fluctuations within the broad O'Malley interval for the Sierra Nevada, a pattern which is remarkably similar to that found here in the Waimakariri watershed.

Correlations of the Barker advance have a worldwide distribution and, being the most recent, is the best-documented of the Holocene advances. In this study the short O'Malley-Barker interval has been established on a small but distinct change in weathering rind thicknesses. This minor recession is discernable on the figures of the comparison of glacial chronologies given by Benedict (1973), in close agreement with an age of 550 to 800 yr BP. found by weathering rind ageing of this study.

Most of the studies made outside of New Zealand are controlled by many more radiocarbon dates than are available in this country and the generally good agreement between the age and duration of the Holocene events of this study when compared with the Holocene glacial histories outside of New Zealand lends confidence in the validity of ageing by weathering rind thicknesses as applied in this study.

II CLIMATIC INTERPRETATION

By comparing past snowline surface elevations and configurations with the present snowlines and climate, inferences may be made about the past climates. Additional inferences concerning past climates are available also from the nature and extent of deposits and from erosional features. A summary of the present climate of the area is given in the introduction, Chapter I.

(1) Past snowline profiles

Although spatially uneven, the snowline surface profiles (figures 7 to 9) show both a strong upward trend towards the east and a consistent parallelism throughout the period of time encompassed by the study. Local divergences and convergences of successive snowline surfaces demonstrate the variable influences of topography on snowlines of different altitudes. The gradients of the incomplete snowline surface profiles of the Pleistocene episodes are generally followed reasonably closely by subsequent snowline gradients, suggesting that there has been little change in precipitation pattern and direction since that time.

By assuming that the present temperature lapse rates have applied from the end of the Pleistocene, it may be calculated how far below the present mean annual temperatures those of the period under study were depressed. The present mean annual temperature lapse rate in the vicinity of Arthur's Pass is difficult to estimate, but by interpolating from the values given by Coulter (1967), for Auckland, Christchurch and Invercargill, a value of 0.50°C/100m was assumed to be a good estimate. By using this value in conjunction with the past snowline surface depressions below the present snowline, the corresponding minimum temperature depressions have been calculated for each glacial advance. These values are given, together with snowline depressions in Table 5, below. Values obtained by Willett (1950), from cirque floor levels, and Porter (in press) for the Mt Cook and adjacent regions south of the study area are included for comparison:-

TABLE 5

SNOWLINE AND TEMPERATURE DEPRESSIONS
BELOW THE PRESENT

	Snowline Depression, (m)		Temperature Depression, (°C)	
	This Study	Porter	This Study	Willett
Present	0	0	0	0
Barker	-200	) -140	-1.0	
O'Malley	-300	)	-1.5	
Arthur's Pass	-400	)	-2.0	
McGrath	-480	-500	-2.4	
Tims Stream	-650	) -750	-3.3	) -6.0
Porter	-750	) -875	-3.8	)
Kowai	-970	) -1050	-4.7	)

(2) <u>Past snowline surfaces</u>

The two snowline surface isopleth maps (figures

10 and 11) show a consistent parallelism over a considerable range of elevations. The surfaces are far from evenly graded, having areas of strong depression and steps within the general upward gradient towards the east.

Along the main divide, snowline depressions tend to occur where summit elevations are low, or where broad low passes occur.

Where a mountain range creates a precipitation shadow, the maximum precipitation does not normally coincide with the range crest. Where the range is high, the "precipitation divide" is to be found on the upward side of the range and occurs [illegible] at an "optimum precipitation altitude". In case of a range being generally lower than this optimum altitude, the maximum precipitation may be expected to occur near the crest or towards the leeward side of the range.

It is postulated that, along the main divide bordering the study area, where broad passes or peak heights fall below this critical altitude, the high precipitation characteristic of the west coast is allowed to pass in varying degrees into the Canterbury side of the divide. This increase in precipitation depresses the snowline in those areas, while the shadow effect of the high ranges tends to elevate the snowlines there. This phonomenon is particularly well displayed near the headwaters of the Poulter River, where the effects of lower ranges, and the particularly low and broad Worsley Pass, allow depressed snowlines of the west coast to extend eastwards into Canterbury. The snowline isopleths indicate that peaks of this locality have been below the optimum precipitation elevation from at least McGrath times up to the present. The present precipitation pattern is reflected in a botanical survey of the Waimakariri where Burrows (Pers. comm.), found that a typical Westland alpine scrubland species Dracophyllum traversii has a distribution in this area which closely follows the isopleths of figures 10 and 11.

Presumably this effect had significance during at least late Pleistocene time, to account for the unusually large Poulter glacier which, during the Tims Stream (Poulter) advance, extended as far downstream as the Waimakariri ice, yet was fed from much lower ranges. There is little possibility that tectonic or isostatic movement has been responsible for this effect because of the comparatively short time interval since the Tims Stream advance.

(3) Climatic interpretation of past snowlines

Table 5 lists the minimum mean temperatures of climatic cycles from the late Pleistocene to the present day. estimated from the lowest past snowline elevations. Each successive minimum was less severe than the preceeding event, and no indications were found to suggest that any significant snowline depression has been exceeded by a preceeding cycle. leading to a glacial resurgence which overrode a previous ice limit. This phenomenon has been detected in a number of other Holocene glacial studies, for example, Karlen (1973), on Baffin Island.

The inferred rapid recession of Tims Stream ice suggests a relatively sudden temperature rise at the close of the Pleistocene Epoch, but the indications of stagnant ice persisting for many tens, or perhaps even hundreds, of years after the initial ice wasting indicates that the end of Pleistocene temperature rise, although abrupt, could not have been of any magnitude.

Throughout the Holocene, the snowline elevations of the glacial cycles show a uniformly gradual rise, revealing a continual rise in the minimum temperatures reached by climatic cycles over the past 10,000 years.

A recent warming, beginning about AD 1890, has initiated a snowline rise of 200m, which indicates a mean annual temperature rise of over 1°C during this relatively short period. Historic temperature records from well-established meteorological stations situated away from the Southern Alps confirm that there has been a small rise in mean annual temperatures over much of this period. Temperature records made within the alpine regions do not have sufficient length of record or reliability to confirm a temperature rise. Present rapidly ascending snowlines indicate that this trend towards warmer temperatures is continuing. Changes in precipitation pattern may be a second significant contributary factor to the ascent of the snowlines, but no such changes have been detected in the present climate as yet.

Dated Holocene wood samples (listed in Appendix III), have been identified by Dr B.J. Malloy as Nothofagus solandri, Coprosma sp. and Phyllocladus alpinus. These are all climatically tolerant species which occur at present near the sample locations, and therefore give little information about the past climates,

(3) Climatic interpretation of deposits

Extensive deep alluvial and colluvium deposits laid down between Tims Stream and McGrath times testify to ample runoff and possibly little protective vegetation cover. This time is interpreted as a cool wet period, when restabilisation of glaciated slopes to fluvial conditions was taking place.

The rock glaciers of the Craigieburn Range, active during Arthur's Pass time, suggest limited precipitation with sufficient frost activity to generate an ample supply of debris. To sustain the other glaciers of the Arthur's Pass advance under conditions of lowered precipitation a significant temperature depression could be invoked, which could conceivably have reached as low as the McGrath minimum. A drier cool period is therefore suggested to have prevailed during the Arthur's Pass stade.

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SECTION I UPPER WAIMAKARIRI
FEATURES

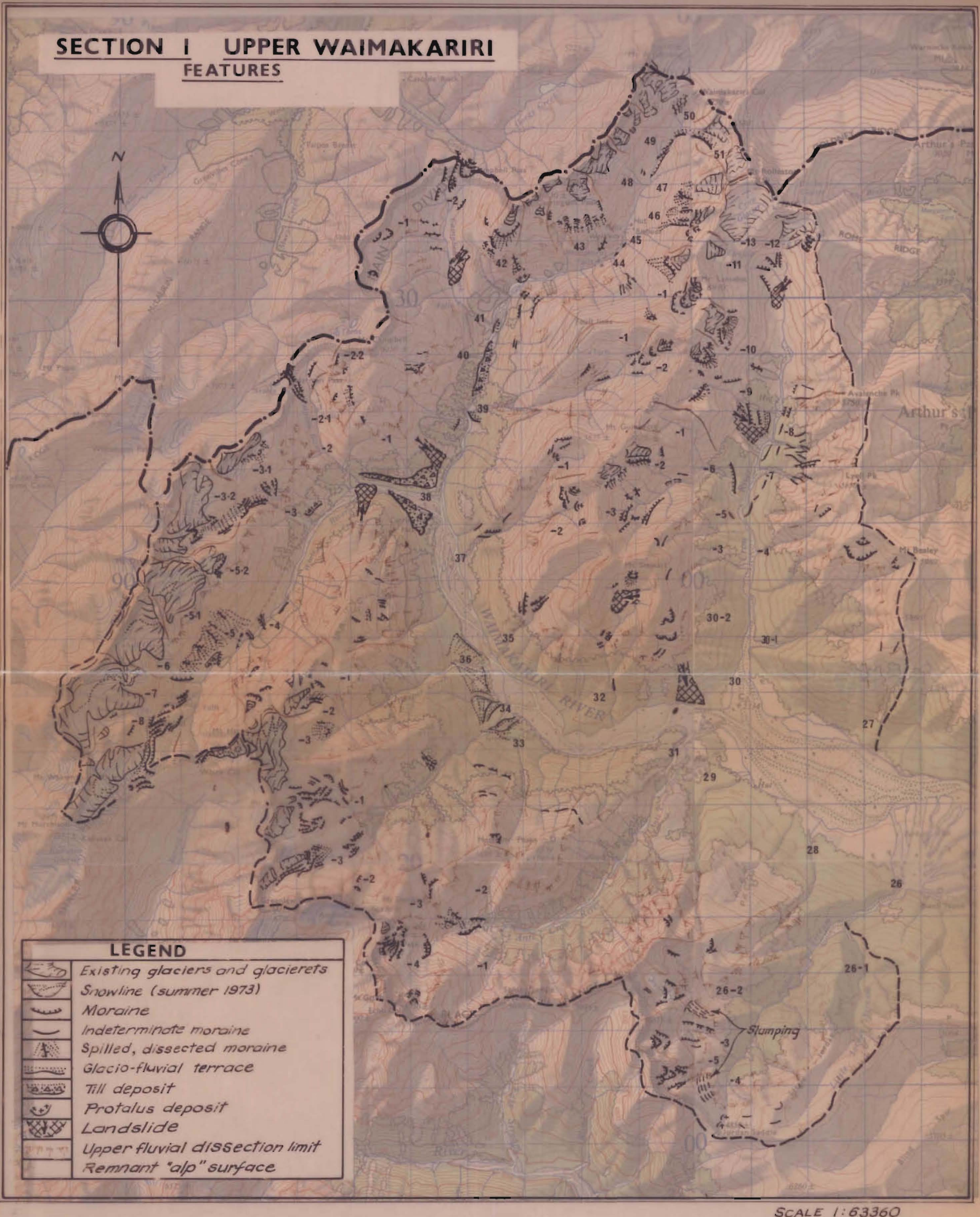

Fig.22

SCALE 1:63360

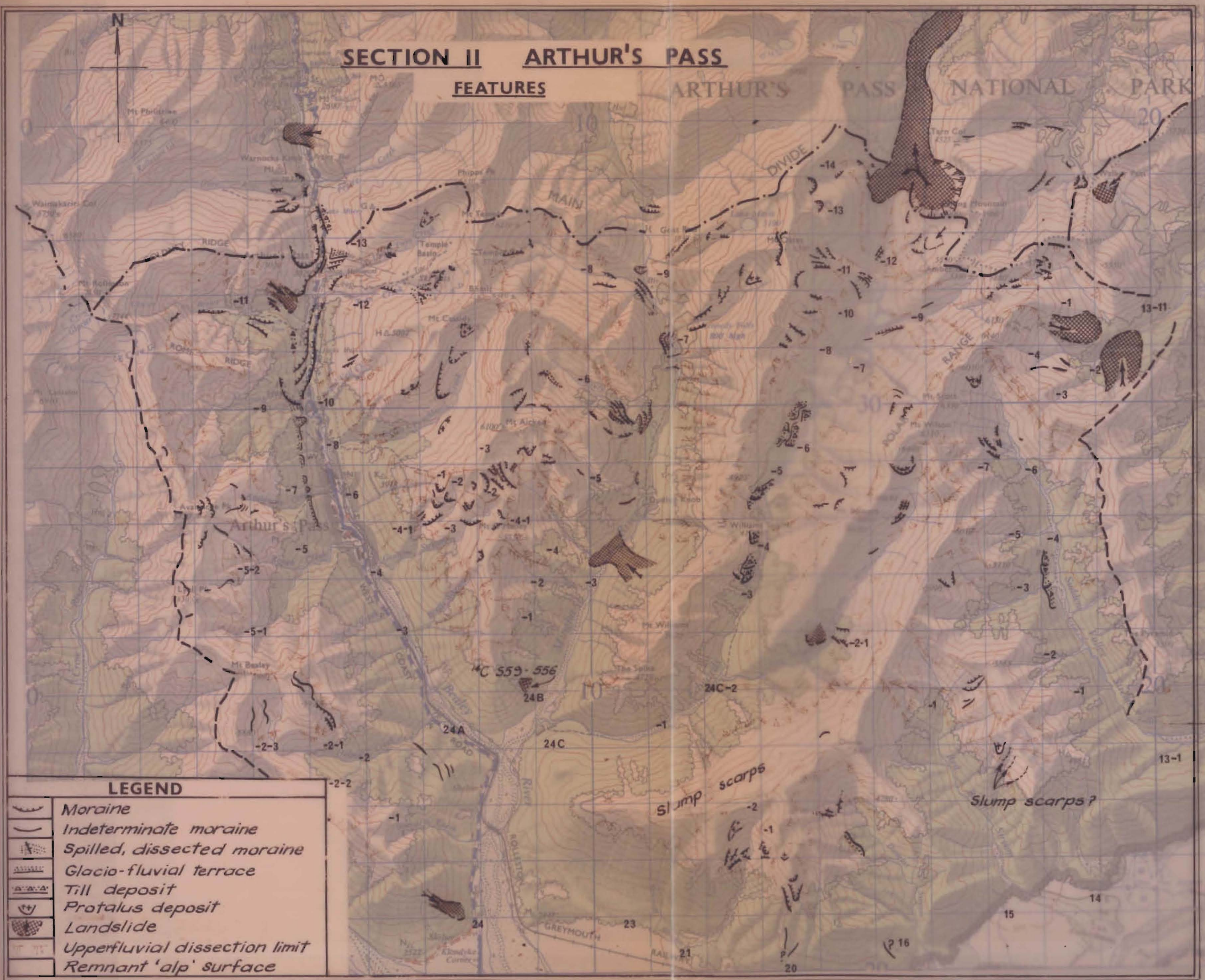

Fig. 23

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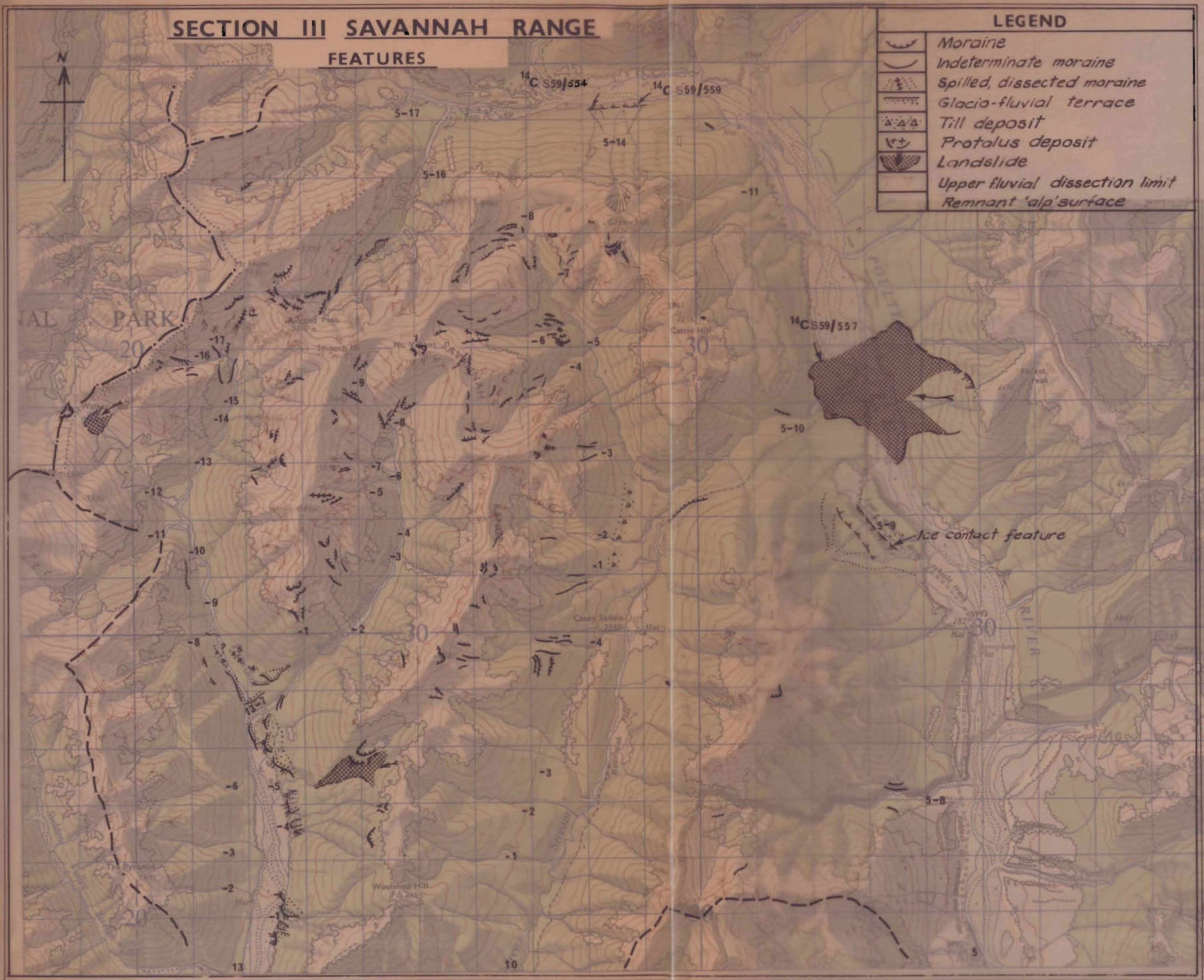

Fig. 24

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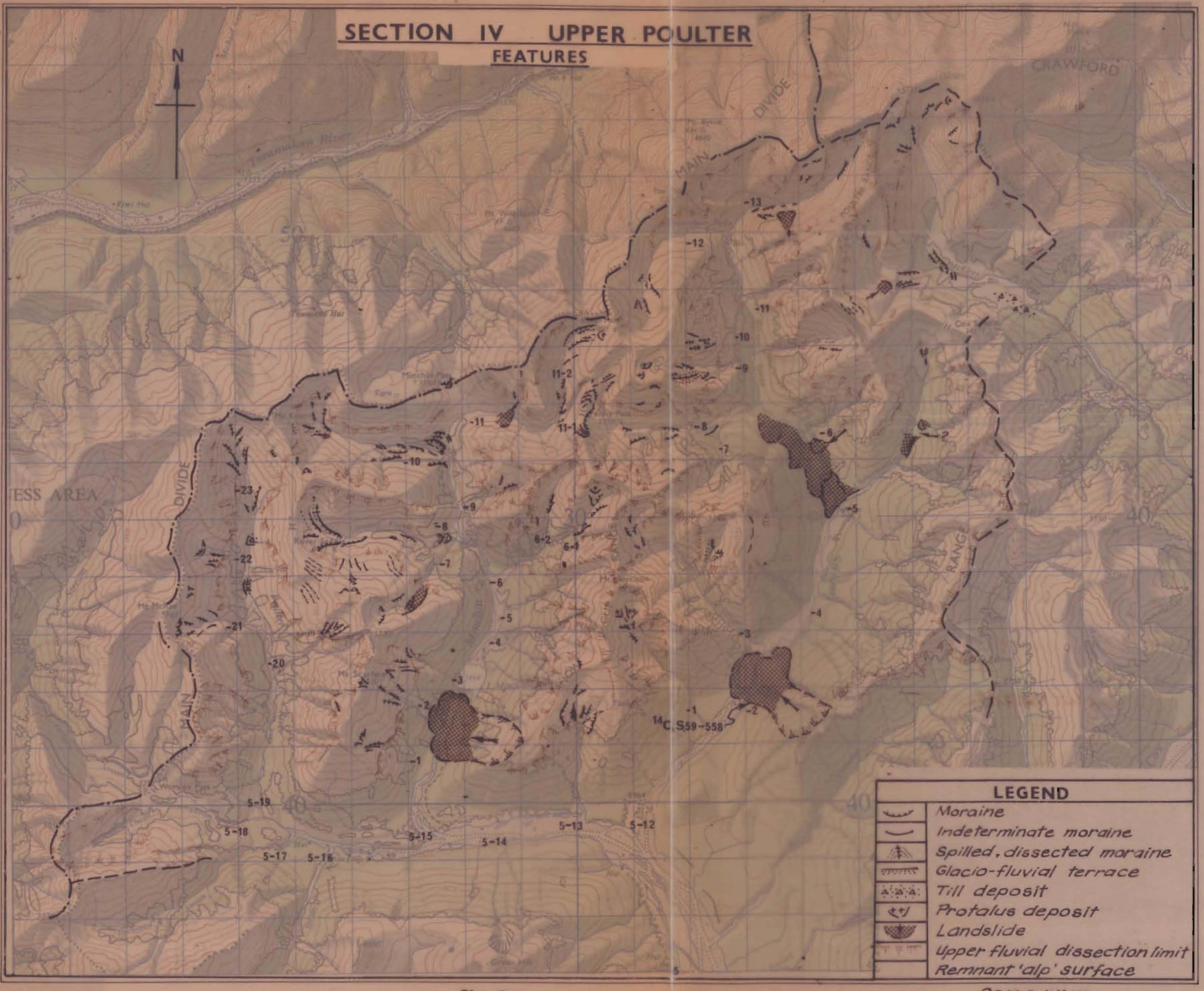

SECTION IV UPPER POULTER
FEATURES
N
Taramakau River
MAIN DIVIDE
CRAWFORD
DIVIDE
RANGE
MAIN
-23
-22
-21
-20
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
11-2
11-1
6-2
6-1
14C,S59-558
5-19
5-18
5-17
5-16
5-15
5-14
5-13
5-12
LEGEND
Moraine
Indeterminate moraine
Spilled, dissected moraine
Glacio-fluvial terrace
Till deposit
Protalus deposit
Landslide
Upper fluvial dissection limit
Remnant 'alp' surface
SCALE 1:63,360

Fig. 25

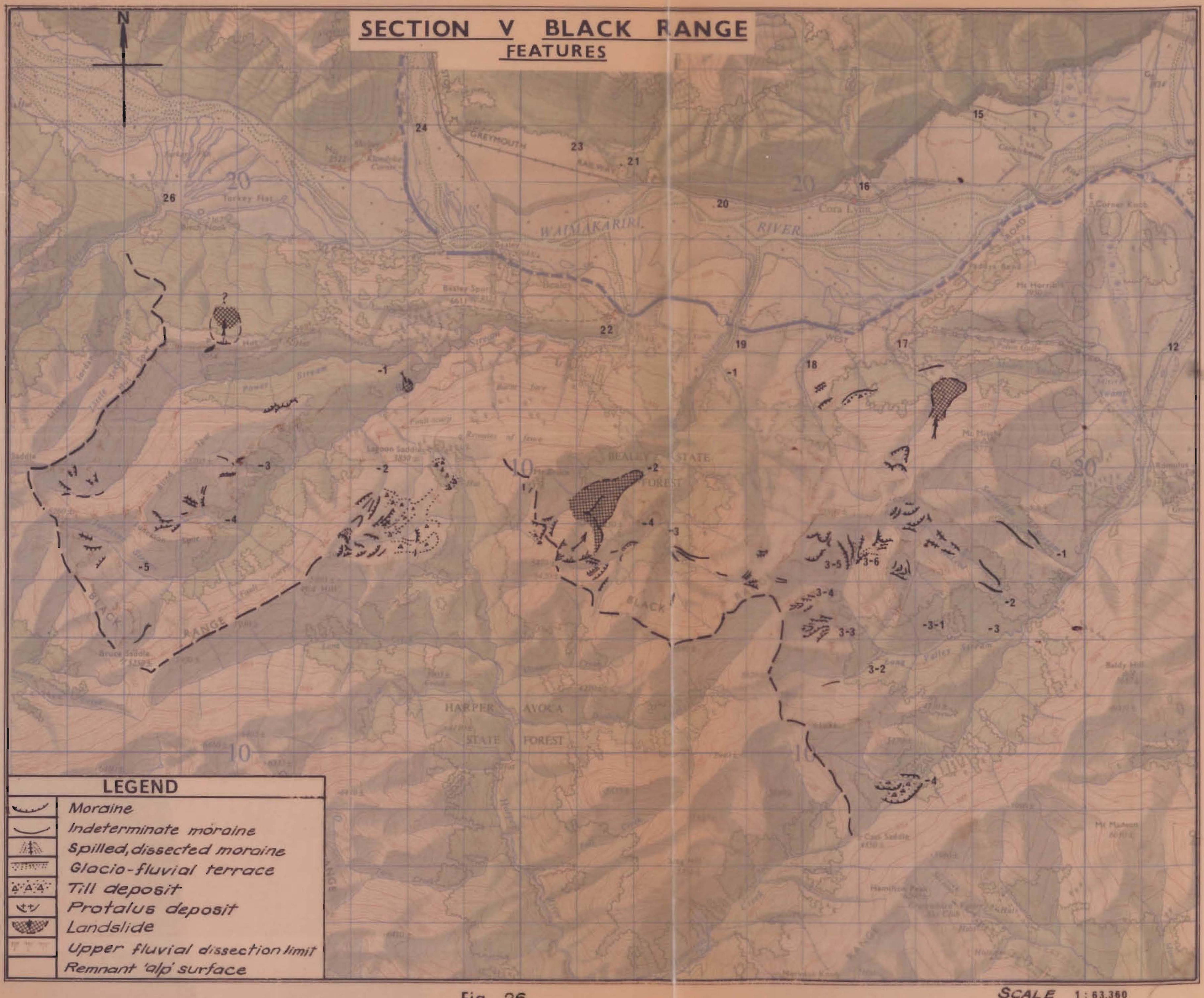


Fig. 26

SCALE 1 ; 63,360

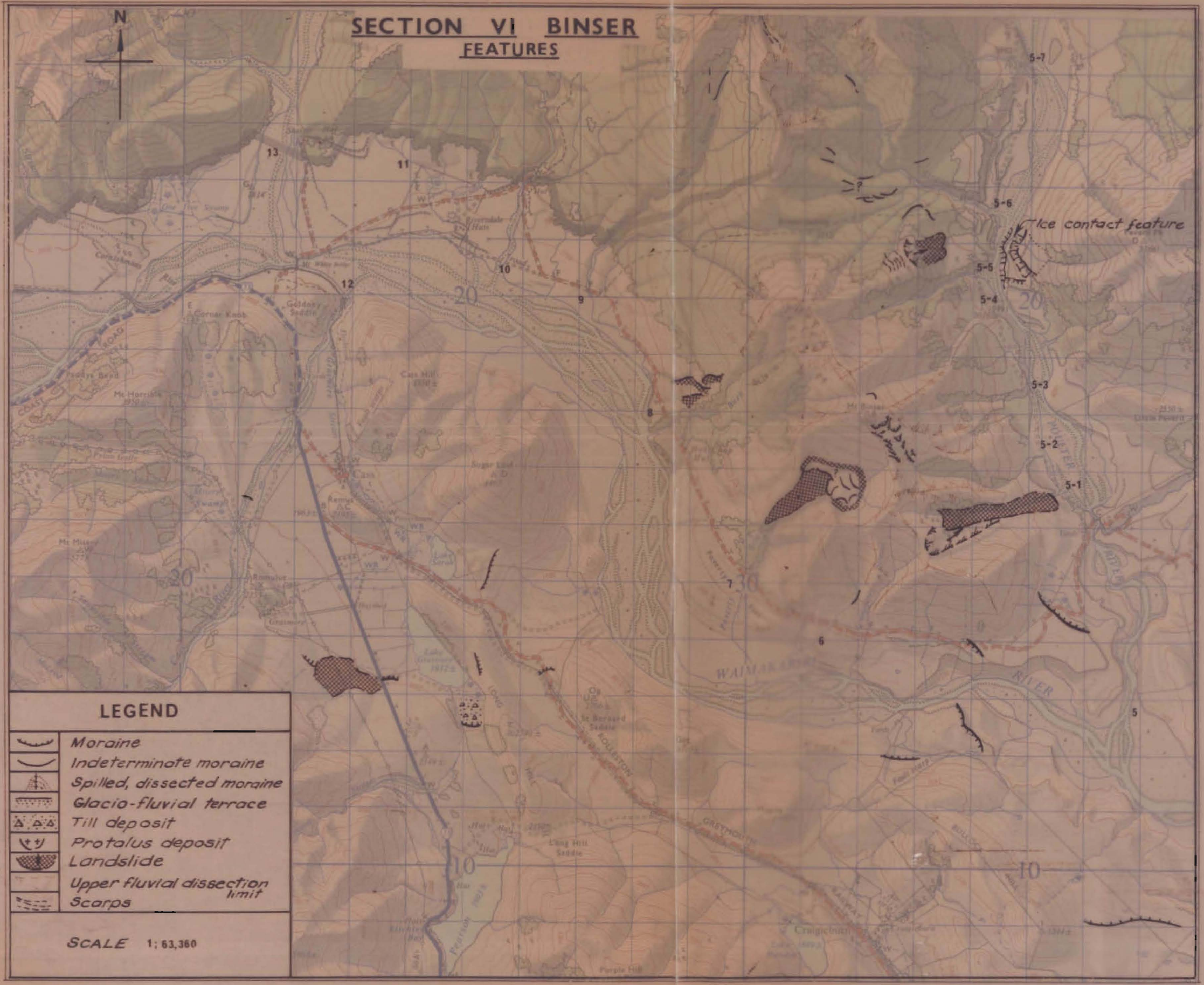

N
SECTION VI BINSER
FEATURES
Ice contact feature
5-7
5-6
5-5
5-4
5-3
5-2
5-1
5
13
11
12
10
9
8
7
6
?
20
30
10
Corner Knob
Goldney Saddle
Mt Horrible
Cass
Cass Hill
Mt Binser
Lake Sarah
Lake Grasmere
Lake Pearson
St Bernard Saddle
Long Hill Saddle
Craigieburn
Purple Hill
WAIMAKARIRI
RIVER
COAST ROAD
ROLLESTON
GREYMOUTH
RAILWAY
LEGEND
Moraine
Indeterminate moraine
Spilled, dissected moraine
Glacio-fluvial terrace
Till deposit
Protalus deposit
Landslide
Upper fluvial dissection limit
Scarps
SCALE 1; 63,360

Fig. 27

SCALE 1:63,360 Fig. 28

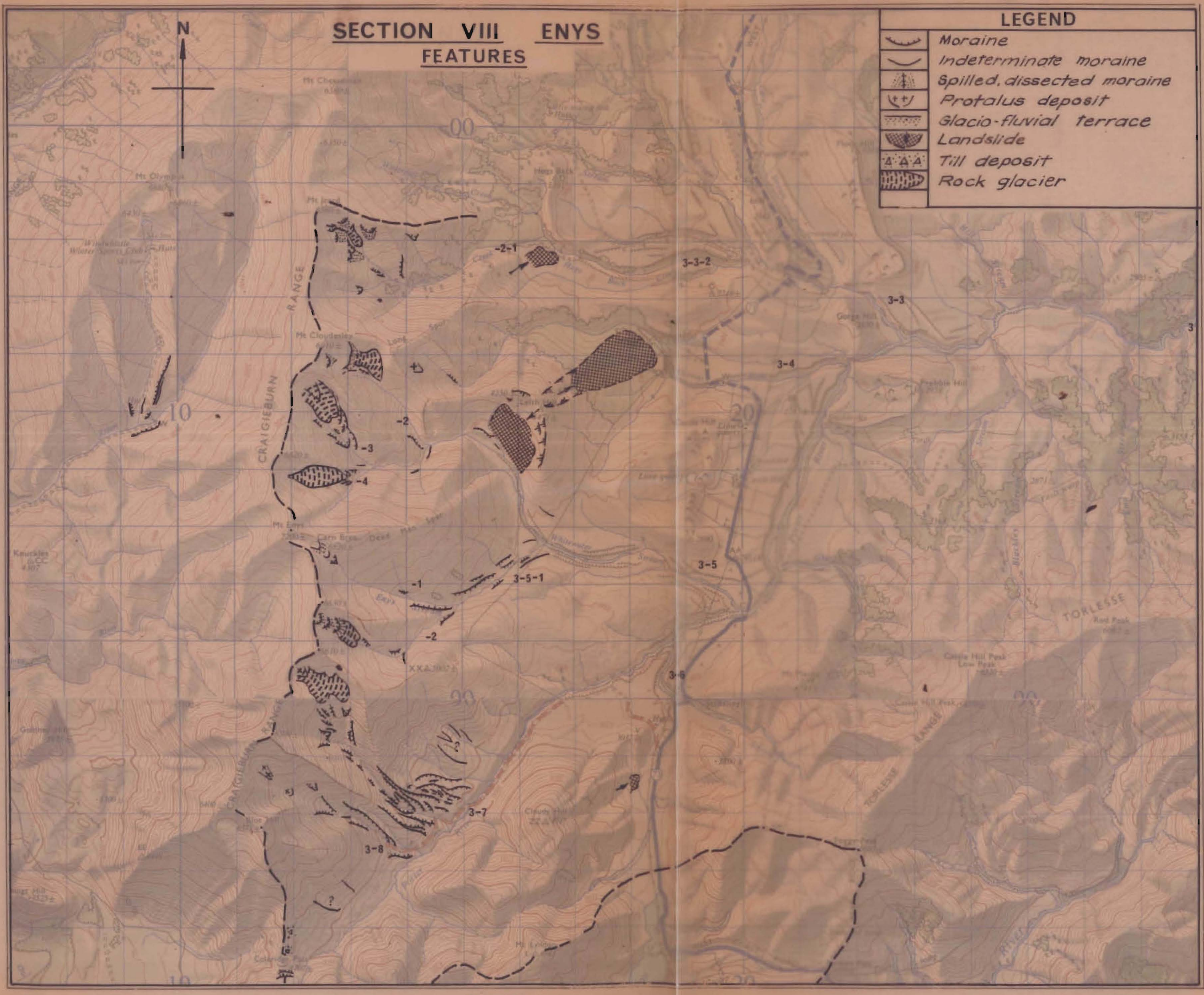


Fig. 29

SCALE 1:63,360

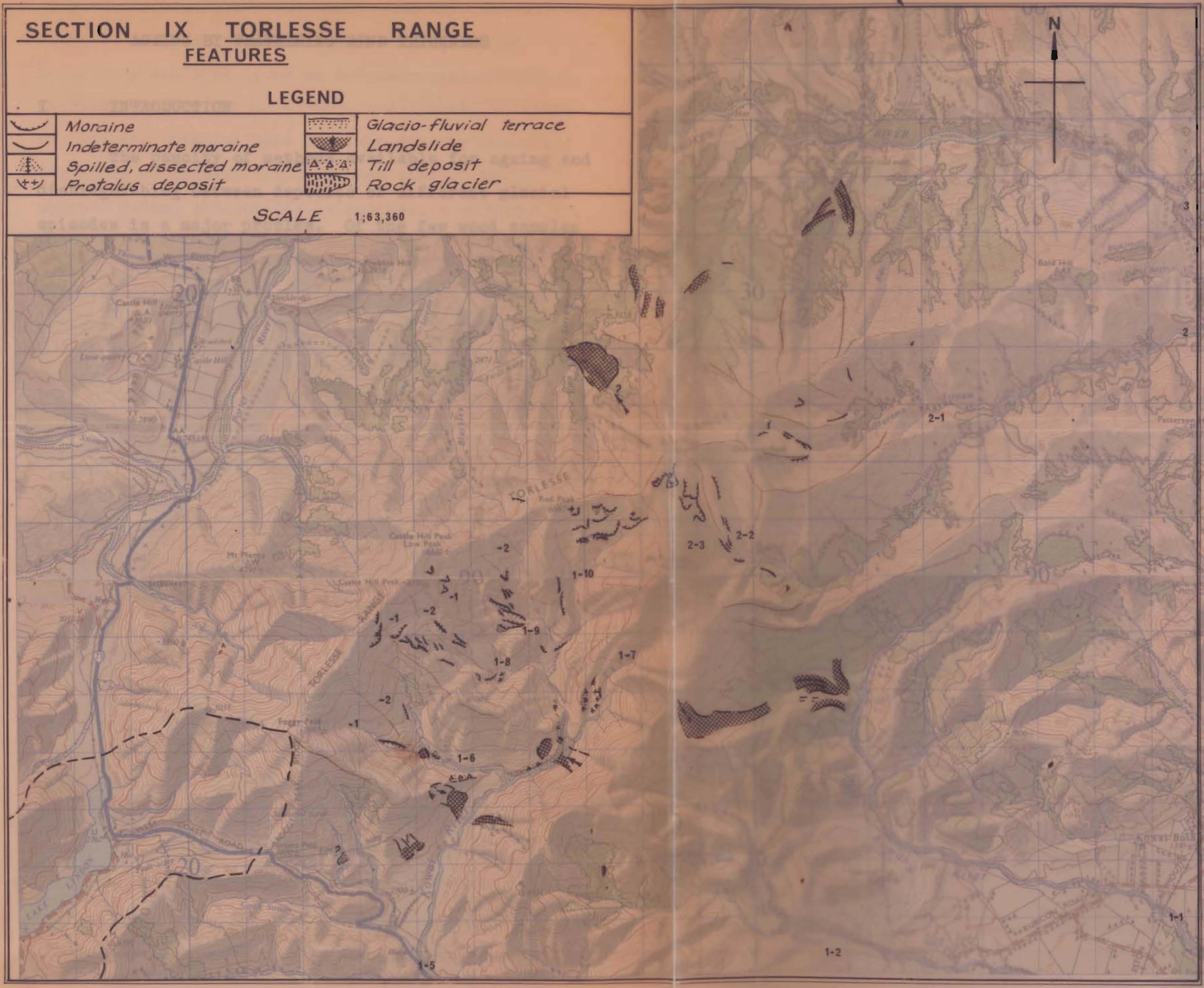

SECTION IX TORLESSE RANGE
FEATURES
LEGEND
Moraine
Indeterminate moraine
Spilled, dissected moraine
Protalus deposit
Glacio-fluvial terrace
Landslide
Till deposit
Rock glacier
SCALE 1;63,360
N
TORLESSE
TORLESSE RANGE
Castle Hill Peak
Castle Hill Peak Low Peak
Mt Plenty
Red Peak
Foggy Peak
Castle Hill
Lake Lyndon
Kowai River
Porter River
Bold Hill
Patterson
COAST ROAD
20
1-1
1-2
1-5
1-6
1-7
1-8
1-9
1-10
-1
-2
2
2-1
2-2
2-3
2
3

Fig. 30

APPENDIX I

AGEING BY WEATHERING RIND THICKNESS

I INTRODUCTION

The paucity of methods available for ageing and distinguishing between deposits of different glacial episodes is a major problem. Of the few wood samples found for radiocarbon dating none were directly associated with glacial deposits. Ageing by lichen diameters is feasible, but this method is accurate only over the past few hundreds of years and requires enough data to construct an age curve for each location. Comparison of the soil profiles provides a rough guide to relative ages, but is often inconclusive. Attempts to establish the relative ages of moraines by their degree of weathering, soil development, and the extent to which the forms have been subdued and dissected were generally unsatisfactory because of their differing aspects, elevations and slopes.

II DEVELOPMENT OF THE METHOD

Early in the field work it is noted that the older exposed boulders showed distinct weathering rinds, which appear to thicken systematically with the duration of exposure to the atmosphere. Recent moraines, deposited within the last 50-100 years have a grey surface appearance and with the commencement of rind development they appear pink, then lichen-and mosscovered, and finally, with the development of soil, they become vegetated. No studies of this subject are known to have been made in this country, and no references could be found on Holocene rind formation. Overseas work by Porter (1968), and others, in which Pleistocene advances were distinguished by measuring the rinds of basalt, i.e., moraine clasts, to the nearest 0.1mm, offered little assistance as they involved much greater time spans and much smaller rind thicknesses. The gradational inner boundaries of the rinds encountered in this study made this degree of accuracy quite impossible. However, because clasts of uniform lithology could be selected throughout the area, the method was tentatively pursued, and boulders from a greater part of the study area were cracked for rind measurements. Initial rind measurements from local deposit sequences showed a consistent increase in rind thickness with increasing age, but with wider sampling of the watershed, many apparent inconsistencies began to appear, and the method was set aside for a time. Finally, because of the lack of alternative ageing methods, statistical counts were made on a sequence of moraines in the Arthur's Pass area to establish whether or not the method was viable. It was found that, although variable in any one population, the rind thickness could give an indication of relative ages of moraines, provided that a sufficient number of samples was taken to construct an unambiguous histogram. The results of these and later rind counts are given in figures 31 to 39. It is believed that the deposits of all significant glacial advances that have occurred in the area since the Pleistocene have been sampled in these rind studies, although within the area widely separated localities had to be visited to gain this full coverage, as indicated in the correlation, table 6.

The availability of sandstones of uniform lithology over the whole of the study area is the key to the method. It allows correlations to be made over the whole area without the problems of changing rind formation rates due to differing lithology of surface boulders. Abundant associated finer grained siltstones were easily recognized and were not included in the measurements.

It is postulated that a particular combination of rock type and climate has produced relatively thick rinds, favouring both consistency in field measurements and sensitivity in applying the age - thickness relationships.

III DEFINITIONS

Statistical counts of rind thicknesses made in the Arthur's Pass area showed that to establish a monomodal relationship in histogram plots, a minimum of some 30 to 40 samples was required from each moraine. These samples were taken from traverses along the moraine, to reduce possible error from sampling a unique deposit, such as an accumulation of previously weathered material.

The weathering rinds tend to form concentric bands within the rock, whose relative thicknesses vary somewhat with differing lithologies and age:-

(1) An outer pink layer, under 1mm thick (and having a finite thickness which distinguishes it from superficial pink lichen), which is usually absent in the older rinds, grading into;

(2) A whitish band, which usually grades without any definite boundary into;

(3) An inner dark band, only sometimes present, especially in the coarser grained rocks. This layer has a sharp boundary with the unaltered rock, but because of its great variability in thickness this layer was ignored in the measurements.

The rind thickness measurements may be subject to considerable personal interpretation, making it desirable to establish a standard from which measurements may be repeated. To this end a set of photographs of selected rinds have been marked to show "measured rind thickness", and are given in plates 37 to 42.

The "rind thickness" employed in this study is defined as; "the thickness from the boulder surface to the inner limit of discernable discolouration of the whitish band". It was considered beyond the scope of this thesis to attempt a full petrographic or mineralogic study of the rinds.

IV RIND THICKNESS VARIATIONS

Rind thicknesses vary in response to other influences besides time. Together with the increase of rind thickness with increasing age, there is also an increase in the range of thicknesses, so that at late Pleistocene age this spread, coupled with other variations, is sufficient to mask the true value of the age mode. Other important factors influencing the rate of rind formation were found to be:-

(1) Petrographic

(a) Degree of induration: Rinds are obviously thicker in less indurated and possibly more porous boulders in the same deposit, while boulders of higher metamorphic grade showed markedly thinner rinds, with irregularities induced by foliation. Degree of induration was found to be the most important single factor leading to variation in rind thickness.

(b) Grain size: Rind thicknesses show a direct increase with grain size, to the extent that rinds on sandstone boulders are up to twice the thickness of those on associated mudstone boulders.

(2) Position

(a) Height of boulder surfaces above soil surface: Significant rind thickening occurred at and near the soil surface, so that as far as possible all samples were taken from surfaces of larger boulders well above soil level.

(b) Proximity to edges and corners: Local thickening occurs at the corners of boulders. Rind measurements were always made to avoid this source of error.

(c) Surface attitude: Downward-facing surfaces of boulders showed noticeably reduced rind development.

(d) Aspect: No differences were detected between north and south facing boulder faces.

(e) Altitude: Rinds of the same age were expected to vary with altitude, but evidence of this variation is inconclusive. In figure 32, histogram No's A to D compared with histogram F, suggest a slightly slower development of rinds at higher altitudes.

(3) Local climatic differences

Rind thicknesses would be expected to vary with climatic conditions, but again no conclusive evidence was found to this effect, despite the relatively large differences in the climate over the study area. A comparison of the upper Waimakariri data with those from the lower precipitation area of the Cameron River suggests that, if climatic differences have any effect, it is masked by other variations.

V ADDITIONAL RIND MEASUREMENTS

Time did not allow for many statistical rind studies being done outside the Arthur's Pass area, so that it was necessary to assume that the relationships established in that area were applicable over the remainder of the watershed. Few good sequences of moraines exist in the area, therefore, to obtain additional sets of data for comparison and to assist in interpolation, considerable field work at a number of widely separated localities would be required. To avoid this and at the same time to provide a basis for correlation with glacial advances in other valley systems, an opportunity was taken to study the moraines of the Cameron Valley (some 55 km south of the Waimakariri catchment) with Dr C.J. Burrows. In this valley is preserved one of the most complete known post-Pleistocene moraine sequences. The observations from this area showed no significant disparity with those from Arthur's Pass (see figures 38 and 39), suggesting that correlation by rind thickness of Neoglacial deposits is valid within the Torlesse Group.

VI RESULTS

(1) Frequency histograms

Frequency histograms derived from the statistical rind counts are given in figures 31 to 39, while other small-population rind measurements were used to assist when ageing the deposit for figures 13 to 21.

The histogram frequency distributions would be expected to be skewed to the left, as each population would be expected to contain samples from fresher surfaces exposed by fracturing since deposition. A lesser tendency towards skewness to the right would result from lithologic variations and "contamination" by the inclusion of previously-weathered boulders in the deposits.

It was found, however, that shapes of the frequency distributions varied widely. The interpretation of the mode was difficult in some cases, but in others explanations can be found for bimodal and other unusual patterns.

(2) Accuracy

Most measurements were made accurate to the nearest 1.0mm, but on younger moraines, rinds were measured to the nearest 0.5mm, up to a thickness of 3.0mm. All rinds over 3mm thick were measured to the nearest 1.0mm, as the diffuse inner boundaries made it unreasonable to attempt a greater accuracy. Consequently, in a number of cases, there are two different class intervals (thickness intervals) for one population. To avoid erroneous plots, the upper classes were split where necessary, and shared between that class and the preceeding unmeasured class. This in no way interfered with the mode position, but as a statistically artificial result occurs, all class-splitting in the histograms is shown by a small arrow.

Many of the readings have a value of 0mm for rind thickness. This does not imply that there was no rind, but indicates a "pink moraine" surface discolouration, which may have penetrated the rock to less than 0.25mm, i.e., to half or less of the 0.5mm class interval. Where no rind formation has occurred, as on "grey moraines" this has been indicated by a rind thickness of "none".

(3) The growth curve

A linear rate of growth of the rinds would not be expected as, following an initial period of relatively rapid development, build-up of weathered products may tend to protect the underlying core, retarding further development. Fortunately a number of radiocarbon dates is available to construct a weathering rind growth curve. These controls come from wood samples found incorporated in landslides which have surfaces suitable for rind sampling. Of these four control points only one, the Casey River landslide, is within the study area; the Lyndon (or Acheron), is just outside the area, while the remaining dates come from the Cameron River.

The growth curve, figure 40, was constructed from the above four dates, with a lower control of 10,000 years BP., given to the McGrath advance. This date is as close as can be estimated at present, being based on sample S73/549 from a colluvium-buried forest soil overlying the Wildman II moraine of the Cameron River, which has been radiocarbon dated at 9520±95 years BP. (Burrows, pers comm.) and sample S59/554 from the base of an assumed McGrath age outwash terrace in the Poulter River, dated at 10,100±200 years BP. Slight errors in this end of the curve will have a negligible effect on the accuracy of the dates of the younger Neoglacial deposits.

The lower end of the curve is fixed by modern deposits which show no rind formation.

Superficial comparisons were made between this curve and ageing curves obtained from lichenometric dating by Burrows (1971). The lichen ages for the younger deposits give a much greater accuracy than do the rinds. Rind dating becomes superior to lichen dating beyond the beginning of the late Neoglacial advances when lichen diameters become unreliable. Lichenometric dating was not attempted in this study because, (a) there is very little evidence upon which to construct a lichen-growth curve for the Waimakariri, and, (b) it was not intended in this study to subdivide the numerous late Neoglacial advances.

VII CONCLUSION

In the rind thickness data from the Torlesse Group boulders, the greatest sources of variation appear to be from changes in degree of induration, and differing grain size. The sensitivity of the method is low by comparison with lichen ageing, but from the results of work in the Cameron Valley it appears to be superior to studies of surface morphology and soil profiles. The rind thickness method appears to have adequate time resolution to allow distinction to be made between the main Neoglacial advances, and to separate events younger than Pleistocene, to within approximately 10% of their age.

The rind thickness method of dating glacial deposits, therefore, appears to be a useful if coarse tool, which should be tested further.

TABLE 6

CORRELATION OF MORAINES ON RIND THICKNESS MODES

Rind Thickness Mode (mm)	Arthur's Pass Area	Mt O'Malley	Greenlaw Creek	Cameron Valley	Glacial Advance
"None"	All grey fresh moraines				BARKER
0 - 0.5			G10		
0.5		V		n,o,p	
1.0		S,T,U,W	G2,G8,G9		O'MALLEY
1.5			G5,G7		
2.0		O,P,Q,R	G3,G4,G6		
2.5		O[1]		m[2]	
3.0	H,I,J,K,N		G1	b,c,d,e,f,g,h,i,j,k,l	ARTHUR'S PASS
4.0	G[3], L[4], M[5]				
5.0	A,C,D,E,F				McGRATH
6.0	B			a	
7.0	No samples of this mode found.				

(1) Moraine O, the oldest of the O'Malley moraines which may thus include a comparatively higher proportion of previously-weathered boulders, indicating an age greater than the true age.

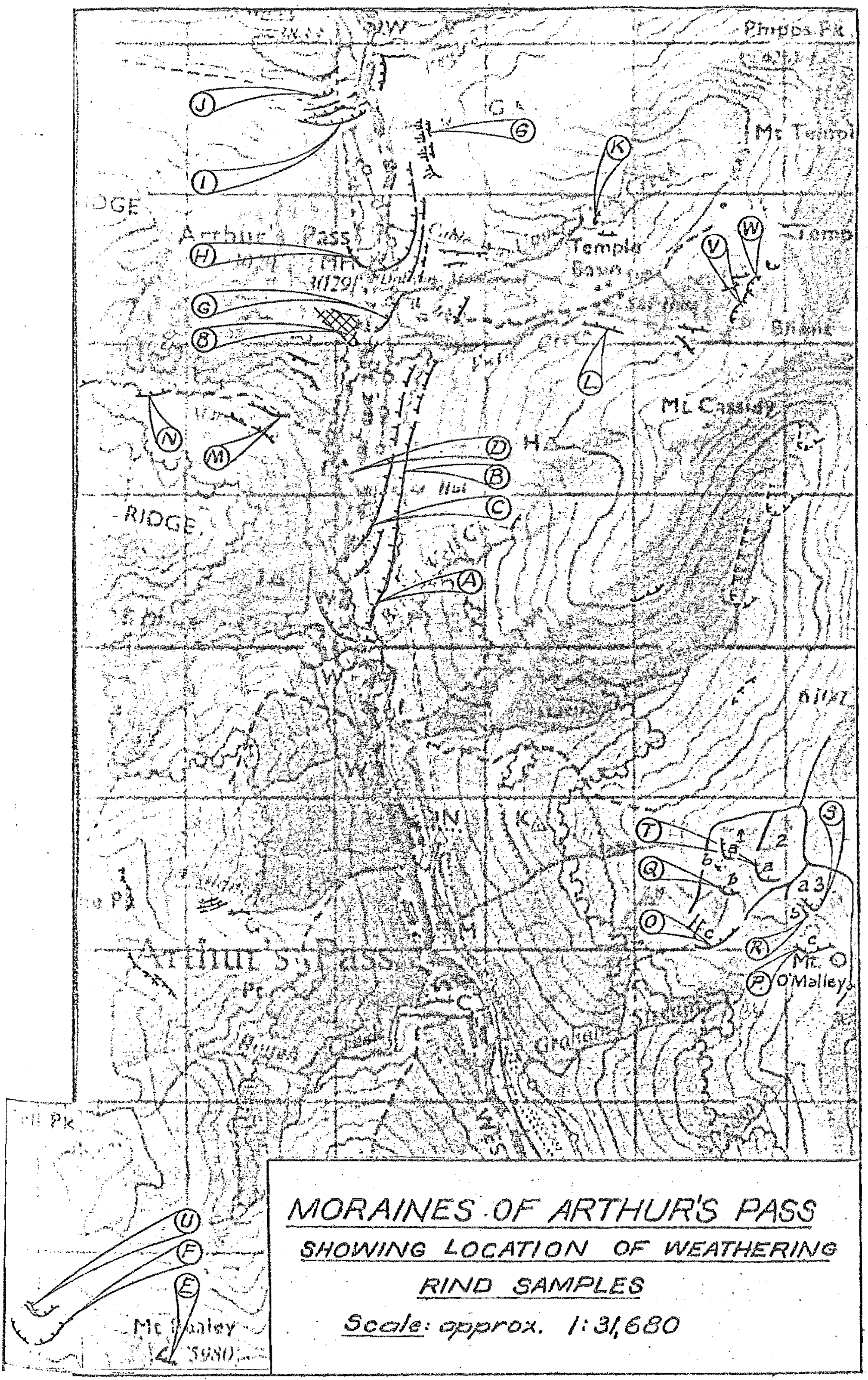
(2) Moraine m, too small a feature to demonstrate an advance at this time.

(3) Moraine G, suggests an early Arthur's Pass advance, although there is no evidence of this event in the Cameron Valley.

(4) Moraine L, again suggests an early Arthur's Pass event, however the apparent anomalies of both this and the previous moraine 'G' could arise from lithologic

variations and/or the possibility that the Arthur's Pass advance began early in "mode 3" time.

(5) Moraine M, samples in this case taken from a till veneer, which could have included boulders of both Arthur's Pass and McGrath tills.


MORAINES OF ARTHUR'S PASS

SHOWING LOCATION OF WEATHERING RIND SAMPLES

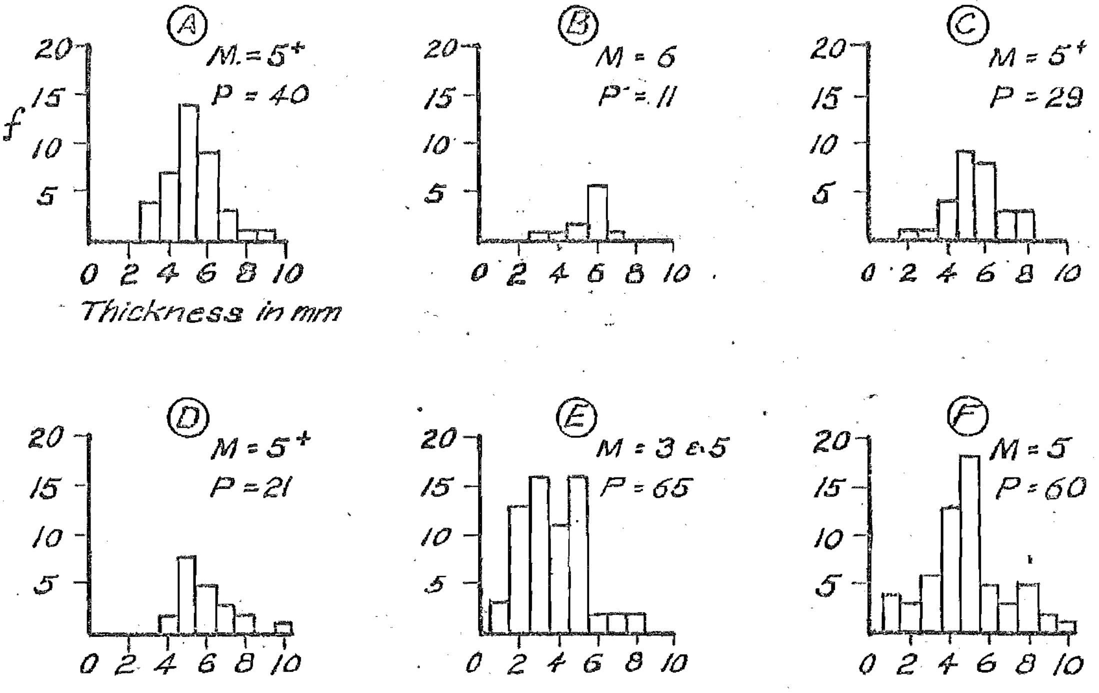
Scale: approx. 1:31,680

FIG. 31

WEATHERING RIND THICKNESSES

HISTOGRAMS FOR THE M^c^GRATH ADVANCE

P = Population M = Mode f = Frequency



Ⓐ McGrath I terminal loop.

Ⓑ McGrath I upper lateral.

Ⓒ McGrath II terminal loop.

Ⓓ McGrath II recessional moraine behind loop.

Ⓔ Mt. Bealy. Bimodal from later debris falls from headwall. Possibly a Neoglacial protalus deposit.

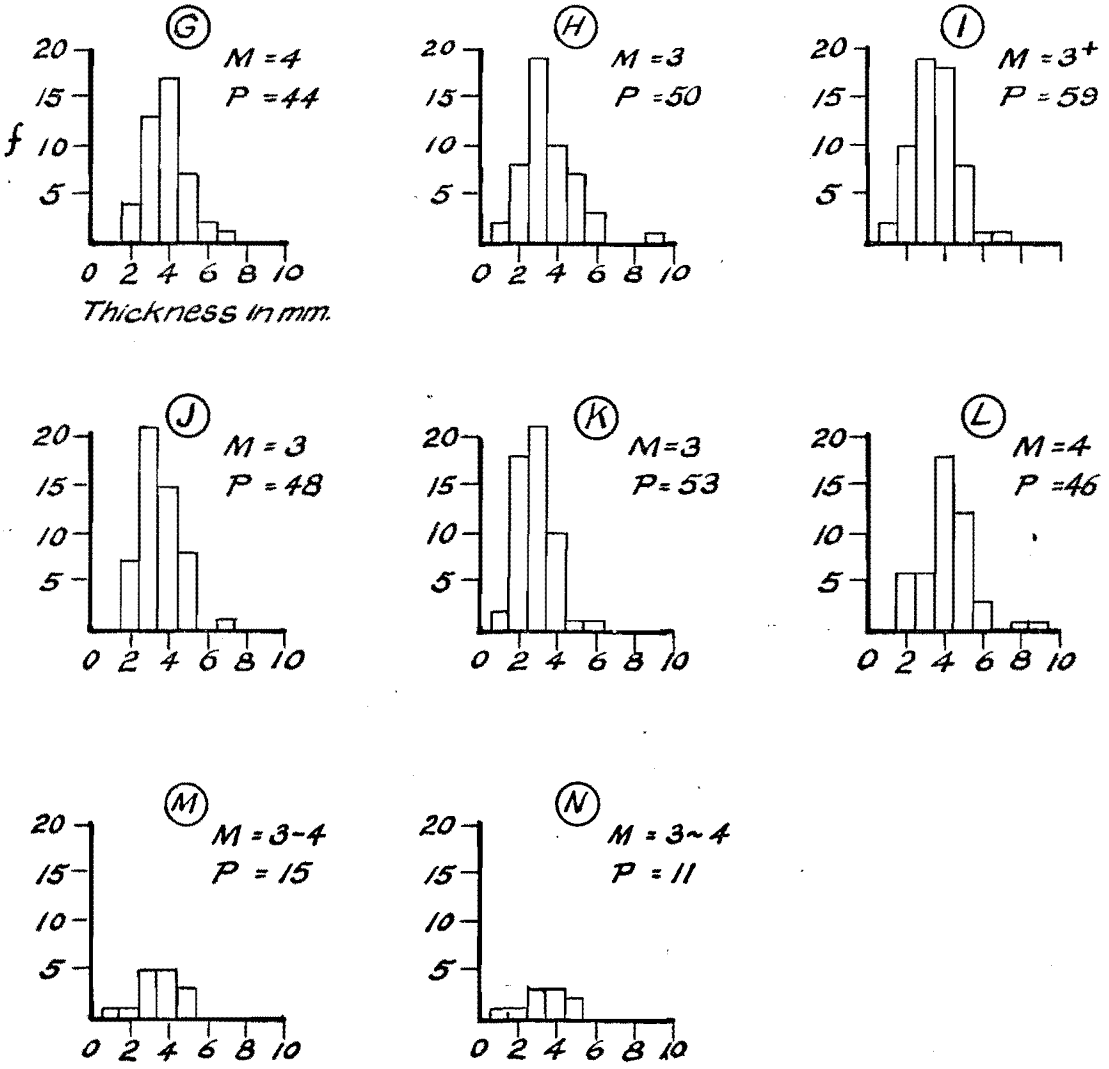
Ⓕ Mt. Bealy. Coarser grain fraction has increased 6mm to 10mm frequency.

FIG. 32

WEATHERING RIND THICKNESSES

HISTOGRAMS FOR THE ARTHUR'S PASS ADVANCE

P = Population M = Mode f = Frequency



Ⓖ Arthurs Pass I

Ⓗ Arthurs Pass II, 'Monument' advance

Ⓘ Arthurs Pass III, Outer Otira lateral

Ⓙ Arthurs Pass III, Inner Otira lateral

Ⓚ Phipps Basin

Ⓛ Temple Basin

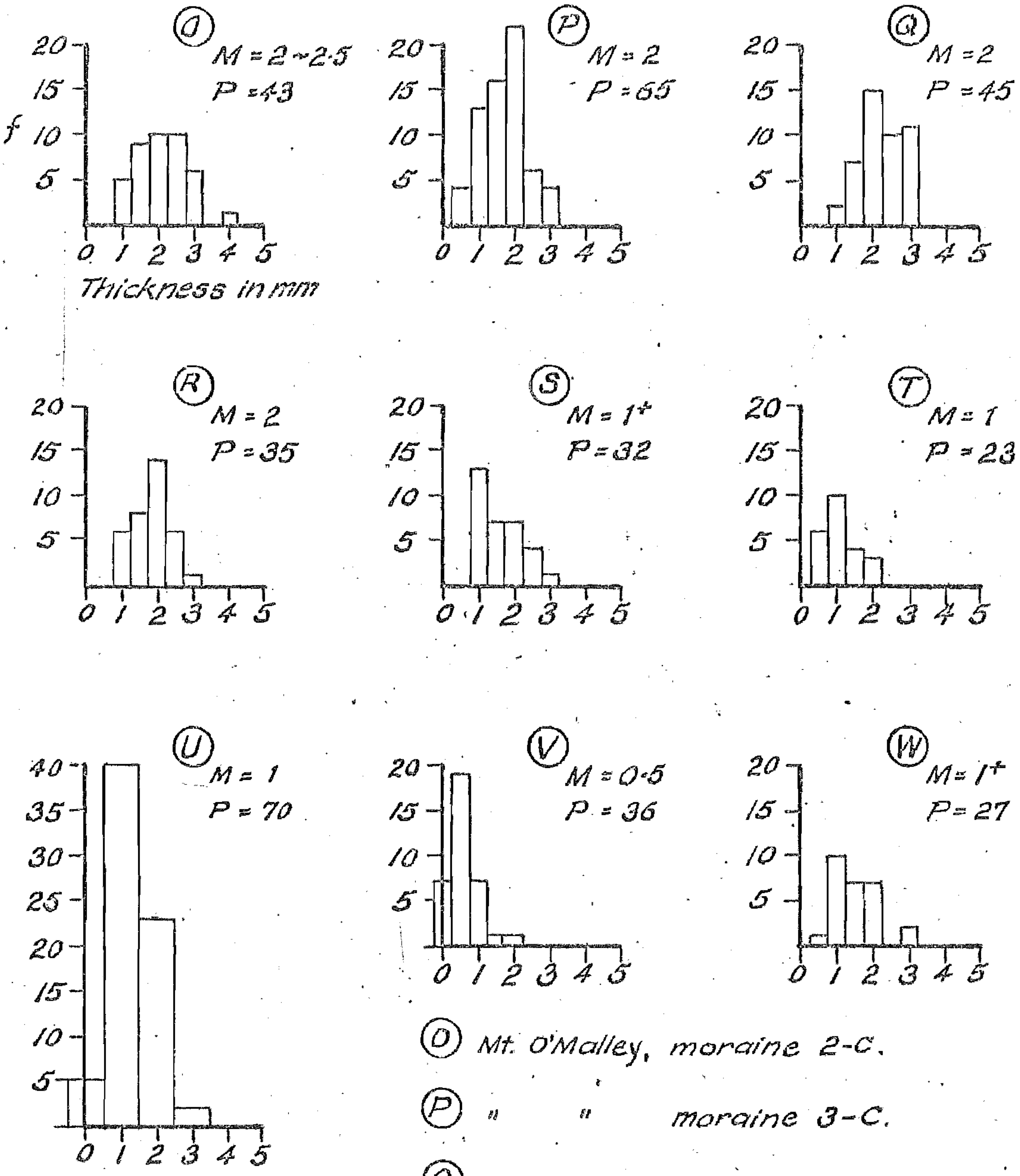
Ⓜ Margarets Tarn

Ⓝ Upper Bealy

FIG. 33

WEATHERING RIND THICKNESSES
HISTOGRAMS FROM MT. O'MALLEY

P = Population M = Mode f = Frequency



Ⓞ Mt. O'Malley, moraine 2-C.

Ⓟ " " moraine 3-C.

Ⓠ " " moraine 2-b, bimodality possibly from bias in measurements.

Ⓡ Mt. O'Malley, moraine 3-b.

Ⓢ " " moraine 3-a.

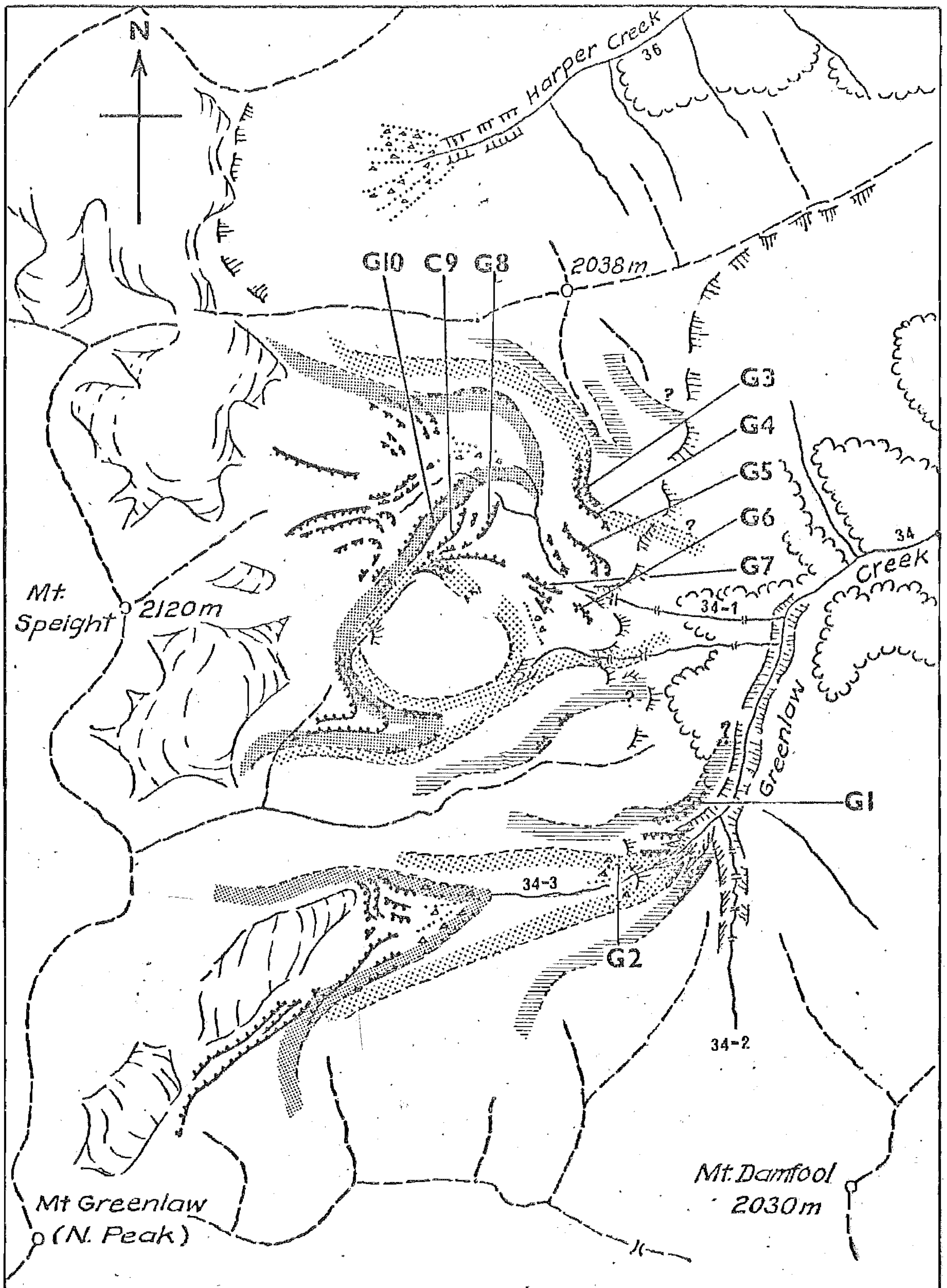
Ⓣ " " moraine 2-a.

Ⓤ Mt. Bealy.

Ⓥ Upper Temple Basin ~ Unreliable, from solifluction disturbed surface outside and older than moraine (W).

Ⓦ Upper Temple Basin.

FIG. 34

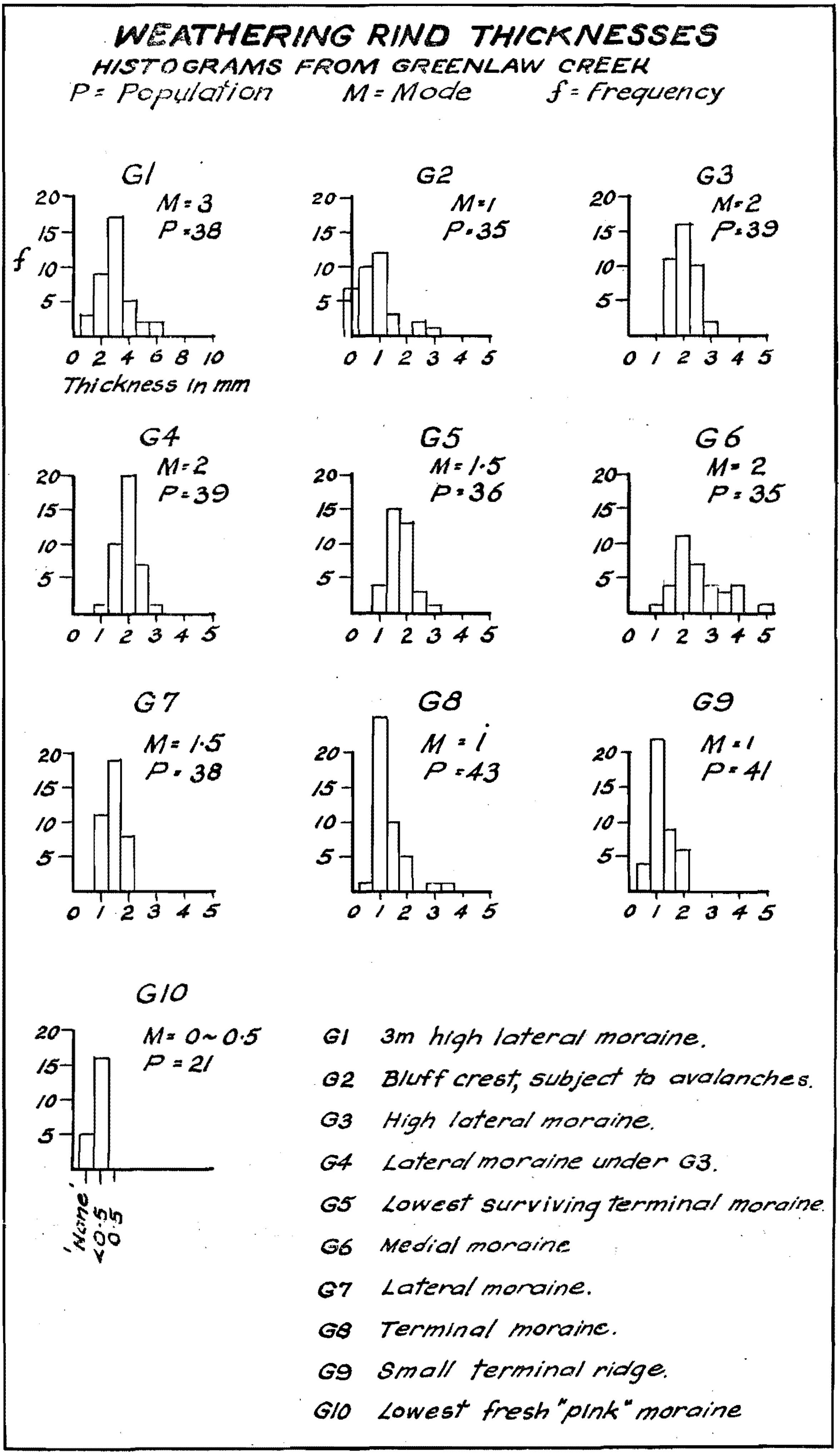


MORAINES OF GREENLAW CREEK

SHOWING POSITIONS OF RIND SAMPLES

SCALE 1:15840 approx.

△	*Moraine and till*
◡	*Existing glaciers*
▓	*Limit of Barker advance*
░	*Limit of O'Malley advance*
☰	*Estimated limit of Arthurs Pass advance*



WEATHERING RIND THICKNESSES

HISTOGRAMS FROM GREENLAW CREEK

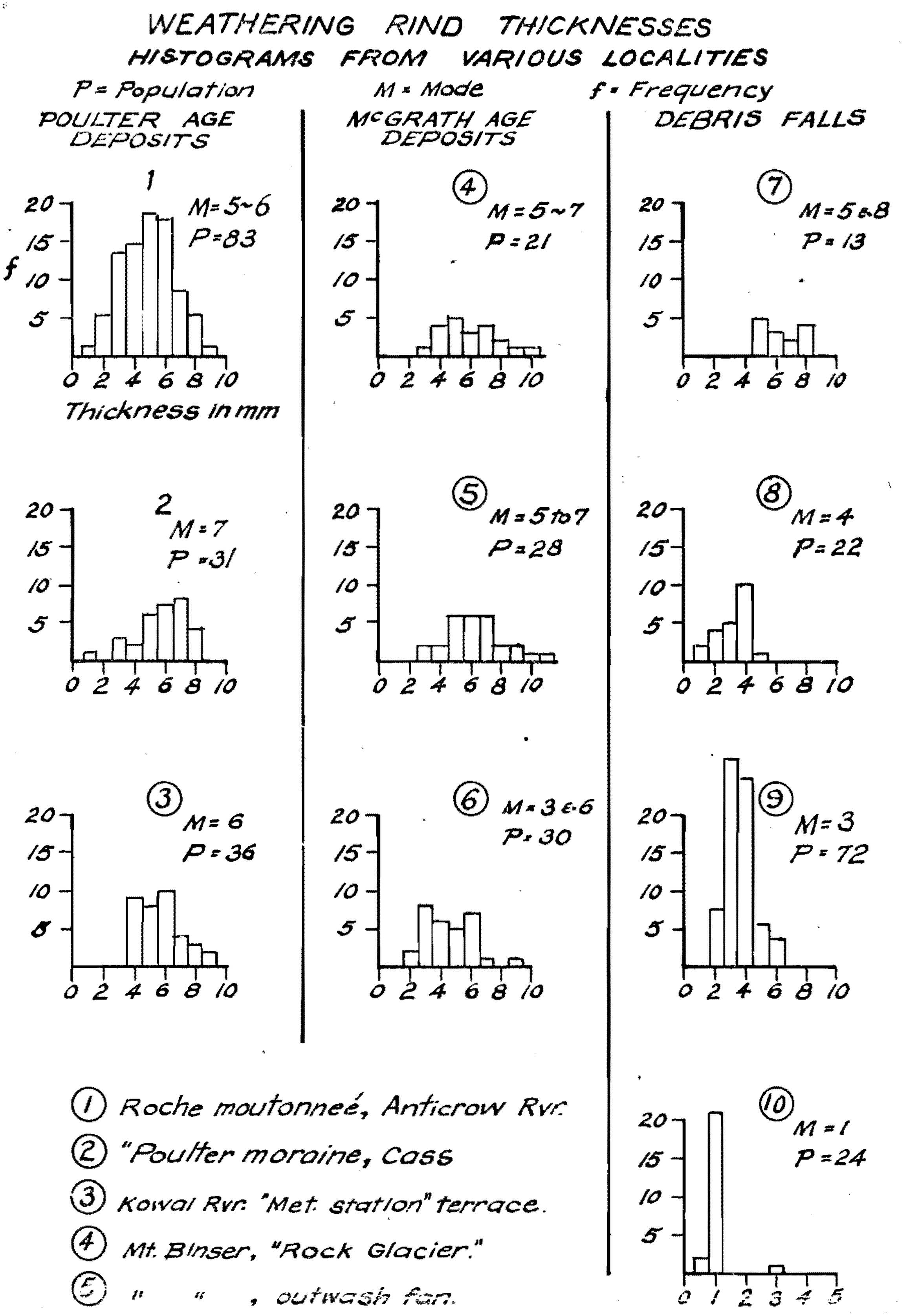
P = Population M = Mode f = Frequency

G1 3m high lateral moraine.
G2 Bluff crest, subject to avalanches.
G3 High lateral moraine.
G4 Lateral moraine under G3.
G5 Lowest surviving terminal moraine.
G6 Medial moraine.
G7 Lateral moraine.
G8 Terminal moraine.
G9 Small terminal ridge.
G10 Lowest fresh "pink" moraine

FIG. 36

WEATHERING RIND THICKNESSES

HISTOGRAMS FROM VARIOUS LOCALITIES



① Roche moutonneé, Anticrow Rvr.

② "Poulter moraine, Cass

③ Koiwai Rvr. "Met. station" terrace.

④ Mt. Binser, "Rock Glacier."

⑤ " " , outwash fan.

⑥ Arthur's Pass "bench." A slumped rock bench having McGrath age moraine (mode 6), slumped at mode 3 time?

⑦ Rockfall of varying age. Arthur's Pass township.

⑧ Rockfall, Twins Creek, Arthur's Pass.

⑨ Debris fall, Casey Rvr. ^{14}C dated.

⑩ Debris flow, Acheron River, Lake Lyndon, ^{14}C dated.

FIG. 37

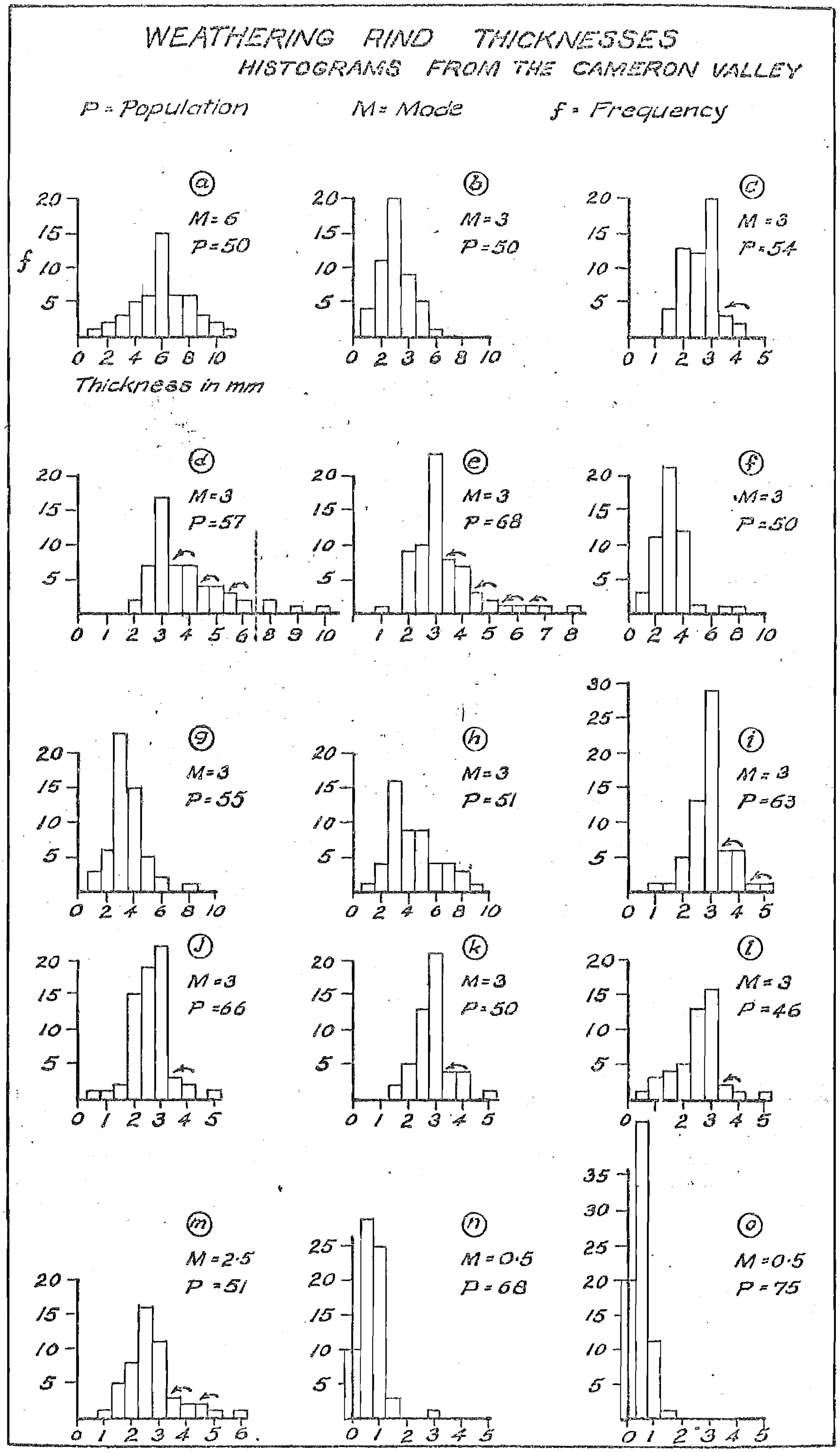
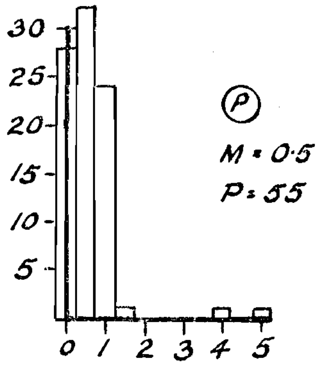
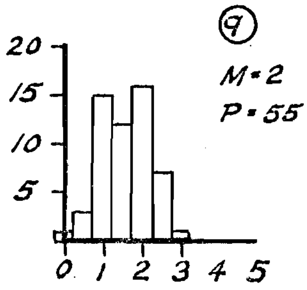

WEATHERING RIND THICKNESSES
HISTOGRAMS FROM THE CAMERON VALLEY

FIG. 38

CAMERON VALLEY CONTINUED





Ⓐ Wildman II.

Ⓑ Lochaber. Moraine below an unstable slope and possibly older than indicated as rinds may be of fallen rocks.

Ⓒ Marquee, outermost fragment.

Ⓓ Marquee, outer loop. Includes boulders having previous weathering?

Ⓔ Marquee, central moraine.

Ⓕ B6, outermost 'B' moraine.

Ⓖ B5.

Ⓗ B4, Left bank.

Ⓘ B4, right bank.

Ⓙ B2, left bank.

Ⓚ B2a, left bank.

Ⓛ B2a?, right bank.

Ⓜ B2a, right bank.

Ⓝ B1.

Ⓞ A3.

Ⓟ "A" series fragment over ^{14}C sample.

Ⓠ Rockfall over ^{14}C sample, dated.

SKETCH MAP OF THE UPPER CAMERON VALLEY

SHOWING LOCATIONS OF RIND SAMPLES

(from Burrows)

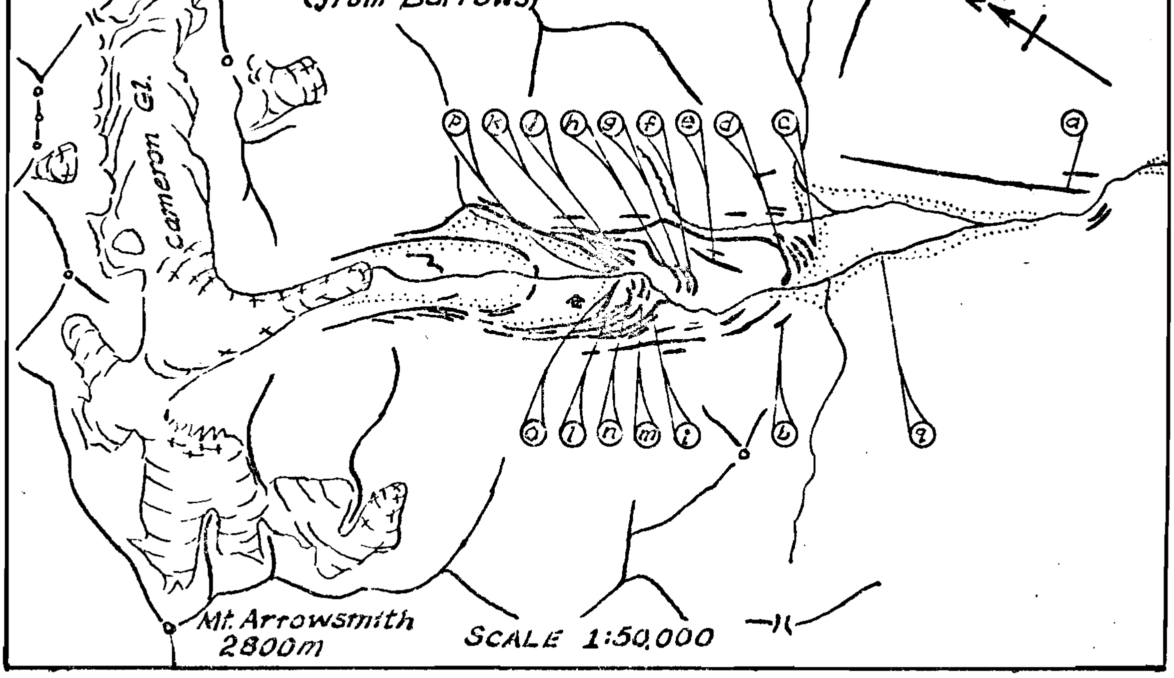
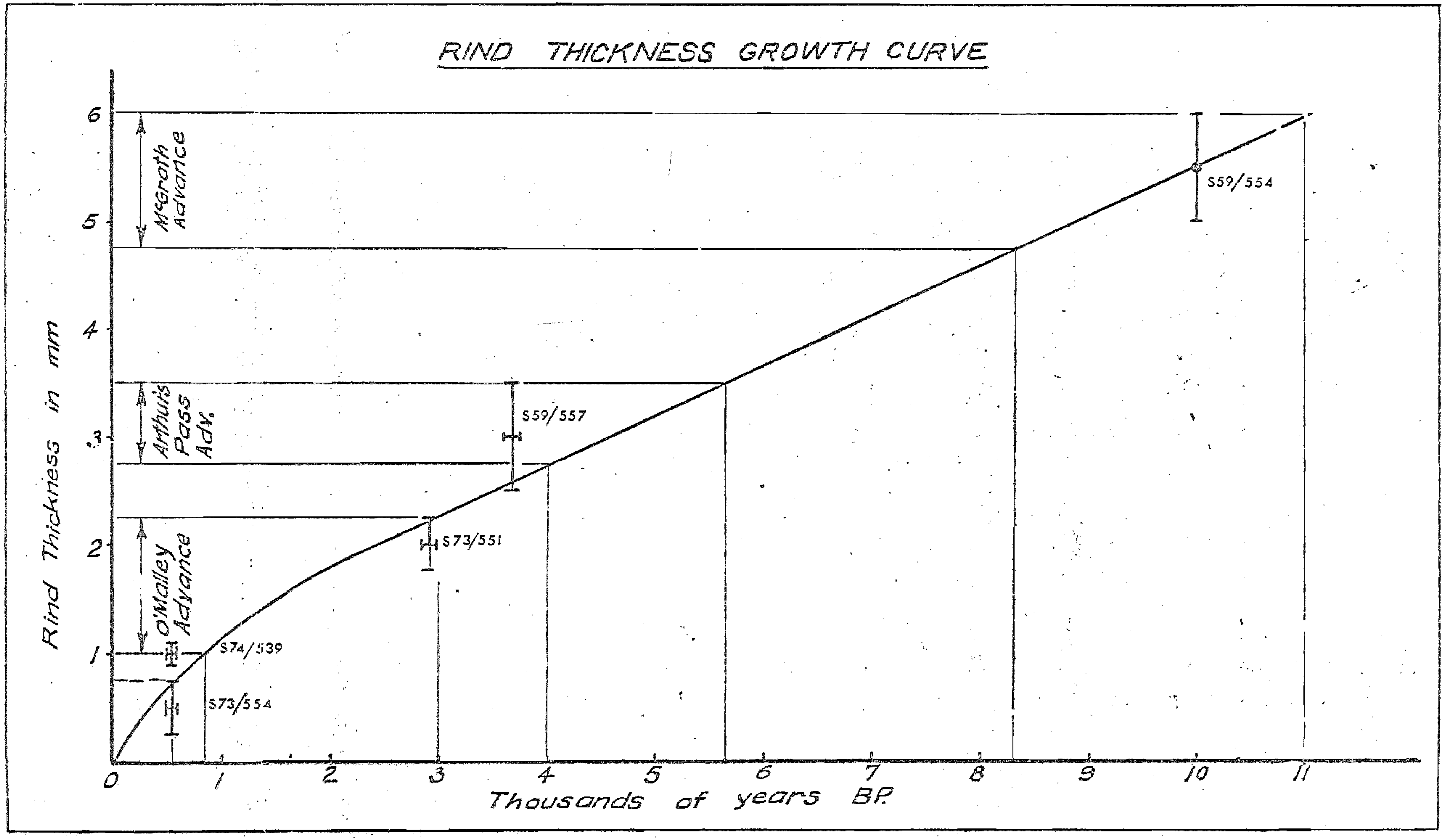


FIG. 39

FIG. 40



RIND THICKNESS GROWTH CURVE

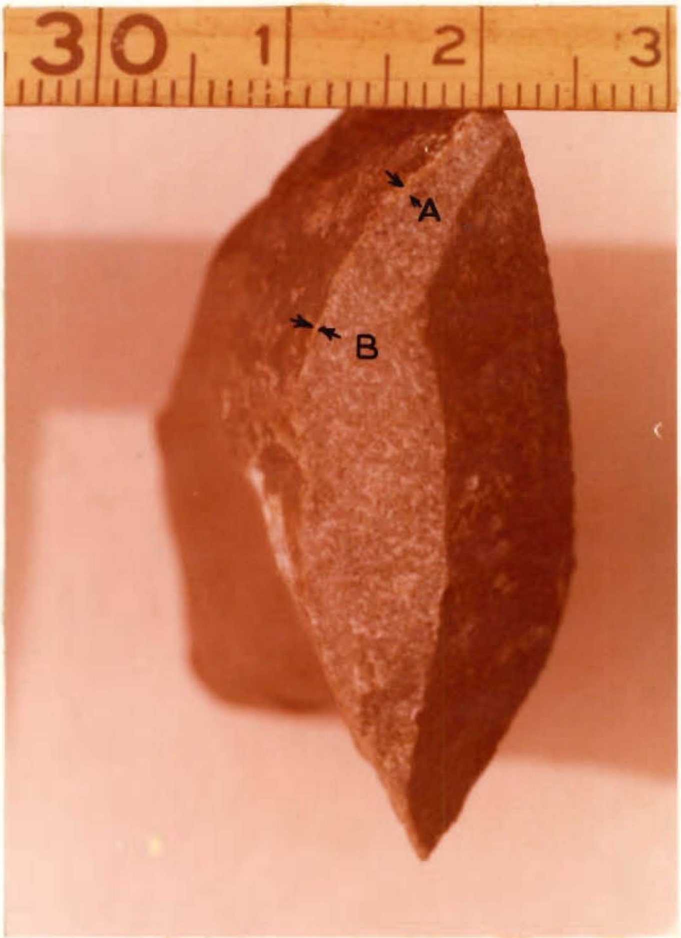


PLATE 37

Weathering-rinds of thickness 0.5mm (A), and "none", (B), on a composite bedrock sample from the upper Bealey Valley. In this case the thinner rind indicates an ice resurgence which removed part of the older weathering-rind. Scale in cm.

Weathering-rind of 0.5mm thickness
(L.H.S.). Scale in cm.

PLATE 38

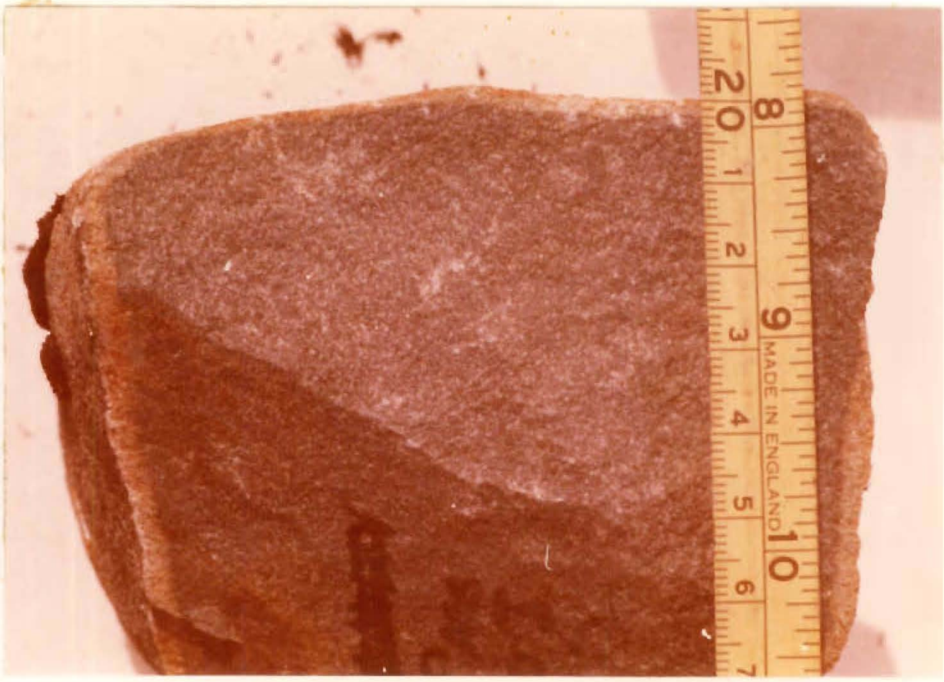


PLATE 39

Weathering-rind of 2mm thickness (top). Scale in cm. and inches.

PLATE 40

Diffuse weathering-rind of 5mm thickness, typical of McGrath moraines. Scale in cm. and inches.

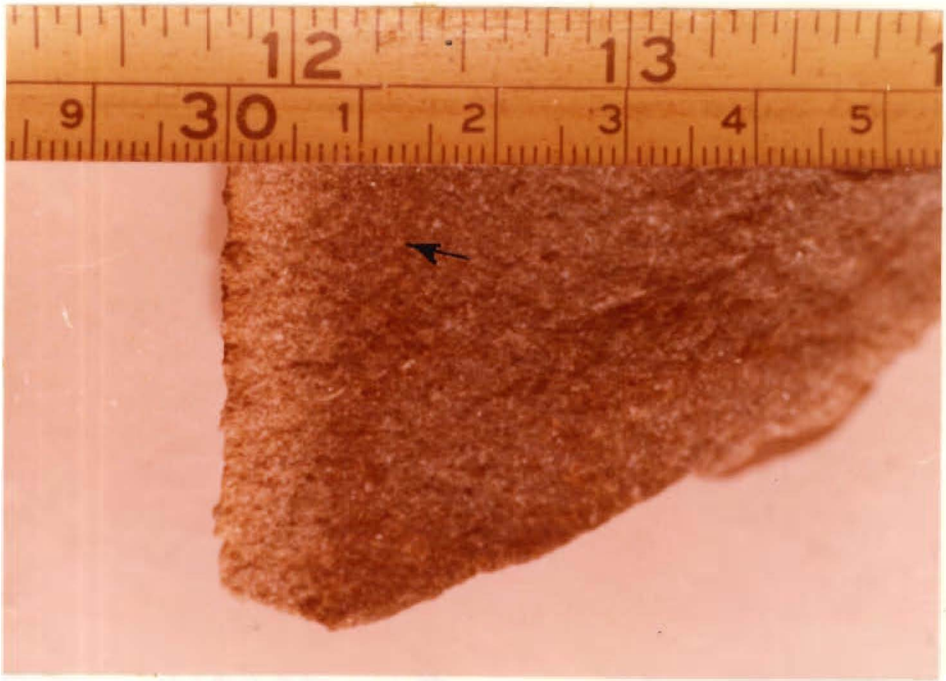


PLATE 41

7mm thick weathering-rind, together with "dark band", arrowed. Scale in cm. and inches.

PLATE 42

10mm thick weathering-rind of a boulder from a Pleistocene moraine. Scale in cm.

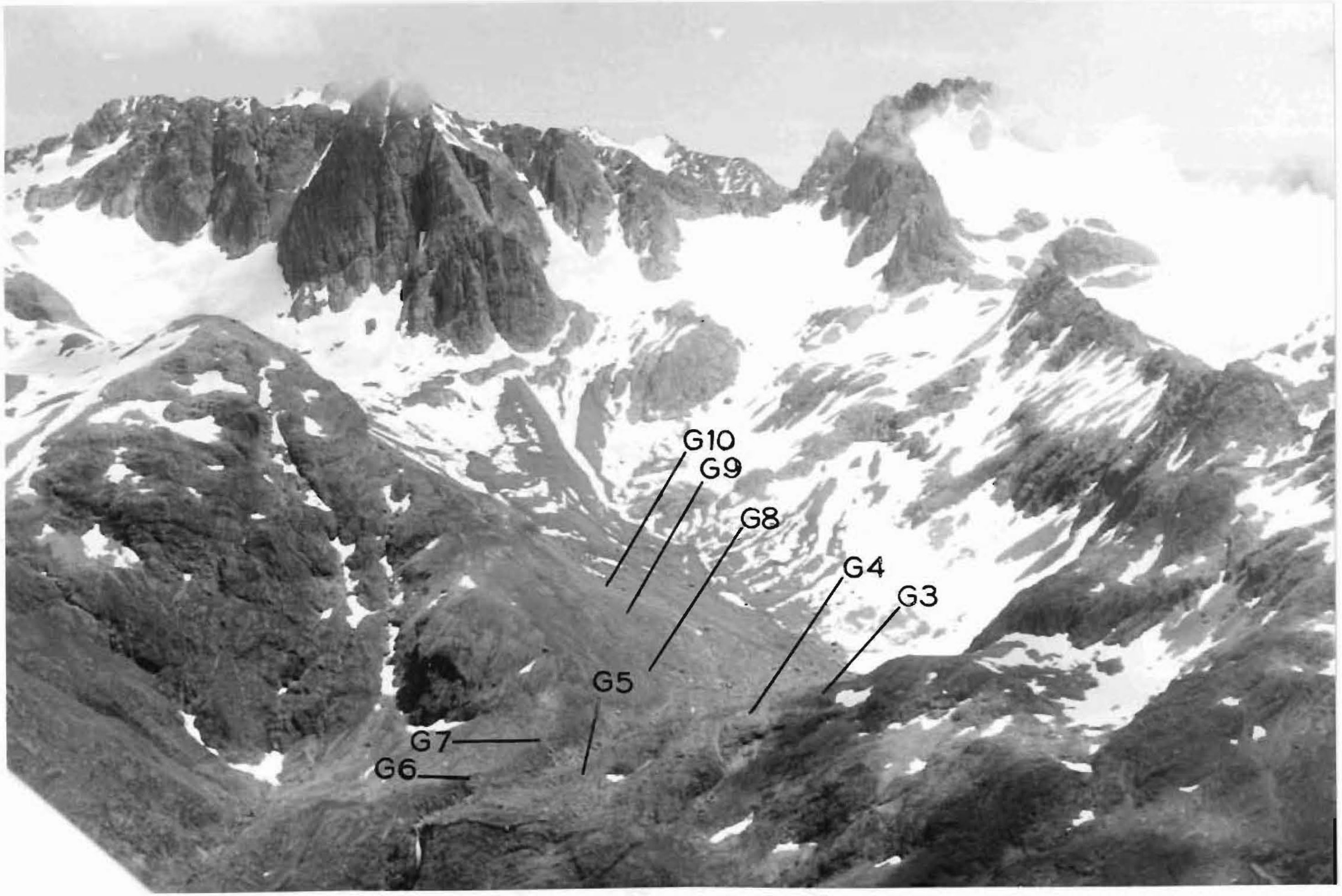


PLATE 43

Weathering rind sample locations, upper Greenlaw Creek 34-1. Compare with figure 35, and plate 35.

APPENDIX II

LANDSLIDES

I INTRODUCTION

Numerous mass movement deposits were encountered throughout the study area, and those which have been identified are mapped as landslides on figures 22 to 30.

The deposits are characteristically the result of bedrock moving under the influence of gravity, but other processes and materials are frequently involved. A number of these mass movements has crossed considerable distances of flat to low gradient ground, testifying to the high velocities frequently attained by these phenomena. The Falling Mountain landslide (figure 44), triggered by an earthquake in 1929, travelled for 4km down-valley before coming to rest, while another landslide at the confluence of the Casey and Poulter rivers crossed 2km of flat riverbed.

Weather horizons have been found, indicating that some of the deposits originated from more than one phase of activity, and many instances of flow diamictons indicate that subsequent mudflow activity on the newly exposed surfaces is common. Churned soils and forest vegetation are commonly found incorporated in the deposits.

The frequent inclusion of wood fragments in landslide deposits which have a bouldery surface has made possible the establishment of the weathering rind-

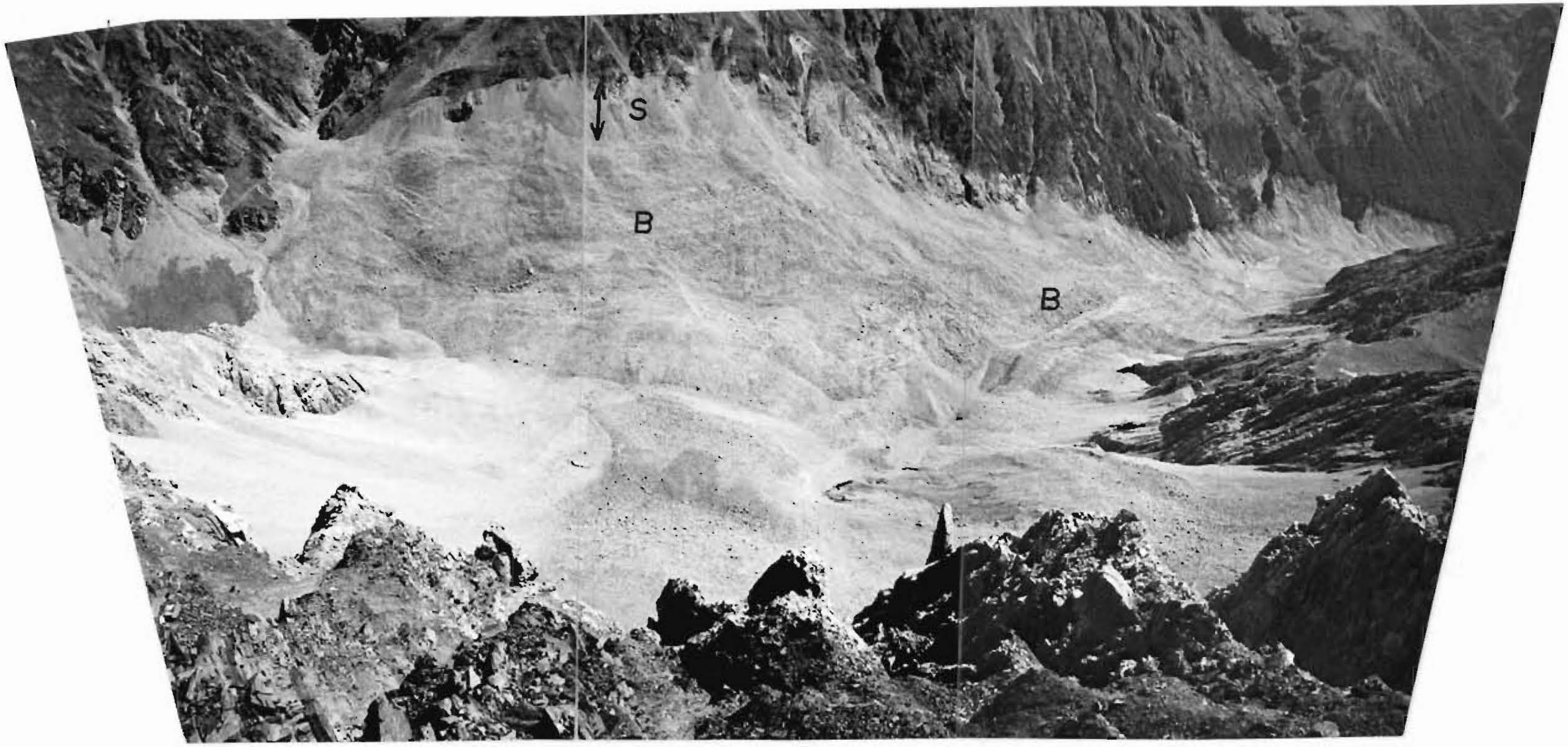


PLATE 44

View down the Falling Mountain landslide from the summit, 1815m.

S "Swash mark".

B Banding retained in the deposits.

PLATE 45

Landslide deposit at Casey River, 5-10 showing segregated debris and wood fragment (arrowed).

PLATE 46

Recently active landslide in the Thompson River, 5-12-2. H, hummocky moraine-like deposits.

age curve, used as a basis for the ages and durations of the Holocene glacial events.

II CLASSIFICATION

Because of the diversity of processes and materials involved, the deposits are not classified simply. The classification of landslides by Varnes (1968), being based on the type of failure and the material involved, is less suitable than Sharp's (1938) classification of mass movement types, which emphasises movement velocity.

Under Sharp's classification, the term "landslide" provides the best overall description of the deposits, as it includes debris slides, debris falls, rockslides and rockfalls.

In addition to these mechanisms, the landslide deposits include high water content rapid-flow colluvium originating from mudflows which are not included under Sharp's landslide classification.

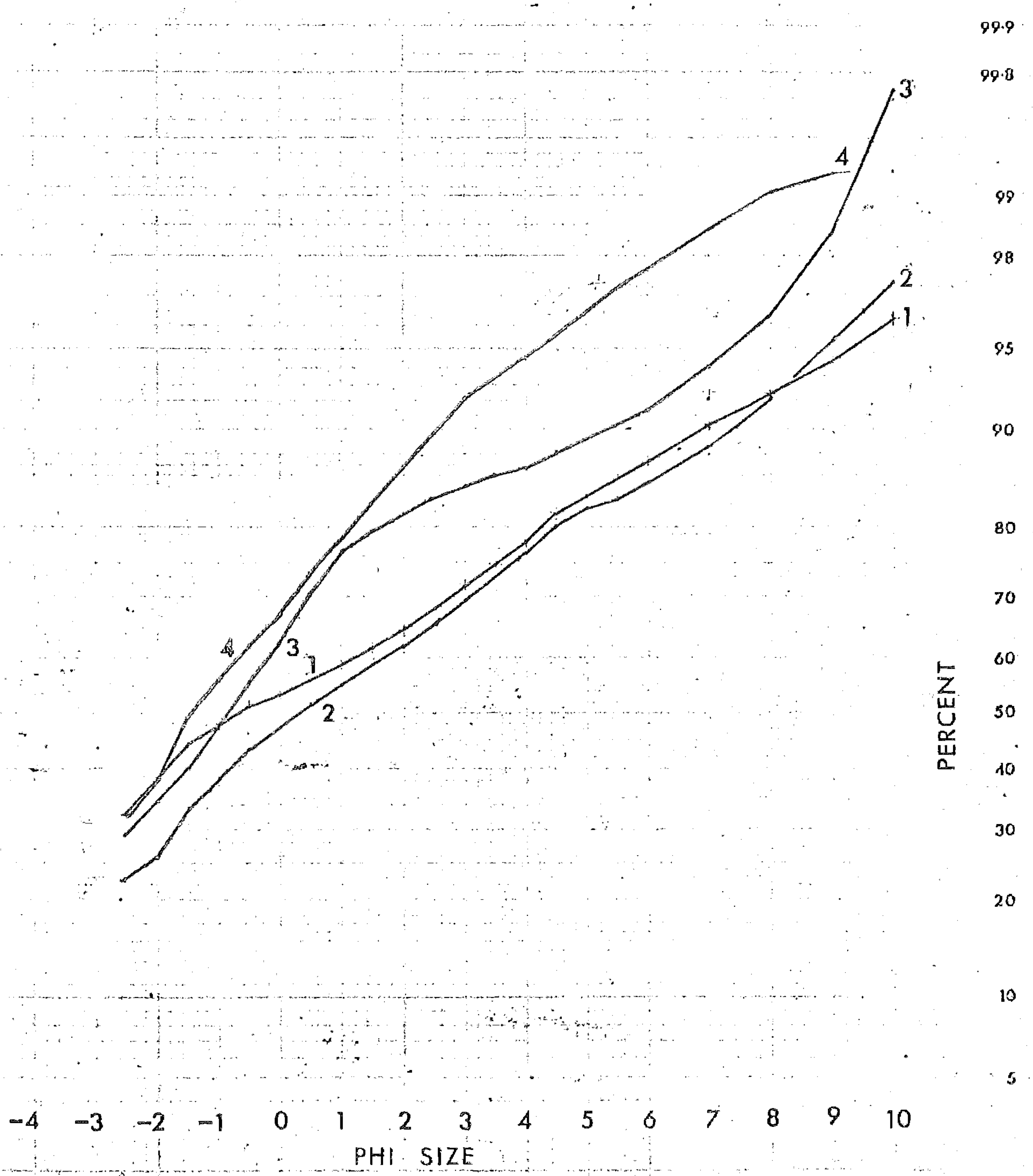
III DIFFERENTIATION BETWEEN TILLS AND LANDSLIDE DIAMICTONS

(1) Size analysis

The occurrence of landslide deposits in and amongst moraines of the area has made it necessary to employ some criteria to distinguish between the two types of deposits. The distinction between tills and other diamictons has been investigated by size analysis by a number of authors, including Landim and Frakes (1968). These studies have indicated that size frequency

GRAIN SIZE DISTRIBUTION CURVES

COMPARATIVE SIZE ANALYSES OF LANDSLIDE AND TILL SEDIMENTS



1 Casey River Landslide
2 Barker Till
3 McGrath Till
4 Arthur's Pass Till

FIG. 41

distributions may be useful in distinguishing tills among other sediments. In an attempt to distinguish tills from landslide deposits by this method, size analyses of three till samples and one landslide sample were made, for the -2.5 phi to +10 phi size ranges. The frequency distributions gained from these analyses are plotted on figure 41. It can be seen by the similarity of the plots that this method does not make any marked distinction between the sources of the sediments in these cases.

(2) Electron microscopy

Electron microscopy has recently become available as a possible tool for sediment environmental interpretation by studying sand grain surface textures. Krinsley and Donahue (1968), in a thorough investigation of quartz sand grain surfaces, concluded that, from surface textures, the following four environments of sediment transportation and deposition and their combinations can be distinguished; littoral, aeolian, glacial and diagenetic. Other studies of this type which have yielded similar results have been made by Nordstrom and Margolis (1972), Blackwelder and Pilkey (1972) and Margolis and Kennett (1968).

Since tills are derived from a single depositional environment, while landslides are likely to contain sand grains showing the influence of the environments both before and during the fall, electron microscopy should reveal differences in surface textures between the two types of sediments. Sand-sized quartz grains were

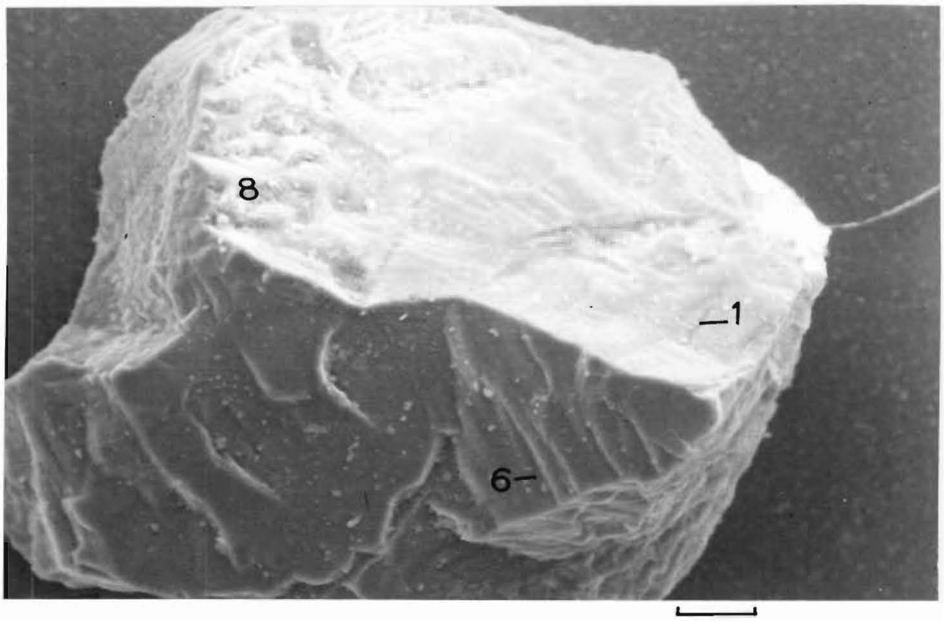


PLATE 47

Electron microscope photograph of
a glacial sediment grain. Scale 40 microns.

Features characteristic of glacial grains,
in order of importance:

1. Conchoidal breakage patterns - from large range of particle size.
2. High relief.
3. Semi-parallel steps - from shear stress.
4. Arched steps - from percussion.
5. Parallel strictions - from scratching.
6. Imbricate breakage blocks.
7. Irregular small indentations - from grinding.
8. Prismatic patterns.

Detail of textures of the glacial sediment grain of plate 47. Scale is 10 microns. See plate 47 for legend of features numbered.

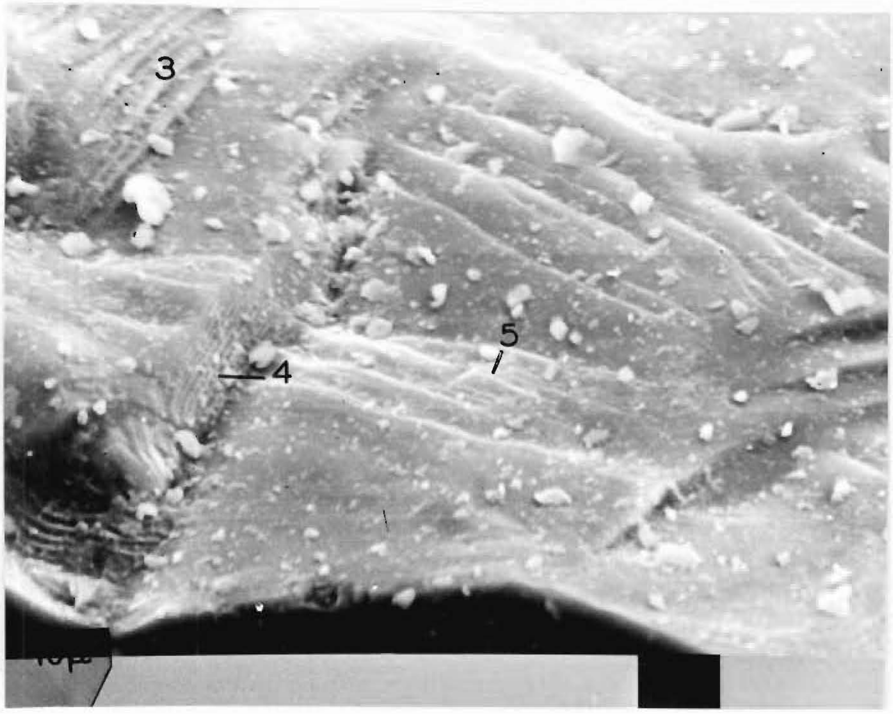


PLATE 48

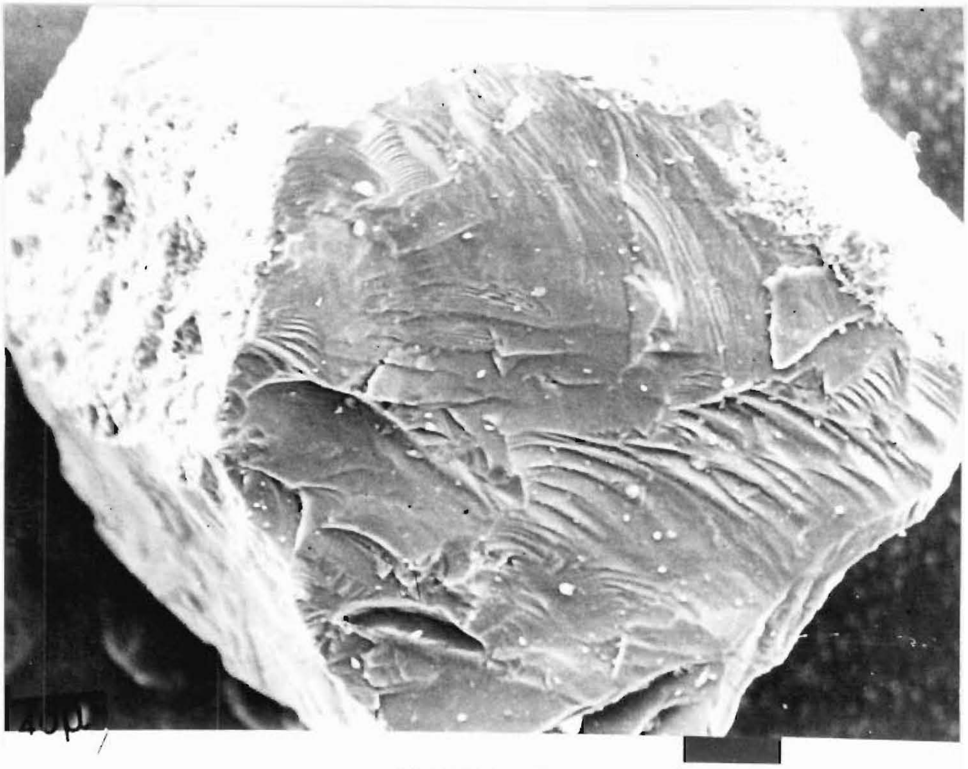


PLATE 49

Electron microscope photograph of landslide sediment grain showing diagenetic textures. Some glacial sediment grain characteristics are present on the fractured surface. Scale, 40 microns.

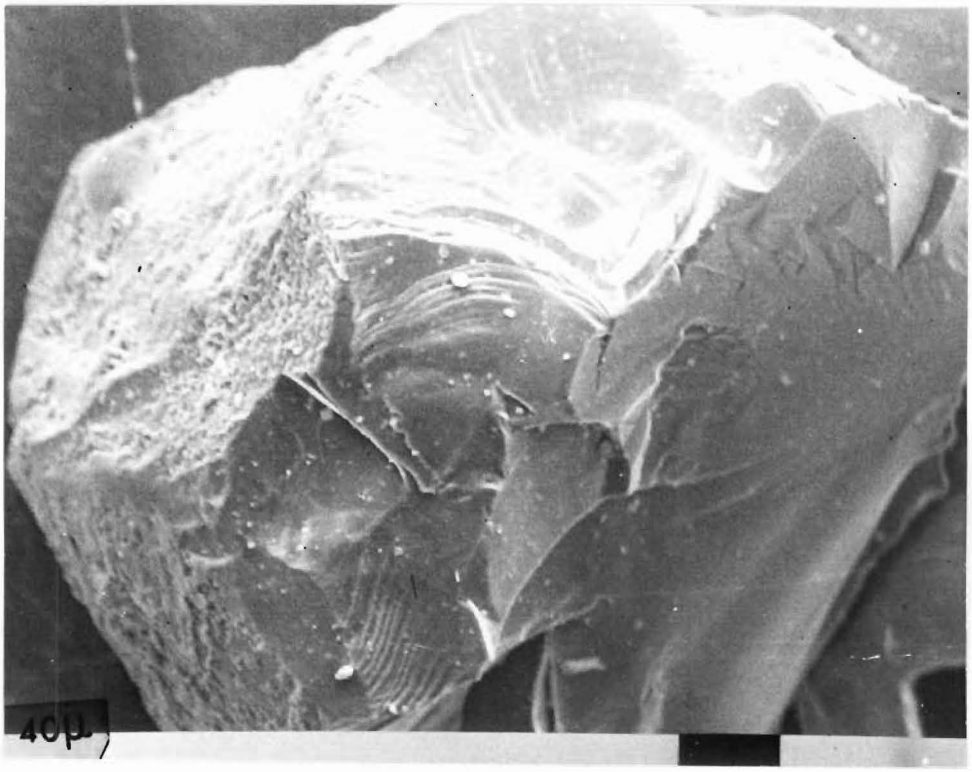


PLATE 50

Landslide sediment grain, similar to plate 49. Textures of two distinct environments apparent. Scale, 40 microns.

compared from samples taken from the Barker moraine and the Casey River landslide.

The grains showed sufficient textural differences to suggest that this is a viable method of distinguishing between the two types of deposit (plates 47 to 50). Krinsley and Donahue (1968), list eight characteristics of normal glacial grains, most of which are shown on plates 47 and 48. The surface textures of glacial grains are produced by slow grinding and crushing, while those of landslide grains may show pre-landslide diagenetic surface textures with impact rather than grinding textures superimposed upon this texture. While landslide impact and glacial textures may have many features in common, the former are unlikely to have the full complement of glacial textures developed.

This investigation has shown that landslide grains do tend to differ in texture from glacial grains. These differences are illustrated on plates 49 and 50. In addition to their diagenetic textures and an absence of some glacial features, landslide grains, having suffered only a limited number of impacts over a short period, tend to have a sharper, less subdued relief. These results give promising indications that electron microscopy analysis may be a useful method of distinguishing between these two types of deposit.

IV CHARACTERISTICS

The majority of the landslide exposures studied in the field showed a distinct failure to homogenise, despite the distance travelled under a presumably turbulent mode of transport. Lenses and undulatory beds of crushed sandstone, mudstone and colluvium occur separately in most of the exposures seen, while surface mudflow colluvium, capping stream channels, is common. One of the largest, and the most recent landslide seen, was that of Falling Mountain (plate 44). This landslide travelled some 4km down-valley, presumably by fluid flow with entrapped air, as high velocities are indicated by a 100m-high "swash mark" on the opposing valley wall. Despite the high velocities and great distance covered by the material, when the upper landslide debris settled into moraine-like hummocks, banding, apparently of lithological differences, was retained.

In a study of mudflows, Lindsay (1968), demonstrated that the motion of particles in a viscous fluid in laminar flow may develop strong long-axis fabrics, which form and disperse cyclically. Such fabrics could develop in "fluid flow" landslides and may account for the surface banding and separation of sediment types seen in these deposits.

Field comparisons of till and landslide materials revealed that, although both landslide and till deposits may be angular in shape, individual till boulders tended to have more subdued corners, due to shuffling and grinding within the glacier, while landslide boulders, having been shaped by impact forces, have a more "jagged" outline. The failure of landslide material to homogenise fully, together with the sharply angular nature of the boulders, were criteria employed for field identification of landslides.

APPENDIX III

TABLE 7

PAST SNOWLINE DATA

Moraine type : T, terminal. L, lateral.

Moraine size : A, large. B, medium. C, small.

Computed snowline reliability : 1, most accurate. 2, accuracy fair. 3, least accurate.

A-A : Area-altitude computation.

All elevations in m.

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
				SECTION I				
26-2-1	L	B	2	E	50	1740	1405	1470-1570
	T	C	1	E	50	1740	1585	1587-1633
	T	B	2	SE	0	1770	1570	1640-1700
26-3	T	B	1	E	50	1800	1540	1600-1640
26-5	L	B	3	E	50	1740	1495	1530-1604
"	T	C	1	E	50	1740	1585	1589-1635
28	T	C	2	E	50	1615	1465	1468-1512
"	T	C	1	E	50	1615	1495	1487-1523
29	T	C	2	NE	140	1710	1540	1460-1500
"	T	C	1	NE	140	1710	1570	1479-1521
30	L	A	2	S	0	A-A		1325-1525
"	L	A	2	S	0	A-A		1405-1570
30-1-1	T	A	1	S	0	1710	1555	1609-1655
"	T	B	1	S	0	1710	1585	1628-1666
30-1-2	T	B	1	SW	50	1770	1630	1629-1671
30-2	T	C	3	SE	0	1710	1390	1502-1598
"	T	C	3	SE	0	1710	1540	1600-1650
30-3	L	B	3	E	50	1800	1525	1571-1653
30-4	L	B	3	SW	50	1740	1390	1462-1568
30-6	T	B	2	E	50	A-A		1440-1565
30-6-2	L	B	2	SE	0	1950	1525	1683-1811

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
30-6-2	T	A	2	SE	0	1920	1650	1745-1825
30-6-3	L	B	3	E	50	1770	1405	1487-1597
"	L	B	3	NE	140	1800	1465	1442-1542
"	T	A	2	SE	0	1950	1710	1794-1866
30-9	T	A	2	SE	0	1830	1525	1636-1728
30-10-1	T	A	2	E	50	2030	1630	1720-1840
30-10-2	T	A	2	E	50	1970	1615	1689-1795
31	T	B	2	NE	140	A-A		1475-1585
31-3	T	C	2	S	0	1695	1585	1623-1657
31-4	T	B	2	E	50	1980	1465	1600-1744
"	T	B	2	E	50	1980	1680	1735-1825
"	T	A	1	SE	0	1970	1710	1801-1879
32	T	B	2	S	0	A-A		1525-1600
"	T	A	3	S	0	1830	1695	1742-1782
33	T	C	2	NE	140	1710	1555	1469-1515
34	L	C	2	E	50	A-A		1600-1690
34-1	T	B	1	E	50	A-A		1675-1740
34-1-3	T	B	2	E	50	2015	1585	1685-1815
34-3	L	B	1	E	50	A-A		1635-1725
"	T	B	1	E	50	A-A		1675-1735
35	T	A	3	SW	50	1830	1160	1345-1545
"	T	B	3	SW	50	1830	1220	1383-1567
36-1	T	C	2	SE	0	1830	1615	1690-1754
36-2	T	B	2	NE	140	1980	1695	1654-1740
37-1	T	B	2	S	0	1740	1585	1640-1686
"	T	C	1	SW	50	1860	1495	1572-1682
37-2	T	B	2	SW	50	1830	1525	1581-1673
38	T	A	2	NE	140	A-A		1360-1620
38-2-1	T	B	2	SW	50	1710	1585	1578-1616
38-2-2	T	C	3	SW	50	1740	1465	1506-1588
38-3-1	T	A	3	SE	0	1860	1250	1463-1647
"	T	B	2	SE	0	1860	1680	1743-1797
38-3-2	T	A	2	E	50	2135	1280	1529-1785
"	T	A	2	E	50	2105	1370	1577-1797
"	T	C	2	E	50	2075	1555	1687-1843
38-4	L	C	3	N	220	2135	1585	1557-1723

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL		CORR.	HEADWALL	MORAINE	
38-4	T	A	3	N	220	2135	1920	1775-1839
38-5-2	T	B	2	E	50	1890	1695	1713-1771
38-6	T	A	2	SE	0	2135	1250	1559-1825
39-2	L	B	2	SW	50	A-A		1535-1605
"	T	B	1	SW	50	A-A		1600-1645
41-1	T	B	2	E	50	1710	1435	1481-1563
"	T	C	2	E	50	1710	1540	1550-1600
"	T	C	2	NE	140	1710	1600	1498-1532
42	T	A	3	S	0	1830	1495	1612-1712
43	T	B	3	SE	0	1920	1525	1613-1731
44-1	T	B	2	SW	50	2015	1770	1805-1879
"	T	B	2	SW	50	2015	1785	1815-1885
44-2	T	B	2	NW	220	1920	1830	1641-1669
45	T	A	2	SW	50	2015	1770	1805-1879
46	T	B	2	SW	50	2105	1830	1876-1958
49,50 51	L	A	2	SW	50	A-A		1660-1750
				SECTION II				
24A-4-2	T	B	1	SW	50	A-A		1530-1590
"	T	A	1	SW	50	A-A		1635-1660
24A-4-2 'a'	T	A	1	SW	50	1740	1630	1618-1652
24A-4-3	T	A	1	SW	50	A-A		1580-1603
"	T	B	1	SW	50	A-A		1600-1645
24A-4-3 'c'	T	A	1	S	0	1725	1570	1624-1670
" 'b'	L	B	2	S	0	1725	1585	1634-1676
" 'a'	T	A	1	S	0	1725	1600	1643-1681
24A-5-2	L	C	3	E	50	1740	1310	1410-1540
"	T	C	2	SE	0	1740	1540	1610-1670
24A-7	T	C	2	E	50	1755	1295	1444-1506
"	T	C	2	E	50	1755	1600	1604-1650
24A-8	T	C	3	SW	50	1770	1420	1492-1598
"	T	C	3	SW	50	1770	1495	1541-1623

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
24A-12	T	A	2	W	140	1800	1710	1601-1629
24A-13	T	C	2	SW	50	1830	1235	1393-1571
24B-2	T	C	2	E	50	1630	1525	1511-1543
24B-4-2	T	A	1	E	50	1770	1585	1600-1655
"	T	C	2	E	50	1770	1695	1671-1693
24B-4-3	L	B	2	SE	0	1800	1370	1520-1650
"	T	C	2	SE	0	1800	1525	1621-1703
24B-6	T	A	2	SE	0	A-A		1340-1540
24B-6-1	T	C	2	NE	140	1770	1465	1431-1523
24B-7	T	C	2	SW	50	1920	1615	1671-1763
24B-8	L	B	2	SE	0	A-A		1480-1650
24B-9	T	C	2	SW	50	1830	1555	1601-1683
24C-2-1	T	B	2	NW	220	A-A		1230-1320
24C-2	T	B	2	S	0	1935	1405	1590-1750
"	T	A	3	S	0	1935	1710	1788-1856
24C-5	T	B	1	NW	220	1800	1665	1492-1532
24C-6	T	B	1	W	140	1860	1585	1541-1623
24C-7	T	B	2	NW	220	1845	1770	1576-1598
24C-11	T	B	3	E	50	1950	1450	1575-1725
"	T	B	2	E	50	1980	1860	1852-1888
24C-13	T	A	1	NE	140	1830	1710	1612-1648
24C-14	T	B	1	NE	140	1845	1600	1545-1619
13-11-1	T	A	3	E	50	A-A		1510-1565
"	T	C	1	S	0	A-A		1630-1655
13-1	T	B	1	SE	0	A-A		1250-1400
"	T	C	3	SE	0	A-A		1325-1435
14	T	C	2	S	0	1740	1525	1600-1664
15-1	T	B	1	SW	50	1695	1555	1554-1596
"	T	B	2	SW	50	1680	1585	1568-1596
20	T	B	2	S	0	1770	1295	1461-1603
"	T	C	2	S	0	1770	1405	1532-1642
"	T	C	2	S	0	1770	1615	1669-1715
21	T	B	3	SW	50	1830	1310	1442-1598
"	T	C	2	SW	50	1830	1600	1630-1700
Otira Rvr. I	T	B	2	E	50	A-A		1000-1290

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
Otira Rvr. II	T	A	2	E	50	A-A		1230-1415
SECTION III								
13-4	T	A	1	NW	220	1370	1310	1111-1129
13-5	T	A	1	SW	50	A-A		1200-1290
13-7-1	L	B	3	S	0	1585	1220	1348-1458
"	L	B	2	S	0	1585	1310	1407-1489
"	L	B	2	S	0	1585	1405	1468-1522
13-7-2	I	C	3	SE	0	1710	1220	1392-1538
13-7-8	T	C	2	SW	50	1680	1295	1380-1496
13-7-9	L	C	2	E	50	1710	1495	1521-1585
13-13	L	B	3	W	140	1740	1465	1422-1504
"	T	B	1	W	140	1740	1665	1552-1573
13-15	T	C	3	SW	50	1680	1280	1370-1490
13-16	L	C	1	E	50	Upper limit		1260
"	L	B	3	E	50	1725	1220	1347-1499
13-17	T	C	2	S	0	A-A		1355-1510
"	T	B	3	S	0	1770	1465	1472-1564
10-1	L	A	3	E	50	1665	885	1108-1342
"	T	B	2	E	50	1665	1495	1505-1555
"	T	C	2	E	50	1665	1600	1573-1593
10-2	L	A	3	S	0	Upper limit		1295
10-3	T	B	3	SW	0	1615	1310	1417-1509
10-4	L	B	3	S	0	1615	975	1199-1391
"	L	C	3	S	0	1615	1250	1378-1488
"	T	C	2	S	0	1615	1465	1518-1562
5-8	T	B	2	SE	0	1710	1555	1610-1656
5-10-1	T	B	2	S	0	1650	1495	1550-1596
"	T	B	2	S	0	1650	1585	1608-1628
5-10-3	L	B	3	E	50	1615	945	1130-1330
5-10-4	T	B	3	NE	140	1680	1130	1182-1348
"	L	C	3	E	50	1680	1340	1409-1511
5-10-5	T	B	1	S	0	1555	1435	1477-1513
5-10-6	T	A	3	E	50	1710	855	1105-1361
5-10-6	T	B	2	E	50	1710	1145	1293-1463

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
5-10-6	T	A	2	E	50	1770	1615	1619-1665
"	T	A	2	E	50	1770	1680	1661-1689
5-10-8	T	C	2	NE	140	1585	1130	1150-1286
5-10-8	T	B	3	NE	140	1585	990	1058-1236
"	T	B	2	NE	140	1585	1325	1276-1354
5-16	L	B	3	NE	140	A-A		1225-1415
"	T	B	2	E	50	A-A		1355-1520
"	L	C	2	SE	0	A-A		1450-1560
"	T	A	1	S	0	A-A		1615-1640
5-17	L	B	3	SE	0	1555	1035	1222-1368
				SECTION IV				
5-20	L	B	2	SW	50	1710	1405	1462-1554
"	L	C	3	SW	50	1710	1465	1501-1575
5-21	L	C	3	E	50	1710	1250	1361-1499
"	T	C	2	E	50	1710	1465	1501-1575
5-22	T	B	1	E	50	1680	1310	1389-1501
5-23	T	A	2	S	0	A-A		1340-1570
"	T	A	2	S	0	A-A		1390-1480
"	T	A	3	S	0	1650	1280	1409-1521
5-15-1	T	C	3	SE	0	1650	1405	1491-1565
5-15-2	T	C	3	E	50	1750	1600	1603-1648
5-15-4	L	C	3	W	140	1680	1340	1319-1421
5-15-6 -1	T	A	2	SW	50	A-A		1415-1475
"	L	C	2	SW	50	1615	1405	1429-1491
"	T	B	2	S	0	1615	1465	1518-1562
5-15-6 -2	L	A	2	SW	50	1525	1250	1299-1379
5-15-7	T	B	2	E	50	1725	1250	1359-1501
"	T	C	1	SE	0	1725	1495	1565-1645
5-15-8	T	B	3	E	50	1585	975	1138-1322
"	T	B	1	SE	0	1615	1160	1320-1456
"	T	B	2	SE	0	1615	1205	1348-1472
5-15-8 -1	T	C	3	N	220	1725	1570	1405-1451

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
5-15-9	L	C	3	SW	50	1510	1325	1340-1396
5-15-10	T	A	1	E	50	A-A		1170-1290
"	L	C	2	E	50	A-A		1230-1415
"	T	B	2	SE	0	A-A		1470-1615
5-15-10 -1	T	C	3	N	220	1695	1570	1394-1432
5-15-11 -2	L	C	3	SW	50	1680	1190	1311-1459
"	T	C	3	SW	50	1680	1340	1429-1501
5-15-11 -1	T	C	1	SW	50	1755	1480	1527-1609
5-13	T	A	2	S	0	1585	1280	1392-1484
5-12-1	T	B	2	S	0	1680	1435	1521-1595
5-12-3 -1	T	C	2	S	0	1615	1295	1407-1503
5-12-3 -2	T	A	2	SW	50	1585	1310	1357-1439
5-12-5	L	A	3	S	0	A-A		1160-1240
"	T	B	2	SE	0	A-A		1310-1480
5-12-8	T	C	3	E	50	1710	1035	1222-1424
5-12-9	T	A	2	E	50	1710	1145	1293-1463
"	-	-	1	SE	0	1710	1495	1571-1635
5-12-12	L	C	2	N	220	1740	1235	1192-1344
"	L	B	1	N	220	1740	1370	1230-1340
5-12-13	L	C	3	SW	50	1770	1005	1223-1453
"	L	B	2	SW	50	1770	1310	1421-1559
5-12-13 -1	L	B	3	S	0	1680	1495	1560-1616
"	T	B	2	S	0	1680	1585	1619-1647
McElroy 'A'	T	B	2	S	0	1710	1005	1252-1464
"	T	C	2	S	0	1710	1495	1571-1635
McElroy 'B'	L	A	1	E	50	A-A		1255-1415
				SECTION V				
12-1	L	A	3	SE	0	A-A		1495-1620
12-2	L	A	3	SE	0	A-A		1465-1680

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
12-2	T	C	1	SE	0	1890	1710	1773-1827
"	T	C	1	SE	0	1890	1770	1812-1848
"	T	B	1	SE	0	1890	1800	1831-1859
12-3-1	L	B	2	SE	0	1830	1650	1713-1767
12-3-3	L	B	1	E	50	1785	1370	1466-1590
"	T	C	2	E	50	1785	1525	1566-1644
12-3-4	T	C	2	NE	140	1800	1615	1540-1596
12-3-5	T	C	2	SE	0	1770	1630	1679-1721
12-3-6	T	B	2	SW	50	1875	1740	1738-1778
12-4	T	A	2	SE	0	A-A		1315-1425
17	T	A	1	NE	140	1860	1555	1522-1614
"	T	A	1	NE	140	1860	1600	1551-1629
19-1	L	C	3	N	220	1755	1615	1444-1486
19-3-1	T	A	3	W	140	1800	1190	1263-1447
"	L	B	3	SW	50	1800	1600	1620-1680
19-4	T	B	3	E	50	1630	1310	1372-1468
"	T	B	3	E	50	1630	1340	1391-1479
22-2	L	A	1	NE	140	Upper limit		1370
"	L	B	3	NE	140	A-A		1370-1450
"	T	B	1	NE	140	A-A		1485-1525
"	T	B	1	NE	140	A-A		1545-1570
"	T	A	1	NE	140	1770	1680	1571-1599
22-3	L	C	3	E	50	1710	1325	1410-1526
22-4	L	C	3	SE	0	1710	1340	1370-1480
"	L	C	3	E	50	1710	1465	1501-1575
22-5	L	C	3	NE	140	1740	1405	1383-1483
22-1	L	C	3	E	50	1830	1555	1602-1684
				SECTION VI				
5-2	L	C	3	SE	0	1830	1280	1472-1638
"	T	B	2	SE	0	1830	1615	1691-1755
5-6	T?	A	3	SE	0	1525	975	1167-1333
"	L?	B	3	SE	0	1615	915	1160-1370
6	L?	A	3	S	0	1325	735	941-1119
7	T	A	1	SW	50	A-A		1225-1285
"	T	A	1	SW	50	A-A		1270-1430

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
9	T	A	3	S	0	1680	1175	1352-1504
				SECTION VII				
3-2-3-2	L	B	3	SE	0	1800	1130	1365-1565
3-2-3-3	T	A	3	SE	0	1770	1220	1413-1577
"	T	C	3	SE	0	1770	1525	1611-1685
"	T	C	3	SE	0	1755	1615	1664-1706
3-2-3-5	L	B	3	E	50	1830	1370	1481-1619
"	T	C	3	E	50	1830	1680	1682-1728
3-2-3-4	L	B	3	E	50	1770	1495	1542-1624
3-2-4-2	T	B	1	SE	0	A-A		1620-1725
"	T	B	1	SE	0	A-A		1725-1830
3-2-5-1	L	B	3	S	0	1800	1035	1303-1533
"	T	B	2	S	0	1800	1250	1443-1607
"	T	C	2	S	0	1800	1615	1680-1736
3-2-5-2	L	B	3	SE	0	1770	975	1254-1492
"	L	C	3	SE	0	1770	1130	1354-1546
"	T	B	2	S	0	1800	1435	1563-1673
3-2-5-2-2	T	B	2	SE	0	1770	1465	1572-1664
3-3-7	L	B	3	S	0	1710	1070	1294-1486
"	L	B	2	S	0	1710	1220	1591-1739
3-3-9	T	A	1	SE	0	1755	1555	1625-1685
3-3-8-1	T	A	2	SE	0	1755	1540	1616-1680
3-3-8-2	T	A	1	E	50	1860	1710	1712-1758
3-3-6	T	B	2	SE	0	1860	1555	1662-1754
3-3-5-1	T	B	1	SE	0	A-A		1495-1615
"	T	A	2	S	0	1860	1650	1724-1786
3-3-5-2	L	A	2	E	50	A-A		1390-1500

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
3-3-5-2	L	B	2	SE	0	1830	1695	1743-1783
3-3-3-1	T	A	1	SE	0	A-A		1280-1510
"	L	B	2	SE	0	1815	1585	1665-1735
"	T	B	1	SE	0	1815	1710	1747-1779
3-3-3-2	T	A	1	SE	0	A-A		1405-1555
"	L	A	2	SE	0	1860	1250	1463-1647
"	L	B	2	SE	0	1860	1340	1522-1678
"	T	B	3	SE	0	1860	1525	1643-1743
"	T	B	1	E	50	1980	1800	1813-1867
3-3-2-2	T	A	2	SE	0	A-A		1540-1700
"	T	B	2	SE	0	A-A		1715-1805
"	T	B	2	SE	0	1890	1615	1712-1794
"	T	B	1	E	50	1920	1725	1744-1802
"	T	C	1	E	50	1920	1770	1772-1818
3-3-2-2-1	L	C	2	SE	0	1770	1250	1432-1588
"	L	C	2	SE	0	1770	1495	1592-1674
3-1	L	A	3	SE	0	1465	855	1069-1251
				SECTION VIII				
3-3-2-1	L	A	2	E	50	1920	1650	1694-1776
"	T	A	1	SE	0	1950	1800	1853-1897
3-4	L	B	3	E	50	1785	1190	1349-1527
3-5-2	T	B	2	SE	0	A-A		1680-1815
"	T	A	1	E	50	2060	1830	1860-1930
"	T	B	1	E	50	2060	1980	1958-1982
3-5-3	T	A	2	SE	0	2015	1480	1668-1828
3-5-4	L	B	3	E	50	2015	1035	1328-1622
3-5-1-1	L	A	2	SE	0	A-A		1585-1815
"	T	B	1	SE	0	2165	1920	2006-2080
3-5-1-2	T	B	2	SE	0	1950	1800	1853-1897

BASIN	MORAINE			ASPECT		ELEVATION		SNOWLINE RANGE
	TYPE	SIZE	REL.		CORR.	HEADWALL	MORAINE	
3-5-1 -2	T	B	1	E	50	1950	1875	1889-1911
3-7	T	A	1	SW	50	A-A		1305-1540
"	T	A	1	SW	50	A-A		1450-1635
"	L	C	2	SE	0	A-A		1600-1720
"	T	A	1	SE	0	1920	1755	1813-1863
3-8	T	A	1	SW	50	A-A		1320-1550
"	T	A	1	SW	50	A-A		1400-1615
"	T	B	2	SW	50	A-A		1605-1715
Mt Olympus	T	A	1	S	0	A-A		1405-1625
				SECTION IX				
1-1	T	A	3	SE	0	1710	610	995-1325
1-6	T?	A	3	SE	0	A-A		1160-1435
1-6-1	L	A	2	SE	0	A-A		1405-1555
1-6-2	L	A	2	SE	0	1830	1585	1671-1745
1-7	T	B	2	SW	50	A-A		1390-1520
1-8	T	A	2	SE	0	A-A		1555-1665
1-8-1	T	B	2	SE	0	1950	1585	1713-1823
1-9	T	B	2	S	0	A-A		1405-1585
1-9-1	T	A	2	SE	0	1890	945	1276-1560
"	T	B	3	SE	0	1890	1465	1614-1742
1-10	T	B	2	SW	50	A-A		1385-1535
"	T	A	1	S	0	1680	1465	1541-1605
"	T	A	2	S	0	1680	1615	1638-1658
2-1	T	B	1	SE	0	1830	1340	1511-1659
2-2	T	B	2	S	0	1830	1160	1395-1595
"	T	B	2	S	0	1830	1340	1511-1659
2-3	L	B	2	S	0	1920	1525	1663-1783
"	L	B	2	S	0	1860	1650	1723-1787
"	T	B	1	S	0	1920	1710	1783-1847

APPENDIX IV

TABLE 8, RADIOCARBON AND FOSSIL SAMPLES.

Site	Grid reference NZMS. 1	Laboratory Number	Date yr BP.	Collector	Material and Stratigraphy
Upper Waimakariri Harper-White Rivers.	S58/955255	S/58/511	9500±100	Burrows	Wood, from peat layer on alluvium, under 3m of alluvium.
Upper Waimakariri Harper-White Rivers.	S58/955253	S58/512	5470±90	Burrows	Wood buried by alluvial fan 1.5m to 2.0m depth.
Summit, Arthur's Pass	S59/053328	-	8960±140	Kelly	Lowermost peat from 3.5m column. On sands, silts over till. Inside Arthur's Pass moraine loop.
Arthur's Pass highway, McGrath Stream.	S59/051303	S59/552	7820±120	Burrows	Peat on silt overlying outwash. Inside McGrath moraine loop.
Mingha River	S59/089247	S59/556	2100±70	Author	Wood (*Nothofagus solandri*) within landslide deposit.
Taruahuna Pass	S59/157340	S59/551	8090±110	Burrows	Peat over alluvium beneath laminated lake silts.
Casey River landslide.	S59/328346	*S59/557	3570±80	Author	Wood (*Nothofagus solandri*) within landslide deposit.
Upper Poulter	S59/284393	*S59/554	9800±200	Burrows Author	+Wood (*Coprosma sp.*) in silt bed 'A', buried by 17m of alluvium and fan material.

APPENDIX IV

Site	Grid reference NZMS. 1	Laboratory Number	Date yr BP.	Collector	Material and Stratigraphy
Upper Poulter	S59/287394	(S59/555 (S59/559	3640±80 3660±80	Burrows) Author)	+Wood, (*Phyllocladus alpinus*) from bed 'C' silts over alluvium buried by 9.5m of alluvial fan.
Thompson River	S59/332419	S59/558	1690±60	Author	Wood within landslide deposit.
Lake Lyndon	S74/147826	*S74/539	530±70	Burrows	Wood within landslide deposit.
Cameron Valley above Wildman moraine.	S73/587748	*S73/551	2850±70	Burrows	Wood within landslide deposit.
Cameron Valley by Cameron Hut.	S73/576165	*S73/554	537±42	Burrows	Wood underlying outwash and moraine, 7m above river.

* Used for weathering rind thickness growth curve.

\+ See plate 7.

Note The radiocarbon dates are given in terms of the old half-life, uncorrected for secular variation.