HOLOCENE GLACIAL ACTIVITY IN MT COOK NATIONAL PARK, NEW ZEALAND

The use of multi-parameter dating techniques to define glacial moraine chronologies

A thesis presented for
the degree of
Doctor of Philosophy
in the
Department of Botany,
University of Canterbury

by

Anne F. Gellatly

University of Canterbury

1982

VIEW OF MT COOK AND THE MOORHOUSE RANGE
FROM THE VALLEY OF THE TASMAN

John Gully,1862

ABSTRACT

Holocene glacial moraines in Mt Cook National Park are re-dated by multi-parameter dating techniques. The deposits from six main valley glaciers were examined. In earlier studies by other workers the glacial moraine chronology of three of these valleys had been specified using radiocarbon, historical and lichen dating. Results from the present study are compared with this earlier work.

A chronology of glacial events is here defined using historical, radiocarbon and rock weathering rind thickness dating. In addition, post-depositional surface modifications are described using changes in plant development, lichen growth and soil properties.

The more precise dating methods delineate up to fifteen separate glacial expansion phases during the last 10 000 years. The weathering rind chronology defines glacial events around 7200,4200,3790,3350,2940,2540,2160,1830,1490, 1150,840,580,340,135 and <100 years ago. The chronology is strongly correlated with the radiocarbon dated glacial sequence; 8000, c.7000, 4200-4000, 3400, 2800, 2500, 2200-2100, 1800-1600, 1100-1000, 800-700, 340 and 250 yr B.P. In recent historical times the glacial record is characterised by a number of local,minor advances prior to 1900, followed by a general still-stand until about 1930-40. During the last forty years all of the glaciers have been retreating. The widespread glacier recession supports evidence of a climatic warming in New Zealand since about 1930 which has intensified in the last thirty years.

The Mt Cook glacial moraine chronology shows good agreement with the Holocene glacial record described from elsewhere in the Southern Alps of the South Island, New Zealand. A brief comparison with events associated with cool climate periods from elsewhere in the Southern Hemisphere demonstrates a similarity with events in South America, New Guinea, Australia and Antarctica.

The present study indicates the need for revision of the original Mt Cook glacial moraine chronology which had implied extensive glacial expansion around the 17th century and which had grouped all of the events listed above as having formed in the last 1000 years.

CONTENTS

Page

SECTION 1

CHAPTER

SECTION II

SECTION III

LIST OF FIGURES

LIST OF TABLES

SECTION I

Everywhere men wonder, but they are deceived through their thirst for easy explanations.

Eiseley

CHAPTER 1

INTRODUCTION

This study examines the use of a number of different methods available to determine the surface age chronology of Holocene glacial moraines. It has been postulated that a detailed chronology of the moraines can be established by using multi-parameter dating techniques. Similar procedures have been used elsewhere and it was decided to test the hypthesis within the confines of Mt Cook National Park, New Zealand.

Recognition of the number and extent of glacial events in a mountain valley is basic to producing correlations and establishing a glacial chronology. Fluctuations of valley glaciers are usually inferred from positions of lateral and terminal moraines indicating the limits of former ice margins (Chinn 1979).

The Holocene glacial moraine sequence within Mt Cook National Park is generally well preserved. Earlier attempts at producing a chronology of glacial events in the area were undertaken by Lawrence & Lawrence (1965), McGregor (1967), Burrows & Lucas (1967), Burrows (1973a, 1980) and Birkeland (1982). With the exception of the study by Birkeland (1982) these earlier works examined only a few dating parameters prior to describing the ages of the various glacial landforms. Lawrence & Lawrence (1965) dated moraines in the Mueller and Hooker Valleys using measurements of tree-ring growth. McGregor (1967) produced a detailed study of the Holocene moraine deposits in the Ben Ohau Range (an area lying to the south-east of the National Park). He used qualitative measurements of rock weathering and post-depositional surface modification and designated four moraine groups which he called Dun Fiunary (youngest), Jacks Stream, Ferintosh and Birch Hill (oldest). Burrows & Lucas (1967) described a glacial moraine sequence based on lichen growth rates and tree-ring growth. The measurements were calibrated with historical evidence of the glacier positions. This study was continued and the glacial moraine sequence in three valleys was defined using the lichen growth curve (Burrows & Orwin 1971, Burrows 1973a). Burrows (1980) specified radiocarbon dates from the area which related to episodes of glacial activity. With regard to the Mueller, Hooker and Tasman Glaciers at Mt Cook, Burrows (1973a) suggested that there had been marked expansions of one or more of the glaciers in the mid-12th century, mid-13th century, mid-15th century, mid-16th century, mid and late-18th century, early, mid and late-19th century and about 1930 A.D.

Birkeland (1981,1982) undertook fieldwork in the Mt Cook region during 1978-9. He described the surface ages of moraines in the Mueller, Hooker and Tasman Valleys using measurements of weathering rind thickness (after Chinn 1981), soil development, mineral vein relief and lichen growth. He suggested that earlier work in the area had underestimated the ages of the glacial moraine surfaces. Burrows (1980) also suggested that the ages of the oldest surfaces had been underestimated using lichenometric dating.

Both workers indicated the need for a re-examination of the Holocene glacial moraine chronology. Birkeland advocated the use of "as many methods as possible and practicable to arrive at the best overall age estimate", (Birkeland 1982,p.445). Only then may the objectively defined and subdivided deposits provide information on the Holocene history of the area and on correlation, or lack of it, with the histories of other areas (Birkeland *et al*.1976).

1.1 AIMS OF THE STUDY

The present study examines historical data, rock weathering rind analysis, soil development, vegetation development, lichen-dating and radiocarbon-dating for defining a sequence of Holocene glacial moraines. The specific aims of the study are fivefold:

i- To describe the glacial moraine chronology in Mt Cook National Park using as many different, appropriate, age-dating parameters as possible.

ii- To assess the suitability of each method as a dating tool.

iii- To relate this study to earlier work undertaken in the Mt Cook region.

iv- To determine whether the main valley glaciers in the region have undergone synchronous change.

v- To develop a model of the timing and magnitude of glacial events near Mt Cook during the Holocene period and to compare this with chronologies established elsewhere in the South Island, New Zealand.

1.2 ORGANISATION OF THE THESIS

For ease of systematic analysis the thesis is described here in three sections. Section I contains the Introduction (Chapter 1) and details concerning the Field Area (Chapter 2). Information presented in Chapter 2 provides the basis of several assumptions made in the following chapters. The remainder of the thesis is concerned with the analysis of the various dating methods (Section II) and the synthesis of the data collected (Section III).

In Chapter 3, the theoretical frameworks,including assumptions which form the basis for the dating systems, are outlined. Chapter 4 considers the use of historical data for the reconstruction of the late-Holocene glacial chronology. Chapter 5 discusses the use of weathering rind thickness as a surface-age indicator. The results from this approach are combined with evidence from Chapter 4 to provide a temporary dating framework with which to discuss the remaining data. Chapters 6,7 and 8 are concerned with the use of soil development, vegetation development and lichenometry as viable dating methods. Chapter 9 describes the sampling of material for radiocarbon dating. Information presented in some of the earlier chapters is used in the interpretation of palaeosoils and other buried organic material. An extensive list of unpublished radiocarbon dates is included and these are used to highlight possible glacial events.

Section III contains the Synthesis (Chapter 10), Discussion (Chapter 11) and Conclusions (Chapter 12). A Holocene glacial moraine chronology is outlined and the relative importance of the dating tools is discussed and general conclusions drawn.

CHAPTER 2

THE FIELD AREA

2.1 INTRODUCTION

The Mt Cook National Park boundaries enclose an area of approximately 70 000 ha. on the eastern ranges of the Southern Alps, South Island, New Zealand. The Park is adjacent to the Main Divide and stretches from Latitude 43°25'S to Latitude 43°48'S.

The area was chosen for two main reasons; it has a well preserved sequence of glacial moraines and there is easy access to three of the six main valleys contained therein. The six main valley glaciers in Mt Cook National Park are the Mueller, Hooker, Tasman, Murchison, Godley and Classen Glaciers. This study considers all six glaciers and their associated moraine deposits. The study area is shown in Fig.2.1 and a more detailed map of Mt Cook region is included in the map pocket, Fig.2.2 . A number of small, tributary and hanging valleys were also examined.

The field area is described in a number of earlier works which have involved studies of parts of the moraine sequence. These are listed below; Speight (1940), Speight J.G. (1961,1963), Harrington (1951), McKellar (1955), Lawrence & Lawrence (1965), Rowley (1966), McGregor (1963,1967), Burrows (1973a,1980), Burrows & Orwin (1971), Archer *et al.*(1973), Tuck (1975) and Birkeland (1981,1982).

This chapter will examine the geological, climatological and geomorphological background to the area.

2.2. GEOLOGICAL BACKGROUND

2.2.1 Physiography

Within the Park there are six main valley glaciers and over sixty tributary glaciers. Separating the main glaciers are a series of high mountain ranges which culminate in Mt Cook 3764m. The Moorhouse Range, part of the Main Divide, forms the western boundary of the Park. Both the Hooker and Mueller Glaciers are bounded by this range for at least half

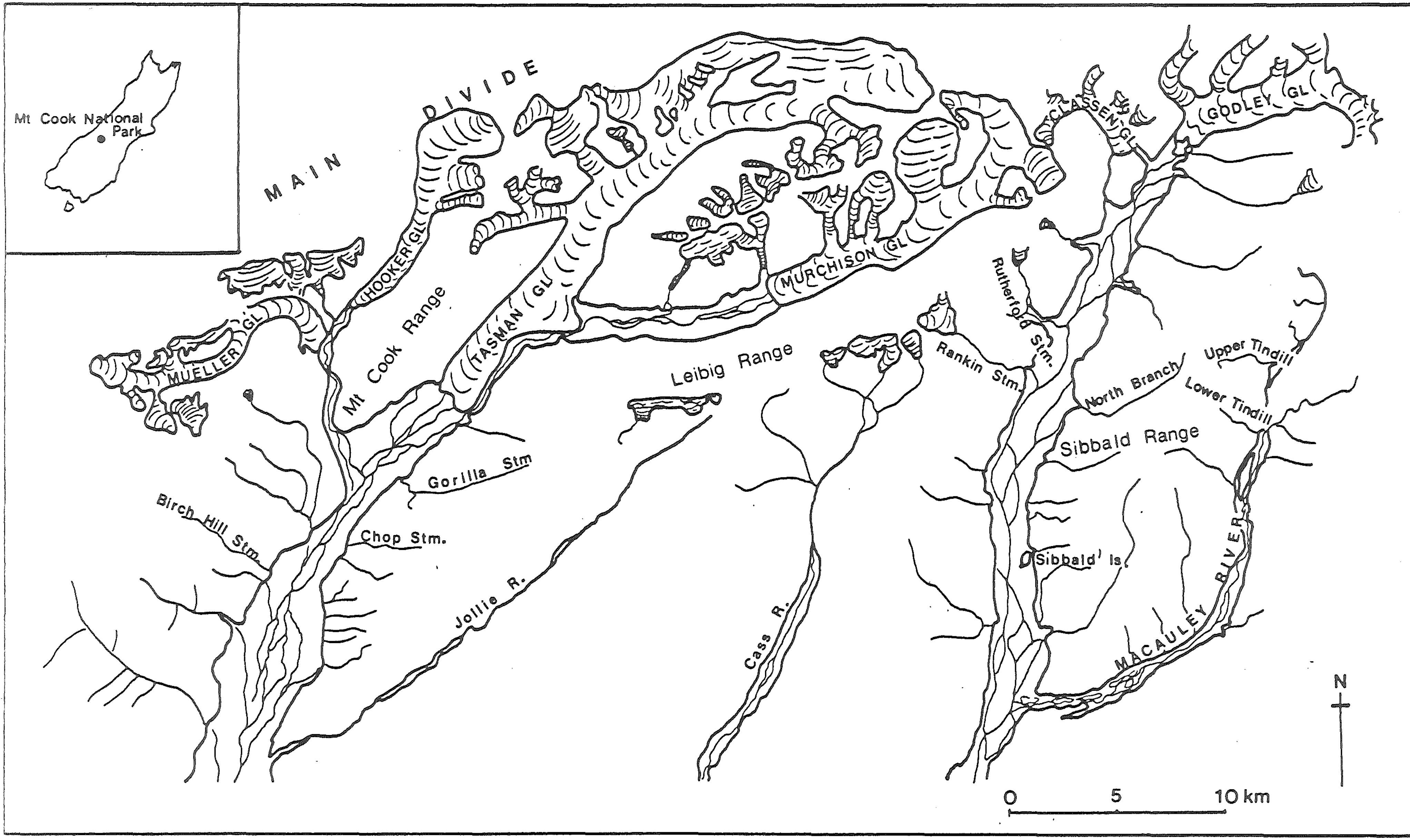


Figure 2.1

The Field Area

of their length. The Hooker Glacier is separated from the Tasman Glacier by the Mt Cook Range. Further east the Murchison Valley joins the Tasman Valley. The Tasman and Murchison Glaciers are separated by the Malte Brun Range but share the same nèvé field on the Main Divide. Melt water from all four valley glaciers flows via the Tasman Valley into Lake Pukaki. The two remaining valleys, the Godley and Classen, are in the north-eastern end of the National Park. Both valleys drain south to Lake Tekapo. The Godley and Classen Glaciers are fed by the nèvé fields on the Main Divide.

2.2.2 Lithology

The Mt Cook region is characterised by two main lithological groups. Torlesse sandstone is the main rock type and outcrops throughout Mt Cook National Park. It is composed of low, indurated greywackes and argillites (Spörli & Lillie 1974)- The second group, Haast Schist, is more common on the West Coast and outcrops only in the areas closest to the Main Divide. Gair (1967) described the Haast Schist Group as comprising weakly schistose,non-foliated greywacke and argillite.

The Torlesse group is defined as a monotonous sequence of metamorphic rock derived from sandstones. siltstones and mudstones, intercalated in varying proportions (Spörli & Lillie *op.cit.*). Outcropping within this group are belts of basic lava (spillites) examples of which can be seen along the Malte Brun Range between the Dixon and Wheeler Glaciers, and on the north-western slopes of the Leibig Range.

Outcrops of the Haast Schist group are noted in the western end of the region, notably on the Moorhouse Range beneath Mt Sefton and on the Sealy and Ben Ohau Ranges (Spörli & Lillie *op.cit.*)

The Torlesse sandstone group is extremely uniform over a wide geographic area, and this is an important factor for the applicability of rock weathering rind thickness as a surface age-determinator (see Chapter 5).

2.2.3 Geological history

The Southern Alps are the product of two major orogenies and one extensive phase of glaciation. The mountains are, relatively speaking, young and are continuing to rise at a rate of 10.6m/1000 years (Stevens 1974). The first phase of uplift was the Rangitata Orogeny which took place during the early Cretaceous. Following intense erosion a second mountain building phase occurred towards the end of the Tertiary with the Kaikoura Orogeny. Glaciation of the Southern Alps commenced in the Late Pleistocene and the general chronology is described by Gage & Suggate (1958). Mansergh (1973) defined three stadials of the Otiran glaciation in the Tasman Valley at the end of Lake Pukaki; the Balmoral (oldest), Mt John and Tekapo moraines. The Otiran Glacial Stage was the last major Pleistocene glacier advance in the Southern Alps and the period lasted from c.70 000 years to c.14 000 years ago.

During the Holocene period the glaciers have undergone extensive retreat punctuated by advances of reduced magnitude. The Holocene glacial activity is recorded in all the main valleys of Mt Cook National Park. Throughout this period there have been some marked changes in the drainage patterns of the main melt water channels. Glacial deposits have been modified by floodplain activity, as was noted by Embleton & King (1969,p.351):-

"Moraines are not always high or continuous. This may result from several possible causes. On the east of the New Zealand Alps, for example, some of the terminal moraines have been considerably eroded by subsequent fluvio-glacial meltwater activity. The lower part of the moraine also has been buried in some areas under the rising mass of fluvio-glacial outwash. The absence of terminal moraines does not necessarily mean that they were never laid down".

2.3 CLIMATOLOGICAL BACKGROUND

2.3.1 Present climate

Details of the present climate of Mt Cook National Park are given in Wilson (1976). A summary of the different components is presented below. Variations in these components are due to a number of factors:

i-proximity to the Main Divide and corresponding W-E precipitation gradients,

ii-influence of the oceanic climate and in particular the westerly airstream.
iii-local variations including local rain shadow effects and exposure to wind, and
iv-incomplete weather records with some errors due to faulty recording and changes in the recording site.

The New Zealand climate record exists from 1853 A.D. onwards. Climate readings from the Mt Cook region were begun in 1901 A.D. but recorded only intermittently. Salinger (1981) described the period of record as extending from 1913 A.D. to the present day. Wilson (1976) noted that rainfall had been measured since at least 1921 A.D. from four sites other than the Hermitage (site of the present village of Mt Cook). Apart from these recordings there are no other records from within Mt Cook National Park.

The location of the main weather station is in Mt Cook village at an altitude of 765m, Latitude 43°44'00"S, Longitude 170°05'06"E. According to Salinger (1981) the site has been neglected at times in the past and he gave details of the site alteration and state of the equipment. Table 2.1 records measurements of temperature, sunshine and rainfall at the Hermitage, Mt Cook during the period 1930-1979 A.D. Table 2.2 presents records of the variation in precipitation from sites in Mt Cook National Park.

Temperature and precipitation patterns are strongly linked to the topography, relief and direction of the predominant airflows over New Zealand (Salinger 1980a,1980b). Strong spatial variations in precipitation are evident within Mt Cook National Park. During the year westerly airflows dominate resulting in high rates of precipitation on the West Coast and a decrease in precipitation further east across the Main Divide, Table 2.2. North-westerlies are often associated with warm air temperatures and strong winds (föhn effect). By way of contrast the southerly airflows which increase in importance in the winter months are associated with cold air temperatures and a decrease in rates of precipitation. Details of the circulation patterns in New Zealand are dealt with in full by Garnier (1958), Trenberth (1976) and Salinger (1979,1980a,1980b,1981).

Table 2.1

Variations in the temperature, sunshine and precipitation records for the Hermitage, Mt Cook. Station no.H30711

Monthly Totals 1930-79	Sunshine hours	Temperature mean daily minimum °C	Temperature mean daily maximum °C	Temperature mean °C	Precipitation mm.
Average	1546	3.4	13.4	8.4	4085
Maximum	1793	4.3(*1978*)*	14.7(*1947*)	9.3(*1971*)	6179(*1967*)
Minimum	1336	2.2(*1951*)	12.7(*1951*)	7.4(*1951*)	1940(*1930*)

* Years in parentheses.

SOURCE: New Zealand Meteorological Service

Table 2.2

Variation in precipitation from sites in Mt Cook National Park.

Station	Altitude m.	Distance from Main Divide km.	Annual mean 1921-1950 mm	Extreme years mm.
Hermitage	760	5.5	4385	1940 (*1930*)* 6179 (*1967*)
Hooker Hut	1130	1.5	7619	
Ball Hut	1130	5.5	5344	
Hooker flats	715	6.0	4246	
Airport	670	10.0	2386	

* Years in parentheses.

Note the sharp decline in precipitation with distance from the Main Divide.

SOURCE: Wilson (1976, Table 1,p.2)

Within Mt Cook National Park the permanent snow-line has been estimated at 2150m (Chinn 1969). The seasonal snow cover reaches 1000m and lower. Snow cover, wind and aspect all exert a strong influence on the environment. Selective sampling of the different age-determining factors, to be discussed in full in Section II, reflects an awareness of the importance of the climatic and environmental variables.

2.3.2 Past climate

Glaciers respond to changes in climate and this response is indicated by ice marginal deposits. For the purposes of this study the past climate is subdivided into two periods: the Immediate Past, that is the period 1853-1980, and the Pre-European Past beginning with the end of the Pleistocene and culminating in the mid-nineteenth century.

A-The Immediate Past The climatic records for the South Island, New Zealand, began in 1853 at Dunedin, 1864 at Lincoln College (Canterbury) and 1866 at Hokitika (West Coast). The composite New Zealand temperature series was described from 1853 onwards by Salinger (1981). Changes in the New Zealand climate during this time were documented by Salinger (1979, 1980a,1980b,1981,1982), Salinger & Gunn (1976), Trenberth (1976,1977) and Hessell (1980). Salinger & Gunn (*op.cit.*) noted the broad temperature trends during this period, in particular a pronounced warming in the most recent decades. This is confirmed in later reports where a 1°C temperature rise is noted since the onset of climate records. According to Salinger (1979,1982),New Zealand temperatures have risen on average 0.5°C since mid-1940 to 1950 A.D. This post 1950's warming is computed to have been less in the Inland Basins area of the South Island - an area which includes Mt Cook National Park.

Trenberth (1977) presented data which supports Salinger's claims for a temperature rise but Hessell (1980) questioned the validity of the assertion that there has been a marked warming since the 1950's arguing instead that the apparent warming is an artefact of the method of recording, site changes and the effect of urbanisation on the recording sites. Salinger (1979,1982) presents independent data to support his claim of a natural temperature rise in New Zealand. These data will be examined at length later in this thesis but mention of the main characteristics are made here.

The evidence for an amelioration of the New Zealand climate this century is supported by independent data which includes glacier shrinkage, decreased number of severe snowstorms and changing circulation patterns (Salinger 1982). Salinger (*loc.cit.*,p.85) concluded that the "profound shrinkage and downwasting (of the glaciers) observed throughout the South Island is concomitant with an absence of exceptional snowstorms reported in the South Island high country". Salinger made reference to a number of key studies, notably Burrows (1976a,1976b), Burrows & Greenland (1979), Wardle (1973), Sara (1968,1970) and Harrington (1958).

Salinger's results indicated that temperatures were lower between 1853 and 1945 A.D. with two cold periods, one in the early 1860's and the other around 1900 A.D. (Salinger 1979). This is supported by evidence of severe snowstorms in the South Island from 1860-1880 A.D. and 1920-1940 A.D. (Burrows 1976a, Burrows & Greenland 1979) and with significant sightings of icebergs in the Southern Oceans between 1852-1858 and 1891-1898 A.D. presented in Burrows (1976b), Table 2.3 .

In addition, Dunwiddie (1979) described years with unusually narrow tree-ring growth from a number of widely spaced sites in New Zealand. The years concerned are 1872, 1887, 1907, 1916 and 1935 A.D., Table 2.3 .

The temperature record for Dunedin, Lincoln College, Mt Cook and New Zealand as a whole is shown in Fig.2.3 . Precipitation trends over the same period (c.1853-1980 A.D.) do not appear to have fluctuated to the same extent. Salinger (1980a) found that precipitation and temperature variations for the South Island west coast glaciers supported each other. A similar study has been undertaken for the Stocking Glacier, Mt Cook (Heine, Salinger & Burrows in prep.) Burrows & Greenland (1979) described data on the occurrence of droughts and floods in Canterbury this century, but no clear relationship to the overall climate record was evident.

Table 2.3

Records indicating exceptionally cold years during the period 1853-1980

Years A.D.	Low temp.[1] recorded	Depressed[2] tree-ring growth.	Severe snow[3] storms	Severe[4] frosts	Iceberg[5] sightings	Ice in[3] Lyttleton harbour
1855-60					+	
1860-65	+		+			
1865-70			+			
1870-75		+	+			
1875-80			+			+
1880-85			+			
1885-90	+	+	+			
1890-95			+	+	+	+
1895-00				+	+	
1900-05	+		+	+		
1905-10		+	+			
1910-15	+		+	+		
1915-20	+	+		+		
1920-25						
1925-30	+					
1930-35	+	+				
1935-40			+			
1940-45	+		+			
1967			+			

+ Event recorded

[1] Salinger (1979,1982)

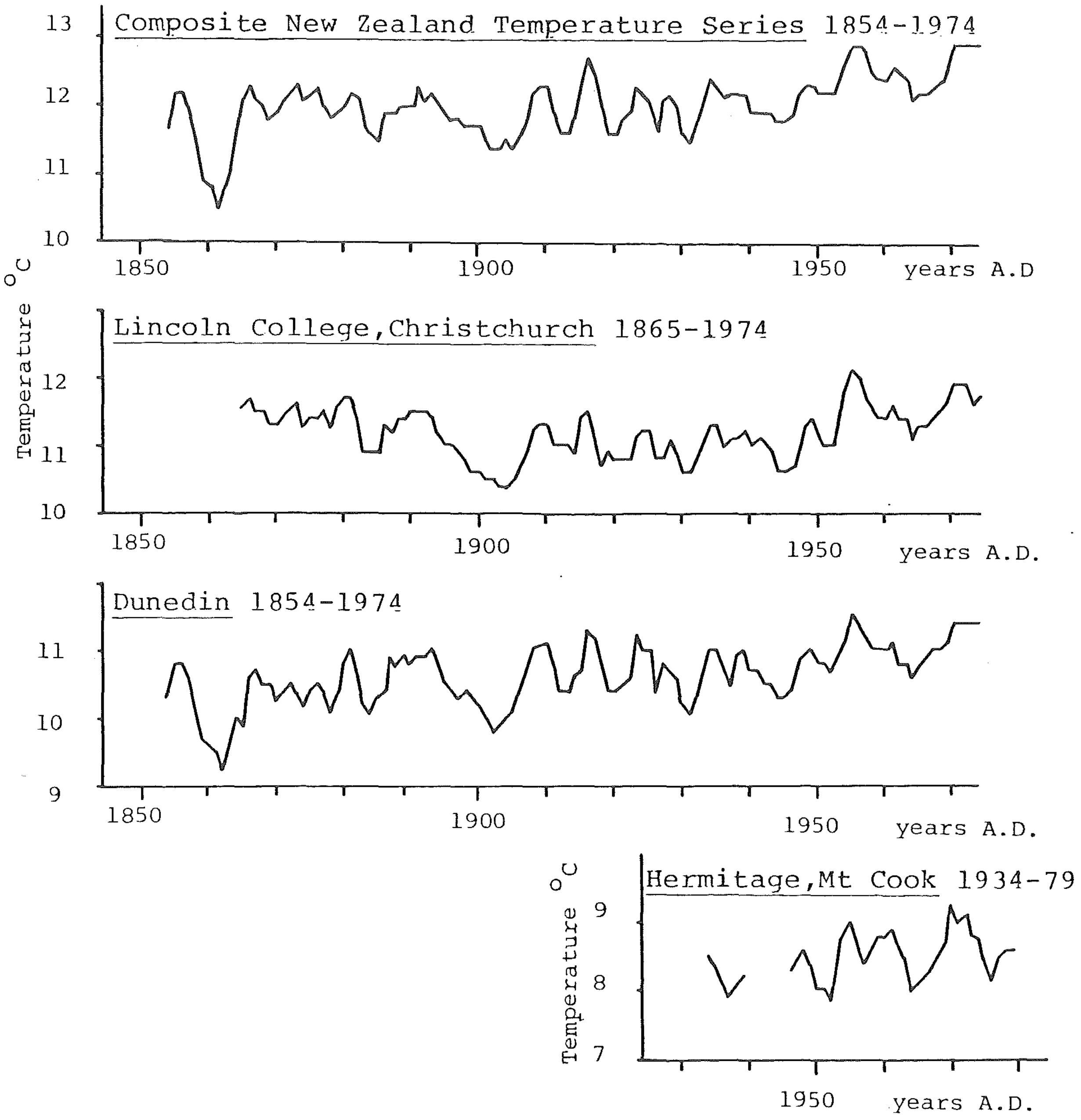
[2] Dunwiddie (1979)

[3] Burrows (1976a)

[4] Burrows & Greenland (1979)

[5] Burrows (1976b)

Figure 2.3 Climate records for New Zealand. Composite temperature series for New Zealand and local temperature records for Lincoln, Dunedin and Mt Cook.



B-The Pre-European Past Evidence for changes in New Zealand's climate during the last 10 000 years is determined from a variety of sources, none as reliable as the record presented for the Immediate Past. Salinger (1976) summarised some of the attempts at using palaeoindicators. The evidence indicated a climatic deterioration starting around 1300 A.D. which was particularly severe during the seventeenth and eighteenth centuries. Burrows & Greenland (1979) described evidence for climatic change in New Zealand during the last one thousand years. They compared the glacial chronology outlined by Burrows (1973a) with speleothem palaeotemperature estimates. The latter showed evidence of cooling around 1450, 1650, 1760 and 1890 A.D. There is some discrepancy between the two records and this was noted by the authors. Grinsted & Wilson (1970) examined variation of $^{13}C/^{12}C$ ratio in cellulose of *Agathis australis* (kauri) as related to climate change. The $\delta^{13}C$ record indicated cold periods around 1070, 1290, 1650 and 1870 A.D. with somewhat less cold periods c.1370 and 1750 A.D. Dunwiddie (1979) recorded depressed tree-ring growth during the early 1600's. A detailed study of dendroclimatology in New Zealand is in preparation (Norton in prep.).

Climatic trends for the last 10 000 years have been estimated from studies of snowline reconstruction (Porter 1975) and pollen analysis. The pollen record indicates a period of climatic amelioration between c.10 000-5000 yr B.P. followed by a change in conditions around 5000 yr B.P. (McGlone & Moar 1977). Species composition changes during the last 5000 years have been related to a more drought and frost prone climate in both the North and South Islands of New Zealand (McGlone & Moar 1977, McGlone & Topping 1977).

Burrows (1979) described a chronology for cool climate episodes in the Southern Hemisphere 12 000-1000 yr B.P. The chronology is based on radiocarbon dates of glacial events and suggests a series of cool episodes c.11 500-9500, 8000, 5400, 4800-4500, 3600, 2700-2000, 1800-1500 and 1100-900 yr B.P. The event dated c.8000 yr B.P. is not indicated in the pollen record, otherwise the two chronologies are similar.

2.4 GEOMORPHOLOGICAL BACKGROUND

2.4.1 Introduction

The landforms in Mt Cook National Park are the product of a series of glacial advances and retreats. It is important that glacial deposits resulting from a glacier advance are distinguished from those deposits formed during a glacier retreat even though they may both be directly related to the same geological event. Thus, deposits in one valley formed during an advance may have only deglaciational equivalents in a neighbouring valley and may not appear to be significantly related in time, only in space. Of course, the converse is true, namely that deposits positioned a similar distance down-valley from the glacier terminus may not necessarily be of comparable age. The landforms studied are frequently complex. Older deposits may be partially or wholly buried by younger events, and some of the older deposits may be destroyed only for the constituent material to be re-worked and deposited with fresh material. Clearly the glacial history, if recorded by valley floor deposits alone, would be incomplete.

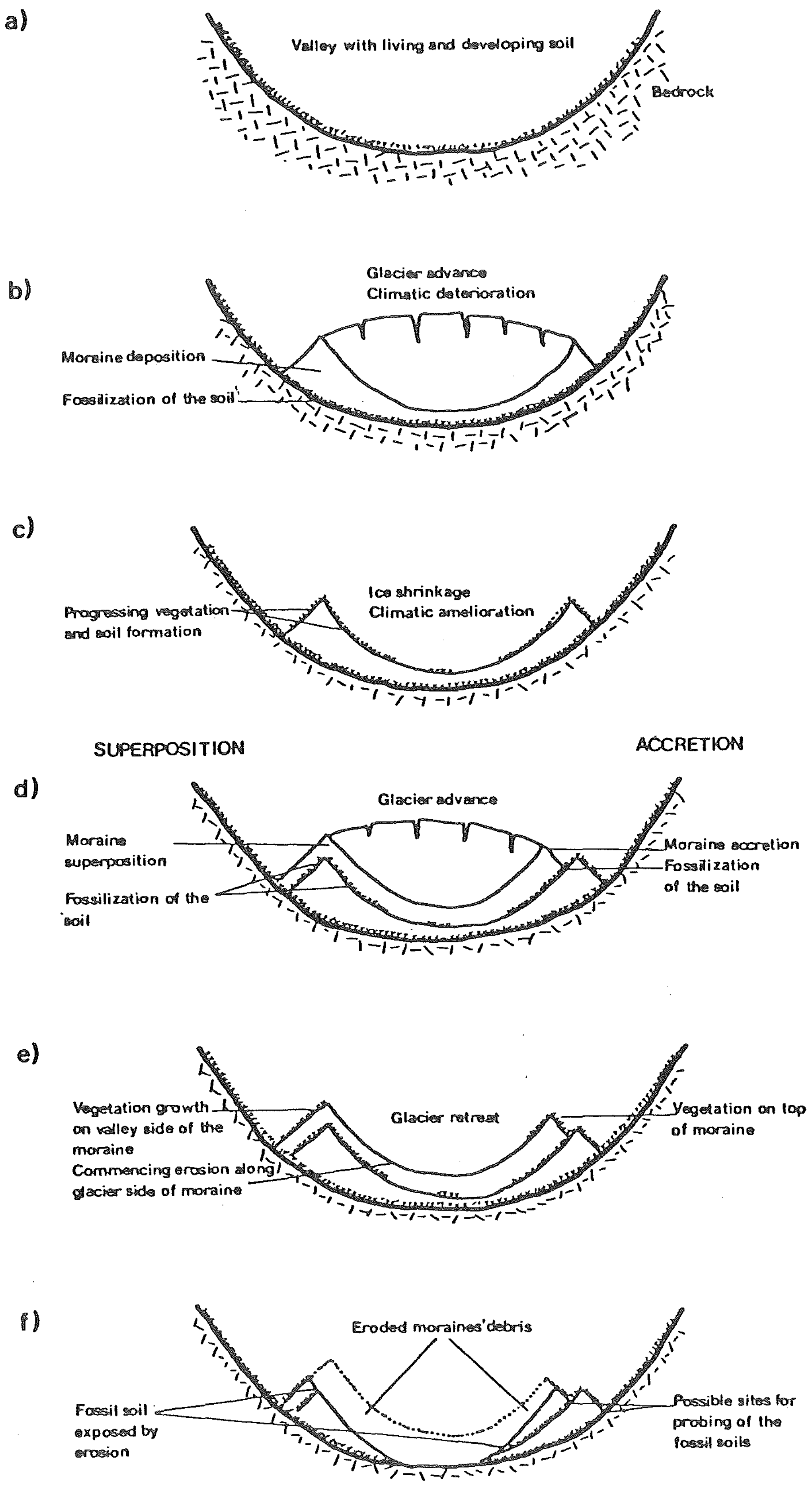
The processes of moraine formation are not discussed here. Suffice to say that the most important mechanisms of glacial deposition include ablation, lodgement, meltout and marginal dumping. These terms are explained in Appendix A. Details of the moraine construction and stratigraphy are of importance and will be discussed further.

2.4.2 Moraine formation

At the termini of most of the valley glaciers being studied there are both old and young moraines which clearly indicate that the glaciers have advanced on several occasions to approximately the same position downvalley. The lateral moraines present in all the valleys demonstrate that the glaciers have also increased in volume to a similar degree on successive expansions and, in some instances, it would appear that the ice levels have exceeded earlier limits. Because the glaciers have oscillated with a similar degree of magnitude, the terminal and lateral moraines often appear as a closely spaced series of deposits of differing age. In some instances the previous moraine sequence is completely overlapped or buried to give a superposed moraine (Röthlisberger & Schneebeli 1979). Elsewhere successive advances produce overlapping or accretion moraines (Röthlisberger & Schneebeli *loc.cit.*) The relation of each moraine deposit to the existing till deposits is extremely important when analysing the stratigraphy of buried soils *in situ* in the moraine walls (see Chapter 9).

The moraine geomorphology was briefly described by Burrows (1973b). He noted that each sharp crested ridge was the result of a glacier expansion. Moraines deposited during the period of deglaciation rarely, if ever, superpose existing deposits although moraines produced during an advance can be deposited as both superposed and accreted moraines. The terminology used in this study is taken from a later, more detailed, account of moraine formation by Röthlisberger & Schneebeli (*op.cit.*). Fig.2.4 is reproduced from their account and demonstrates the processes of burial of an existing surface by a younger period of moraine formation. The detailed caption accompanying this figure is sufficient explanation.

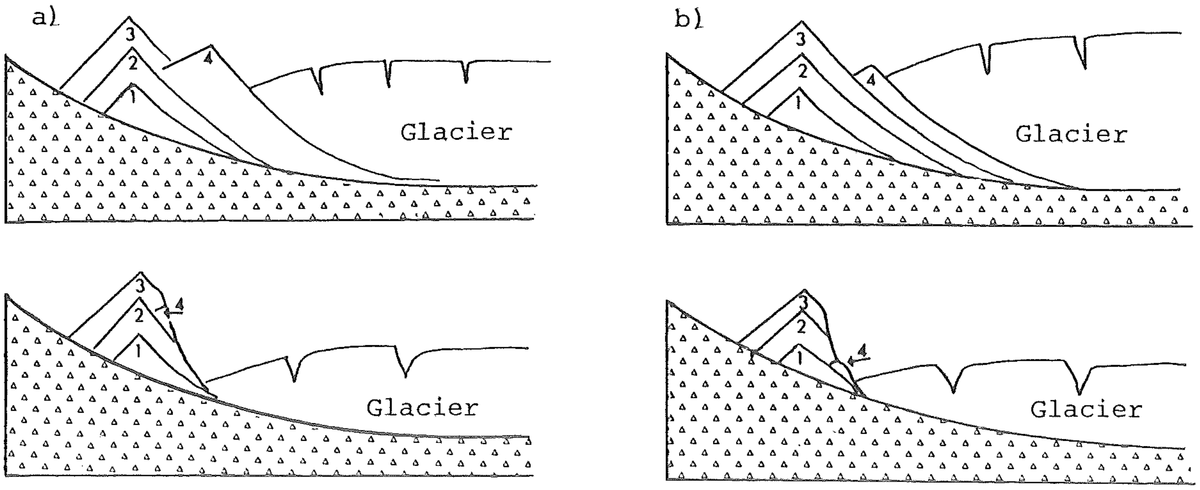
It remains to be said that the situation described so far is inevitably more complex in the field situation. Moraine series may be made up of a number of components with representatives of both modes of deposition. This is shown in the Tasman Valley. Along the Ball Hut road examples of accreted and superposed moraines are found side by side. The lateral moraines of the Hooker Valley are an excellent example of accreted moraines whilst those of the Classen Glacier are once again a mixture of the two. The problem is heightened when examining buried surfaces down eroding moraine walls which have been exposed by recent glacier shrinkage. With the original moraine crest no longer clearly shown and only the soil surface as an indicator of its former position the stratigraphic interpretation becomes both very difficult and of critical importance. At this stage it is probably unlikely that the distinction between accretion and superposition can be made. However, the orientation of the projecting boulders in the till and the angle at which the soil dips backwards into the moraine wall face enables an estimate to be made of


a)
Valley with living and developing soil
Bedrock
b)
Glacier advance
Climatic deterioration
Moraine deposition
Fossilization of the soil
c)
Ice shrinkage
Climatic amelioration
Progressing vegetation and soil formation
SUPERPOSITION
ACCRETION
d)
Glacier advance
Moraine superposition
Fossilization of the soil
Moraine accretion
Fossilization of the soil
e)
Glacier retreat
Vegetation growth on valley side of the moraine
Commencing erosion along glacier side of moraine
Vegetation on top of moraine
f)
Eroded moraines' debris
Fossil soil exposed by erosion
Possible sites for probing of the fossil soils

which side of the original moraine surface is exposed. This point will be elaborated in Chapter 9. Where the boulders project upwards in the till they represent the distal moraine slope in the original deposit. Conversely, where the boulders project downwards, they represent the original proximal moraine slope. Likewise, the inclination of the palaeosurface, assuming that it has not been disturbed through slumping, will indicate its original slope position and aspect.

This introduces the final point in this section. Where a soil is found buried in the moraine wall amongst a series of other buried surfaces and it is evident (for the reasons explained above) that it is from a distal slope position when all the other soils are dipping downwards and assumed to be indicating proximal slope positions, the situation can be interpreted in one of two ways. The soil may represent a moraine that was accreted against the existing moraine wall later in the sequence (Fig.2.5a). Alternatively the soil may represent a moraine surface which has slumped from a position higher up-slope (Fig.2.5b). In both situations the soil stratigraphic sequence will appear 'out of order'. Slumping is commonplace along most of the high lateral moraine ridges throughout Mt Cook National Park, and is attributed to the loss of support by the ice following deglaciation (Burrows 1973a), (cf. Fig.9.1B, p.146).

Fig.2.5 Possible stratigraphic relationships of palaeosurfaces and till with suggestions for their interpretation.



2.4.3 Ancillary evidence of deglaciation

In addition to the moraines exposed through the downwasting and retreat of the glaciers, a number of other modifications to the landscape indicate extensive glacier retreat. Chief amongst these is the formation of frontal glacial lakes. The Mt Cook glaciers have retreated up to 5km since the middle of the last century. Frontal glacial lakes have formed on the inside of the end (terminal) moraines in recent years, the most spectacular example being the lake formation in the Godley and Classen Valleys. Lawrence & Lawrence (1965) indicated the presence of an ancient glacial lake in the Hooker Valley but did not specify its origin.

Associated deglacial features include spillways and abandoned melt-water channels, examples of which can be found around the Blue Lakes (Tasman Valley) and at the Mueller Glacier terminus. Extensive areas of disintegration moraine have formed on the recently exposed glacier forefield. Chaotic piles of moraine debris up to 2m high litter the floodplain marking the rapid recession of the glacier and the melt-out of ice-cored moraine stranded on the valley floor,as seen for example at the Classen Glacier terminus.

Details of the moraine complexes at each glacier terminus will now be presented.

2.5 MUELLER VALLEY

A complex series of terminal and lateral moraines enclose the Mueller Glacier terminus. The glacier descends to a height of 762m. The southern moraine, commonly known as White Horse Hill, reaches a height of 915m. The Northern moraine which traverses the entrance to the Hooker Valley is 955m high. Together with the moraine at Kea Point they form the lateral moraines of the Mueller Glacier. White Horse Hill is a latero-terminal moraine complex, About 200m down-valley of the lowermost slopes of White Horse Hill is a second latero-terminal moraine complex called Foliage Hill. To the east of White Horse Hill are two terminal moraine loops, about 100m apart. Younger, more recent, glacial deposits lie to the inside of White Horse Hill and the inner and outer loops. Fig.2.6 shows the terminal moraines of the Mueller Glacier

Fig.2.6 Mueller Glacier terminus showing White Horse Hill in the left foreground and Northern moraine in the background.

looking north. White Horse Hill is formed by a series of accretionary moraines but the lateral moraines are comprised of superposed till and palaeosurfaces have been found in the Northern moraine (cf. 9.4.1 p.153). The Hooker River cuts through the lateral moraines beneath Wakefield Spur and combines with melt water from the Mueller Glacier which cuts through the terminal moraines.

Between White Horse Hill and Foliage Hill is a small, low lying terminal moraine. This is positioned behind the car park. Downvalley of Foliage Hill is Mt Cook village. Located just over 1km from the terminus the village is built on a landslide deposit which originated from Glencoe Stream. A moraine on the lower slopes of Mt Sebastopol further downvalley was described by Burrows (1980). The oldest Holocene moraines are at Birch Hill in the Tasman Valley and were deposited by both the Tasman and Mueller glaciers. A full description of the Mueller Glacier terminus is given in Burrows (1973a).

2.6 HOOKER VALLEY

The moraines of the Hooker Valley are described by McKellar (1955) and later by Rowley (1966) and Burrows (1973a). High lateral moraines on both sides of the valley, formed by accretion, descend in a step-like fashion from 1036m to 853m at the glacier snout. The highest moraines are assumed to be the oldest, as are the terminal moraines furthest downvalley. Geomorphologically it is difficult to assess where the outermost Hooker terminal moraines merge with the outer lateral moraines of the Mueller Valley. The terminal moraines of the Hooker Glacier are distributed over 1km downvalley of the present day ice margin, Fig.2.7 . The Hooker River dissects the moraines and a small valley side stream separates the lateral from the terminal moraines on the eastern side. Small hanging glaciers descend from the Moorhouse Range on the western side the principal ones being the Stocking and Eugenie Glaciers. The glacial history of the Stocking Glacier is described by Burrows & Heine (1979) and Heine, Salinger & Burrows (in prep.).

Fig.2.7 Glacier moraine deposits in the Hooker Valley from the Sealy Range looking towards Mt Cook. Note the step-like lateral moraines on both sides of the Valley. Mueller Northern moraine in the foreground, Stocking Glacier descending from Moorhouse Range to the left foreground. Hooker River, mid-foreground dissects the terminal moraines. Photo: M.Heine.

2.7 TASMAN VALLEY

High lateral moraines extend along both sides of the Tasman Glacier. There are no surviving terminal moraines but a prominent group of latero-terminal moraines enclosing the Blue Lakes are located slightly up-valley of the present day glacier terminus. The glacier snout is at a height of c.760m. The moraines at Blue Lakes are over 40m higher and rise to over 1076m along the Ball Hut road. The moraines around the Blue Lakes are shown in Fig.2.8. 400m downvalley of the Blue Lakes is a low moraine ridge which was undated in previous studies of the area. Over 1km downvalley near the Blue stream is an exposure of till by a waterfall[1] at grid (S79 813 347, H36 806 186)[2]. Upvalley of the terminus the eastern side of the glacier forms a distinctive bulge as it widens out into the entrance to the Murchison Valley. Palaeosurfaces have been dated in the moraine walls about 8km upstream at the junction with the Ball Glacier.

Fig.2.8 Latero-terminal moraines at Blue Lakes taken from a point over the glacier terminus. High lateral moraine extends north to the junction with the Ball Glacier.

---

[1] The waterfall is unnamed and shall hereon be referred to as the Wakefield Waterfall in this study.

[2] Imperial grid reference is followed by metric grid reference and this format is adopted for the remainder of the study.

2.8 MURCHISON GLACIER

The Murchison Glacier presumably deposited glacial debris in the past, but as is shown in Fig.2.9, the structures have been mostly destroyed by melt water action. Only three separately identifiable moraine loops are recorded at the terminus on the north-western side of the Murchison River. A large frontal glacial lake is forming. Lateral moraines are preserved on the northern side beneath the Malte Brun Range and between the small tributary and hanging glaciers. The glacier descends to a height of c.1000m, over 9km distant from the junction with the Tasman Valley downstream. The principal side valleys are the Burnett, Onslow, Cascade, Baker, Wheeler and Dixon. A much reduced glacier occupies part of each of the side valleys.

Fig.2.9 Terminal moraines of the Murchison Glacier.

2.9 CLASSEN VALLEY

Rapid recession of the Classen Glacier this century has left extensive tracts of deglaciated terrain enclosed by high, unstable lateral moraines. The Classen Glacier terminates in a 60m high ice cliff at the northern end of a frontal glacial

Fig.2.10 Terminal moraines of the Classen Glacier. Note the juxtaposition of older, vegetated moraines and the more recent, high, unstable lateral moraines. Godley River in the foreground.

lake which is nearly 2km long and is drained by the Classen River which cuts through the terminal moraine loops. The Classen River joins the Godley River within 1.5km of the lake. The lateral moraines rise to over 150m above the lake. Recent deposits have encroached on the older vegetated deposits as shown in Figure 2.10 above. The lake actively undercuts the inside of the lateral moraines which are subsequently very steep and unstable. A large "bouldery" moraine loop upstream of the terminal moraines marks the former position of the glacier when it expanded laterally rather than advance forward downvalley.

2.10 GODLEY VALLEY

A large tract of deglaciated terrain extends in front of the rapidly receding Godley Glacier. Until recently the Godley Glacier merged with the Grey and Maud Glaciers but recession has continued to such an extent that the Godley Glacier terminates in a small lake which drains into a very much more extensive lake fronting the Maud Glacier. Recent terminal moraine deposits just south of Separation Stream mark the position reached by the glaciers in the mid-nineteenth century. High lateral moraines surround the main lake and freshly cut river terraces are modified by the changing drainage pattern. Fig.2.11. A distinctive trim line perched over 150m above the floodplain delimits former ice levels.

A very much earlier advance which has been equated with the Birch Hill advance in the Tasman Valley, produced the moraine complex at Sibbald's Island 17km downvalley. Both moraine sets are believed to have formed at the Pleistocene/Holocene boundary according to Speight (1961), McGregor (1963), Gair (1967) and Tuck (1975). Although Birch Hill and Sibbald's Island moraines are outside of the Mt Cook National Park boundary, they will be included here to complete the Holocene glacial chronology being investigated.

Fig.2.11 Deglaciated terrain and recent glacial deposits in the Godley Valley. Godley Glacier is in the valley to the right background of the picture, out of sight.

SECTION II

Nothing is permanent except change.

Heraclitus

3.1 RELATIVE DATING METHODS

3.1.1 Selection

Numerous RD methods are described in the literature but only four satisfied the conditions of selection operating in this study. Relative dating is based upon the premise that certain weathering and other parameters are time-dependent, and therefore they can be used to delineate episodes of deposition (Burke & Birkeland 1979). Other non-temporal weathering or developmental factors are reduced as far as is possible through careful, selective sampling. Selection of the methods is according to five criteria:-

- Methods should be capable of objective, quantitative measurement[1].
- Methods should be reproducible among workers.
- Where possible criteria being measured should be ubiquitous throughout the field area to enable comparison between moraine sets[2].
- Criteria to be measured should be present continuously throughout any one sequence of moraines except where time restricts development. This ensures an unbroken series.
- Together,the methods chosen should cover the whole time span under investigation, and individual methods should, where possible, overlap, cf. Fig.3.1 .

According to Thorn:

> "The strength of relative age-dating lies neither in greater precision nor in the individual parameters, but in the agglomeration of several independent measures". (1975, p.375)

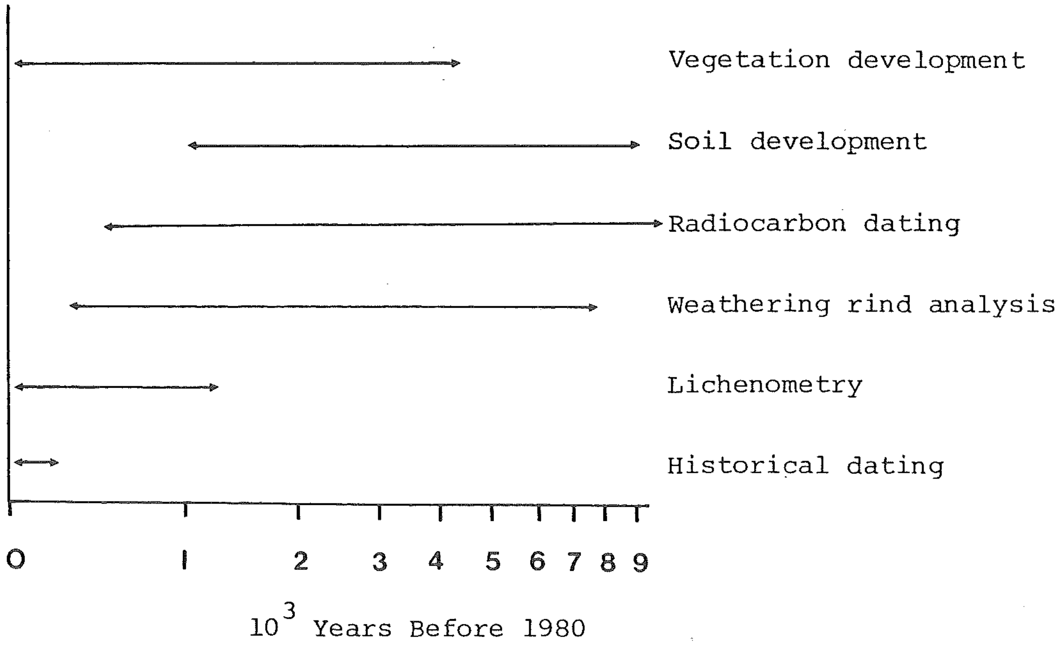
The RD measures used in this study are indicated in Fig.3.1 which shows the effective age-dating range of each approach.

---

[1] This excludes methods such as the 'Hammer Blow Weathering Ratio', 'Fresh to Weathered Ratio' and 'Pitted to Non-pitted Ratio' described by Burke & Birkeland (1979), 'Roundness Analysis' defined by Carroll (1974) and 'Grain Relief' specified by Birkeland (1982).

[2] For example Weathering Rind Analysis. 'Mineral Vein Relief' as used by Birkeland (1982) was found to be localised and therefore not included in this study.

Figure 3.1 Effective ranges of methods used to date Holocene glacial deposits in Mt Cook National Park. Rates of lichen growth, soil development and vegetation development are calibrated with numerical-age estimates. Weathering rinds are calibrated with radiocarbon measurements, cf. Chinn (1981).



3.1.2 Weathering rind thickness analysis

Weathering rind thickness (WRT) is the measure of the extent to which oxidation of the minerals has penetrated below the surface of a clast. It is considered by several workers to be the best single RD method (Birkeland 1973, Mahaney 1973, Williams 1973, Carroll 1974 and Chinn 1981). It has not found favour with other workers and Thorn suggested that:

> "Identification of weathering rind thicknesses as the best, or most useful relative age-dating measure appears inappropriate. Rather, weathering rind thickness is the most sensitive measure, responding to both temporal and spatial conditions. Widespread sampling with the use of mean values to produce smoothing, is advisable".(1975, p.375).

He went on to say that the designation as a 'best' measure is hazardous since only a very small increment of thickness is used to distinguish glaciations.

Colman (1981) described a series of controlled sequences of weathering rind growth. These included the work by Birkeland (1973), Carroll (1974), Carrara & Andrews (1976) and Chinn (1981). Dating control in the former three studies was through the use of lichen dating and other factors whilst Chinn (1981) calibrated weathering rind thickness with radiocarbon measurements. The radiocarbon dates were derived principally from landslide events (cf. Table 5.1 ,p.66). The instantaneous nature of these events renders them very useful for the purpose. Following the work of Chinn (*op.cit.*) in New Zealand, I have measured weathering rind thicknesses on surface clasts throughout Mt Cook National Park.

The approach used in this study closely follows that outlined by Chinn (*op.cit.*). This approach differs from that of other workers overseas in its use of the mode rather than the mean result from a rind count of up to 50 clast measurements at any one site. The modal value is used for two reasons. Firstly to maintain continuity with the existing work by Chinn (*op.cit.*). Secondly I believe that the modal value avoids over-estimation of the age of the deposit where previously weathered clasts are incorporated in its formation. Birkeland (1982) used the weathering rind curve described by Chinn (*op.cit.*) when working in the Ben Ohau Range and he used the mean rind value throughout. He noted a close correspondence between mean and mode values.

A number of factors have been observed to affect measurements of weathering rinds on different lithological groups. These include the influence of fire (Burke & Birkeland 1979, Birkeland 1973, Meierding 1977), vegetation (Clark 1967), climate (Porter 1975, Colman 1977), snow cover (Thorn 1975), position of moraine (Sharp 1969, Burke & Birkeland 1979) and sample variance (Porter 1975, Burke & Birkeland 1979, Anderson & Anderson 1981, Chinn 1981). Lithological variations were recognised by all workers as being the most important factor. Colman & Pierce (1981) described attempts to evaluate the influence of criteria other than time and found that the influence of rock type and climate could not be separated completely. Chinn (1981) suggested that the difference due to climate may be masked by other effects. He concluded that time explained 98% of the variance in rind modal values even though he was sampling in areas with up to 6600mm difference in annual precipitation.

Rates of rock weathering rind thicknesses clearly vary with the nature of the lithology. Colman (1981) described a series of studies which have used weathering rind measurements with varying degrees of age-control. Most studies indicate a decrease in rates of rock weathering with time. Colman suggested that:

> "the more a material weathers, the slower it weathers, and the thicker the residual layer, the slower its thickness increases". (Colman 1981, p.262).

Fig.3.1 shows the effective range of weathering rind thickness measurements used in the present study. After about 8000 years surface clasts within the Mt Cook region showed signs of being completely weathered and the rind was often no longer distinct. Rind measurements could not be obtained on the younger surfaces, which are dated using historic data and lichenometry.

3.1.3 Lichen dating

The basic premise of lichenometry is that the diameter of the lichen thallus is directly proportional to the surface age. The technique was first described in English by Beschel (1957, 1958, 1961) and Platt & Amsler (1955). There have followed a great many studies which have recently been reviewed by Lock, Andrews & Webber (1979).

Lichen measurements have been commonly used to date glacial moraines, both as a relative and numerical age dating tool (Benedict 1967, Burrows & Lucas 1967, Burrows & Orwin 1971, Burrows 1973a, Matthews 1973, 1974, 1977, Beschel 1973, Denton & Karlèn 1973a, Miller 1973, Jochimsen 1973, Carrara & Andrews 1973, Birkeland 1873, 1981, 1982, Carroll 1974, Calkin & Ellis 1980, Gellatly 1982).

Apparent in the literature is the lack of consistency among workers with regard to sampling techniques. A procedure has been outlined by Lock *et al.*(1979) which emphasises four points:

- the diameter measured be that of the largest inscribed circle,
- that fixed-area searches are preferred to fixed-time or exhaustive ones,
- that the mean of the 5 largest thalli be less variable than the single maximum, and
- that the application of multiple methods, where time permits, is to be preferred to the use of only a single method.

This procedure has been adopted for the present study. It differs in several respects from earlier work in Mt Cook National Park, which places limits on the comparisons made between the studies.

Burrows dated the moraine surfaces in Mt Cook National Park (Burrows 1973a), in the Cameron Valley (Burrows 1975) and in the Upper Rakaia Valley (Burrows & Maunder 1975, Burrows & Russell 1975), using the lichen growth curve described by Burrows & Orwin (1971). Measurements were made of the single largest diameter of thalli from the genus *Rhizocarpon*. Burrows & Orwin (*loc.cit.*) recorded sampling of two species,*Rhizocarpon geographicum* and *R.candidum*. A later study by Birkeland (1982) suggested that because of problems with lichen taxonomy sampling of members of the yellow-green *R.geographicum* complex at the species level is unrealistic. Birkeland referred solely to the use of the genus *Rhizocarpon*. He used a different measuring parameter to earlier workers in so far as he recorded the minimum x maximum diameters.

Burrows & Orwin (1971) used exhaustive searches whereby Burrows (1973a) stated that "all likely boulders were examined for lichens". They sampled from both sides of the moraine ridges. Birkeland does not elaborate on his procedure. However he did describe lichenometry in relation to a series of other well defined RD techniques.

Details of the effect of environment on lichen growth are discussed by Orwin (1970, 1972). She suggested that whilst lichens are generally sensitive to micro- and macro-climatic differences, *R.geographicum* apparently does not reflect the sensitivity of the lichen flora as a whole. Burrows & Orwin (*op.cit.*) presented lichen growth curves for both the *Rhizocarpon* species sampled. The growth curves are linear and the rates of growth amongst the highest recorded in the world. Birkeland (1981,1982) suggested that a slower rate of growth after about 1890 A.D. might be more realistic. He examined soil development on two moraine surfaces dated 1890 and 1850 A.D. by Burrows (1973a) and found these to be minimal age estimates.

The value of lichen dating lies in its ability to date closely spaced, recent, events where other techniques may, for various reasons, be inappropriate (Beschel 1973). Fig.3.1 shows the effective range of lichenometry as it was used in the present study. Lichen measurements were collected from three areas: the terminal moraines of the Mueller, Tasman and Classen Glaciers. The Tasman and Mueller sites were chosen to enable comparison with earlier work and the Classen sites were selected as the moraines have not been previously dated.

3.1.4 Vegetation development

The vegetation of Mt Cook National Park is described by Wall (1925) and Wilson (1976). Early plant succession studies in the area include a brief unpublished report by Moar (Goldthwaite pers.comm.) and a study of the vegetation on the Hooker Valley moraines by Rowley (1966). Burrows (1973a) briefly indicated the composition of vegetation on surfaces of increasing age in the Tasman, Mueller and Hooker Valleys, Burrows & Heine (1979) described the vegetation on the older moraines of the Stocking Glacier, Hooker Valley.

The use of vegetation as a RD method is based on the premise that the major vegetation groups found on a series of spatially separated moraines are related to the age of deposition and stability of that surface. Numerous workers have used vegetation analyses as indicators of the length of time that glacial deposits have been exposed, (Lawrence 1958, Stork 1963, Rowley 1966. Viereck 1966, Sigafoos & Hendricks 1969, Rampton 1970, Reiners *et al*. 1971, Matthews 1979 , Wardle 1980 and Birks 1980). Other workers have described vegetation development in relation to soil formation on glacial deposits (Crocker & Major 1955, Crocker & Dickson 1957, Franzmeier & Whiteside 1963, Stevens 1964, Tisdale & Fosberg 1966, Ugolini 1968).

The vegetation sequence is dependent on a series of variables which are in turn not always temporally based. The influence of these different variables changes over time. The most important factors include: availability of disseminules of potential colonists, substrate and microclimatic conditions (which will alter with establishment of seedlings and subsequent plant growth), changes in soil conditions affecting seedling establishment and interaction between individuals and species present.

Time may be relatively unimportant in the initial stages of surface colonisation given all the other controlling factors. The moraine habitat is extremely variable depending on its stability, composition and position. Moraines which are either very unstable due to a melting ice core or the addition of fresh material, or which are constructed out of extremely large boulders, will have bare surfaces for a longer period of time than a stable, silty-sandy moraine surface. The colonising pattern may be interrupted at various times by the erosion and redeposition of loess, or by small changes in microclimate created by oscillating positions of the glacier terminus. The pattern described by the vegetation in any area must be interpreted carefully.

Fig.3.1 refers to the effective range of plant development studies for relative age-dating in the present study. Moraine surfaces examined varied in age from c.0-4000 years. Fire has been a major source of disturbance in the region (Wilson 1976). The sites chosen were from areas known to have escaped extensive burning because fire could override the effects of time on vegetation development. Plant development sequences are presented from the Hooker and Classen Valleys.

3.1.5 Soil development

The soil profile is the net product of all the changes that have taken place over time. It is assumed (because it cannot be unequivocally demonstrated in the soil profile) that there will be a response to change in environmental factors. This response, which includes changes in the vegetation development, will precipitate feedback mechanisms in the soil related to weathering transformations, declining soil fertility, changes in biochemical dynamics and so on.

A sequence of soils which share a similar history throughout the duration of the soil formation and which developed in a similar environment (uniform climate, parent material and topographic situation) may be examined within the concept of a chronosequence, (Crocker & Major 1955, Crocker & Dickson 1957, Stevens 1964, 1968, Viereck 1966, Tisdale & Fosberg 1966, Goldthwait *et al.*1966, Stevens & Walker 1970, Campbell 1975 and Ross *et al.*1977).

Monogenetic soils developed on moraine surfaces at different times, e.g. a sequence of recessional moraines, are described as 'post-incisive' (Vreeken 1975). It is of interest to note that a second classification of chronosequence will be examined in this thesis. Sequences of palaeosoils exposed in the lateral moraine walls are examples of 'time-transgressive' chronosequences without historical overlap (Vreeken 1975).

The surface soils in Mt Cook National Park are classified as 'high country yellow-brown earths' Cutler, 1968). Detailed studies of soil development in areas adjacent to the Mt Cook region are given in Archer (1976) and Webb (1976). Birkeland (1981,1982) described soil development on two recent moraines in the Mueller Valley, and on Holocene glacial surfaces in the Ben Ohau Range.Other studies make reference only to the physical properties of the soil profile. McGregor (1963) and Tuck (1975) described the soil cover on Sibbalds Island, Godley Valley. Burrows (1980) recorded soil characteristics on moraines near Mt Cook.

McGregor (1967) noted the thick loess cover on Sibbalds Island and Birch Hill moraines. Loess is a major source of input to the high country soils. Steady addition of loess material may accelerate soil profile change. Rapid accumulation, however, may overload the soil system and decelerate the rate of change in the soil profile. Loess when added in such quantities, may result in a polygenetic soil (cf. Fig.6.1 p.84).

The soils examined in this study are from surfaces aged c.800-8000 years old. It is assumed from studies of climate, parent material and vegetation history that the soils are monogenetic. Fire, which affects the rate and nature of vegetation change (cf.3.1.4,p.32) is also considered as a source of environmental change in relation to soil development. Fire causes profound, immediate changes to soil systems and will often also initiate erosion and deposition thereby altering the depth and nature of the soil profile.

The soil development was investigated in three comparable areas: Tasman, Mueller and Classen Valley latero-terminal moraines. Other valleys were excluded due to higher precipitation rates (Hooker Valley), increased schistosity of the parent material (Hooker Valley) and the absence of older glacial deposits (Murchison and Godley Valleys).

3.2 RADIOMETRIC AND HISTORICAL DATING METHODS

Wherever possible the rates of post-depositional surface modification as determined by RD are calibrated against more accurate dating control. In the present study the Holocene glacial history is recorded by historic data and radiocarbon dating of palaeosurfaces in the lateral moraines.

3.2.1 Historical dating

The use of historical dating to describe the fluctuations in glacier front positions is well known, particularly in Europe where the period of observation extends back several hundred years (Lamb 1977, Ahlmann 1953, Schneebeli 1976).

Recorded observations of the Mt Cook glaciers began in 1862. The available information is drawn from paintings, photographs, maps and written accounts. Events are recorded with an accuracy of < ±5 years. Studies of New Zealand glaciers using historical accounts include work by Wardle (1973) and Sara (1979) on the West Coast glaciers, and Heine & Burrows (1980) on the Stocking Glacier, Mt Cook.

3.2.2 Radiocarbon dating

Alternating deposits of palaeosoils (representing former surface soil cover on buried moraines) and glacial till are exposed in the eroding lateral moraine walls. Dating of the *in situ* soils and/or the wood or plant litter resting on them, provides information on the intervals between glacial episodes, the ages of the soils and the periods of glacial expansion depending on which materials are dated. Burrows (1973a) described a radiocarbon date from wood,buried by avalanche material,which was collected by I.C.McKellar from near the Ball Hut, Tasman Valley. Subsequent investigations have resulted in futher finds of material for radiocarbon dating (Burrows 1979, 1980, Burrows & Gellatly 1982). Radiocarbon dates from some glaciers in Westland, New Zealand, are described by Wardle (1973, 1978) in relation to periods of glacial expansion. Reference will be made to the work of Röthlisberger (1976), Schneebeli (1976), Röthlisberger & Schneebeli (1979) and Röthlisberger *et al.*(1981) who have produced a detailed reconstruction of Holocene glacial events in the European Alps based on radiocarbon dated material.

The radiocarbon chronology for Mt Cook National Park extends from c.300-c.8000 yr B.P. Dates presented normally have an error of ±50 yr. Röthlisberger *et al.*(1980) specified four factors which determine the numerical value and deviation of a radiocarbon age[1]:

i-the influence of cosmic rays on the upper atmosphere,
ii-the mathematical-physical laws of radioactive decay,

---

[1] Assuming that the stratigraphic position has been correctly assessed when the sample was collected.

iii-the type of sample materials

iv-the laboratory equipment

These and other problems are elaborated in Appendix B. The problems of dating palaeosoils using radiocarbon ages are discussed by Geyh *et al.* (1972), Olsson (1974) Matthews (1980) and Röthlisberger & Schneebeli (1979). Griffey & Matthews (1978) recognised the need for more detailed understanding of age/depth relationships in present day 'analogue' soils. This would permit an evaluation of the apparent mean residence time (A.M.R.T.) which is an essential part of the interpretation of radiocarbon dates derived from soil samples. Matthews (1980) observed a steep age/depth gradient from within the upper horizon of a buried podzol soil which confirmed findings by Sharpenseel (1972) in present day soil profiles. Matthews discusses the implications of this age/depth gradient with respect to the accuracy of radiocarbon dates and noted that:

> "the 'age/depth effect' alone may be a potential source of error in excess of 1000y" (Matthews *loc.cit.*,p.472).

Matthews (*loc.cit.*, p.474) concluded that "if estimates of date of burial of a palaeosoil are required...samples should be selected from as near as possible to the top of the upper horizon, in order to minimize A.M.R.T." (apparent mean residence time).

Approximate concordance of radiocarbon dates with solar years can be obtained by applying two corrections; the use of the accurate half-life for C14 and the use of the calibration curve for C 14 obtained with the aid of dendrochronology. Baillie (1982) points out that solar years or calendar dates cannot be reliably deduced from conventional radiocarbon dates.This point was also made by Röthlisberger *et al.*(1980) using data from Porter (1979). They showed that any radiocarbon year may be equivalent to more than one calendar year and gave examples from the last 400 years.

Details of the sampling of palaeosoils are presented in Chapter 9. Radiocarbon dates are recorded for a series of glacial events from four main valleys; Tasman,Hooker,Mueller and Godley, and from three side valleys; Baker, Dixon and Wheeler.

CHAPTER 4

HISTORICAL INFORMATION

4.1 INTRODUCTION

The most accurate control points in the glacial moraine chronology for Mt Cook National Park are established using historical records which exist from 1862 onwards. The information presented has been obtained from published work, private collections and the majority of it from three National collections; the Alexander Turnbull Library Wellington, the Canterbury Museum Christchurch, and the Hocken Library Dunedin. Details of the glacier recession since 1862 are related to climatic records for the same period (Salinger 1979, 1982). Neither the historical nor the climatic records are complete.

4.2 THE CLIMATIC RECORD A.D.1853-1982

The climatic record for the period 1853-1982 A.D. in New Zealand was described in section 2.3.2 (p.10). The reader is reminded of the main points arising from this section:

i- Mean temperature records have increased by 1°C in New Zealand since the beginning of weather recording.

ii- An increase of 0.5°C is recorded for the composite New Zealand mean temperature record since 1950.

iii- Temperature warming in the Inland Basin area since 1950 may have been as little as 0.1°C.

iv- Two cold periods are recorded; the 1860's and 1890's. In addition a number of relatively cold years are recorded with the aid of proxy climatic indicators; 1861 & 62, 1863, 1867, 1870, 1877, 1879, 1884-88, 1895, 1902-5, 1908, 1912 & 1913, 1916, 1918, 1926, 1931, 1935, 1939, 1944 & 45, 1967.

4.3 THE HISTORIC RECORD A.D.1862-1982

The earliest recorded observations of the glaciers in the Mt Cook region were made in 1862 by Julius von Haast. Sheep stations had already been established in the Tasman and

and lower Godley valleys. According to Dobson (1930), who accompanied von Haast, the shepherds were unaware of the true nature of the heads of the valleys. He noted (*loc.cit.*, p.203) that "a few shepherds had been up the valley of the Tasman and reported it to end in a wall of rock". One runholder who did explore the area up-valley was Nicolo Radove and his comments were recorded by Hutton (1888). Von Haast made detailed observations of all that he saw including a number of pencil sketches[#] later interpreted in water colour by John Gully[#], (Paul 1974). Haast also made plane-table surveys of the termini of the Godley and Classen Glaciers, and of the Tasman Glacier[#], (Fig.4.1). Von Haast revisited the Mt Cook region in 1865 and 1870 (Hilgendorf 1932).

In 1867 E.P.Sealy visited the Mueller Glacier and amongst his early work is a small sketch map of the Mueller Glacier, and a number of early photographs. The sketch map is reproduced in Hutton (1888) and a photograph of the Moorhouse Range and the Mueller Glacier by Sealy was published in von Haast (1970). Further early photographs of the Mueller Glacier were taken by F.A.Coxhead ‹pre-1886›[*], Burton Brothers ‹c.1875›[*#+], Wheeler ‹1888›[*] and Morris ‹undated but c.1880's›[*].

An early account of the glaciers around Mt Cook is given in Green's description of his travels and climbing in 1882 (Green 1883). Dr von Lendenfeld completed a detailed map of the Tasman Glacier in 1883,(Fig.4.2), and this was used by Green in the preparation of a sketch map of the Tasman Glacier in 1884, (Fig.4.3). In 1884 H.G.Wright, the District Surveyor, produced a sketch plan of the Hooker Valley (Fig.4.4), and this contains useful detail on the state of the vegetation in this area.

Hutton (1888) described in detail the Mueller Glacier and included his own sketch map in this account. In the same year Aubrey painted a picture of the Tasman Glacier by the Blue Lakes, (held in a private collection, Mr Hyde, Whakatane). Broderick, a Government Surveyor, produced

---

[#] Held in the Alexander Turnbull Library, Wellington, New Zealand.
[*] Held in the Hocken Library, Dunedin, New Zealand.
[+] Held in the Canterbury Museum, Christchurch, New Zealand.

a plan of the Godley and Sinclair Districts in 1888 (Fig.4.5) and this was followed in the succeeding years with topographical maps of the Mueller District 1889 (sheet 39T), Tasman and Murchison Glaciers 1891 (sheets 60T & 61T)[x]. A sketch plan of the Mueller Glacier terminus in Broderick's field notebook (Timaru field notebook no.387)[x] shows in detail the ice front position in October 1890.

Baker compiled a map of the Mt Cook glaciers in 1890 using both von Lendenfeld's and Broderick's surveys, (Fig.4.6). The following year, Baker (1891) measured the distance that stones were transported on the Mueller Glacier surface and he drew a diagram to indicate glacier motion. The measurements were repeated and a second diagram produced by Mannering in 1905, (Fig.4.7).

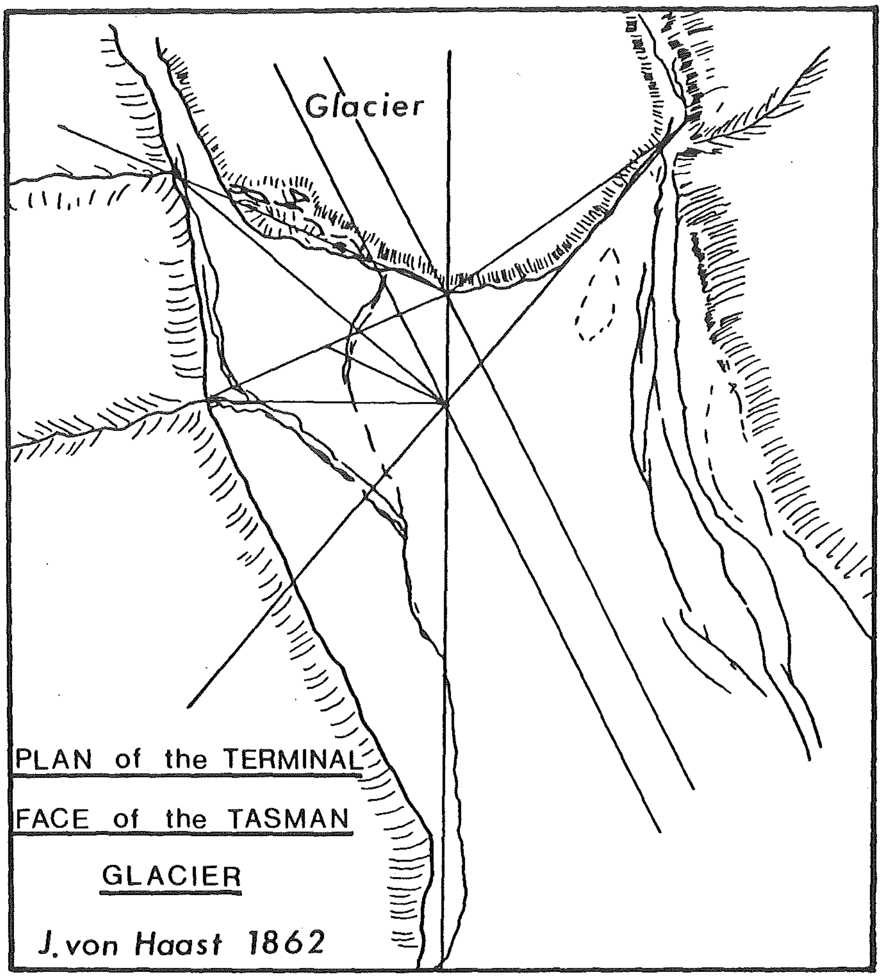
The Murchison Glacier was mapped twice in this early period. Firstly by Mannering in 1890,(Fig.4.8) and then two years later by Harper *et al.*(1892) as part of a general map of the Southern Alps (Fig.4.9) Mannering compiled a sketch map of the Godley Glacier in 1892,(Fig.4.10).

Later maps have relied strongly on these early surveys and appear to have paid little attention to changing positions of the glacier termini, for example the map of the McKenzie Country 1909 by Strauchon *et al.*. More recently a topographic map series was compiled using aerial photographs dating from 1964-65. This present map series is currently undergoing metric conversion. (see footnote 2, p.22)

On the following pages Figs. 4.1-4.10 are presented. All of the diagrams and maps have been redrawn from the originals which were generally in too poor a state to be clearly reproduced. In redrawing the maps particular care has been taken to reproduce exactly the style and detail of the originals. A discussion of the photographic record follows on p.51.

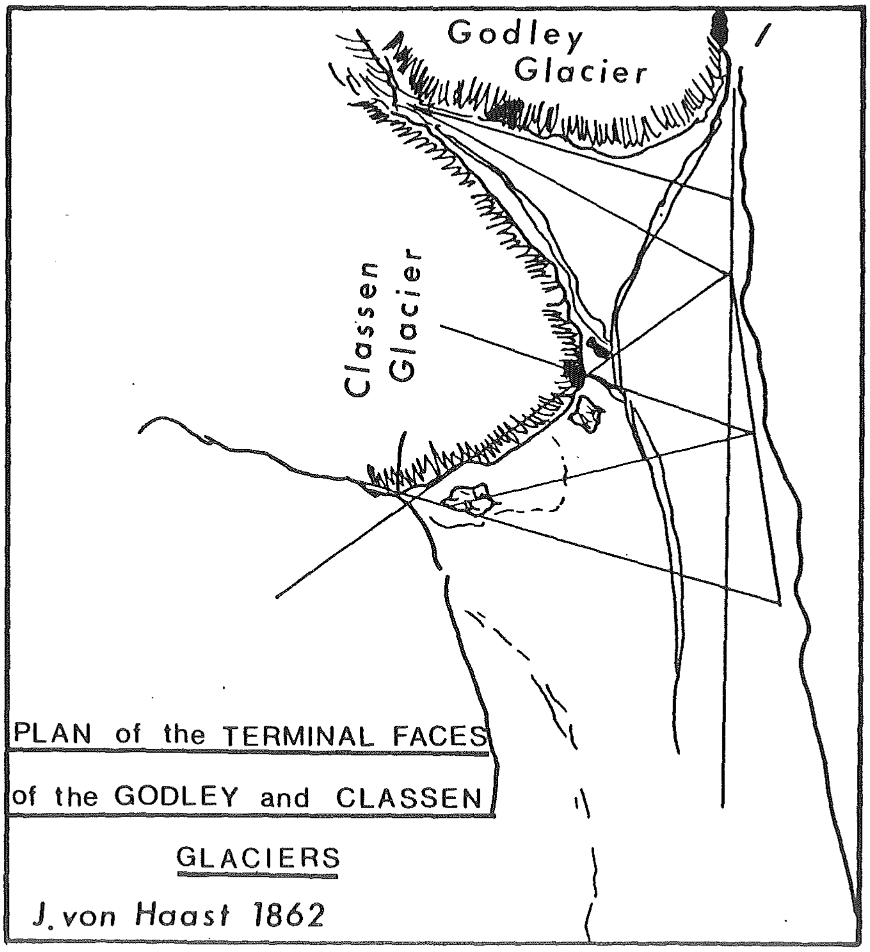
---

[x] Held in the map archives, Department of Lands and Survey, Christchurch New Zealand.



PLAN of the TERMINAL FACE of the TASMAN GLACIER

J. von Haast 1862

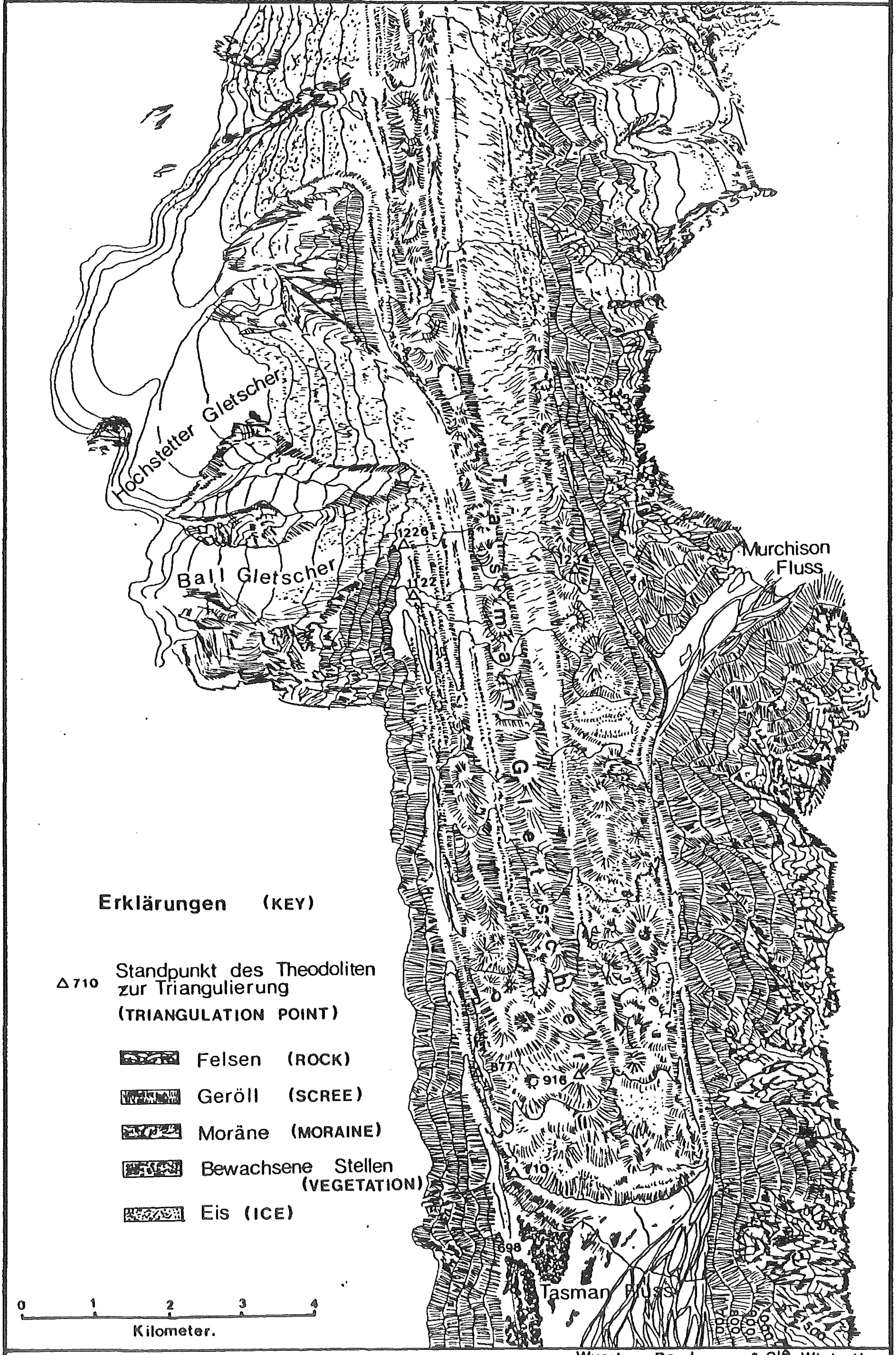


PLAN of the TERMINAL FACES of the GODLEY and CLASSEN GLACIERS

J. von Haast 1862

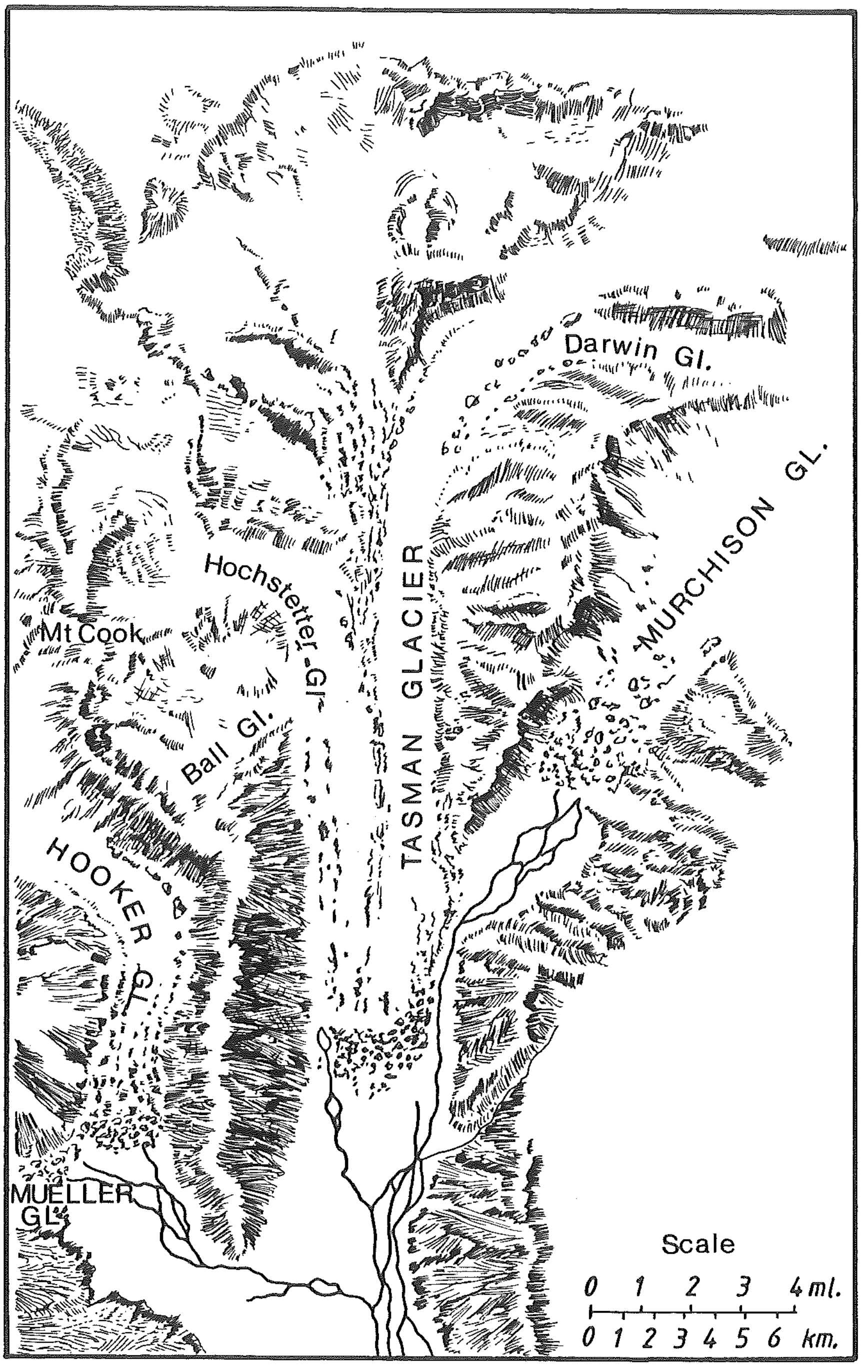
KARTE des TASMAN-GLETSCHER (1883) von DR. R. von LENDENFELD

MAP of the TASMAN GLACIER (1883) by Dr. R. von LENDENFELD



Wurster, Randegger & Cie. Winterthur

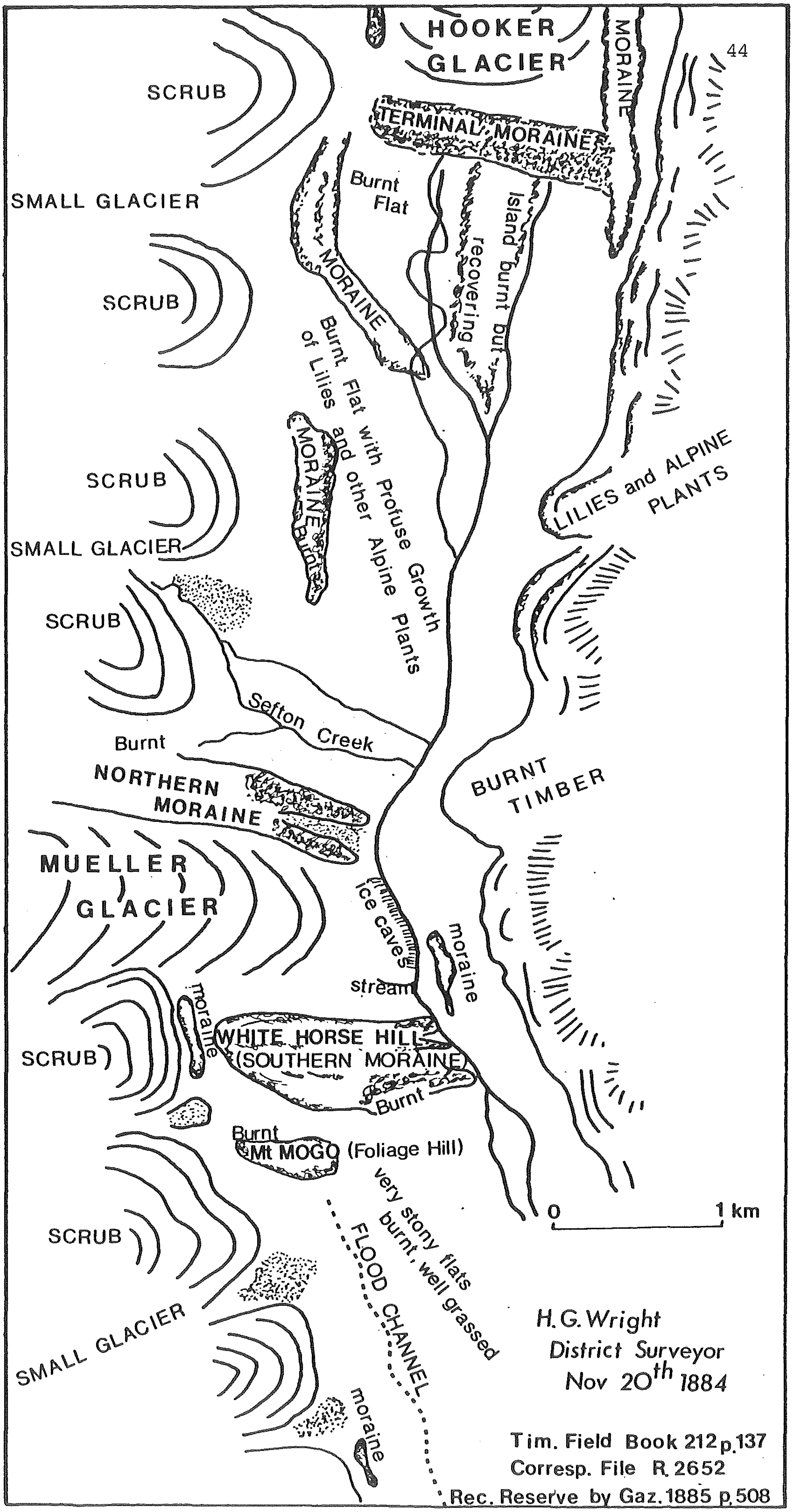
GOTHA: JUSTUS PERTHES 1884



SKETCH MAP of THE GREAT TASMAN GLACIER and its TRIBUTARIES (1884)

by the Rev^{d} W.S. Green, M.A. with additions from D^{r} von Lendenfeld's Map

Published for Proceedings of Royal Geographical Society, 1884



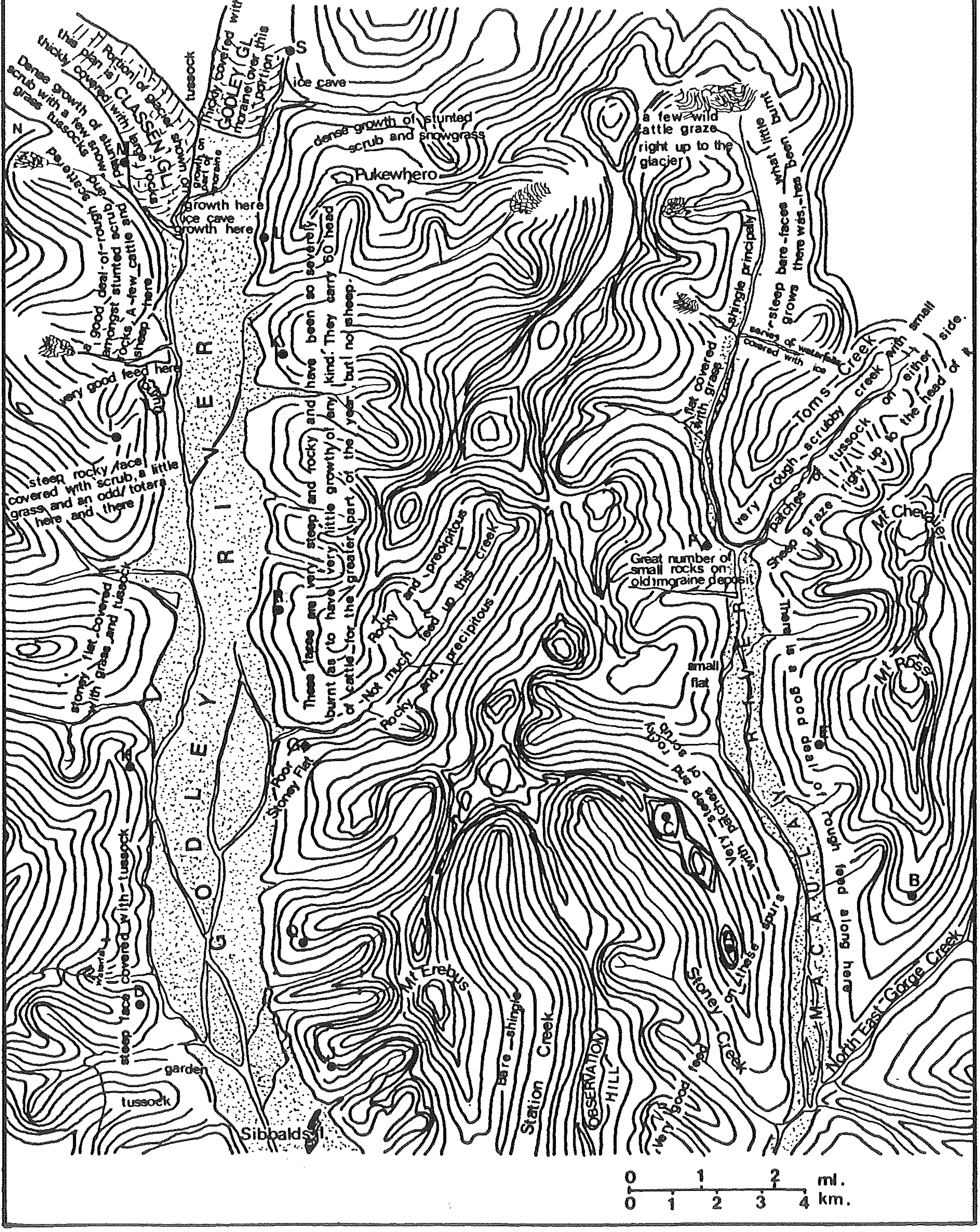
H.G. Wright
District Surveyor
Nov 20th 1884

Tim. Field Book 212 p.137
Corresp. File R.2652
Rec. Reserve by Gaz. 1885 p.508

SKETCH PLAN of the VALLEY of the 'HOOKER' showing the Habitable Land in the Vicinity of the MUELLER GL.

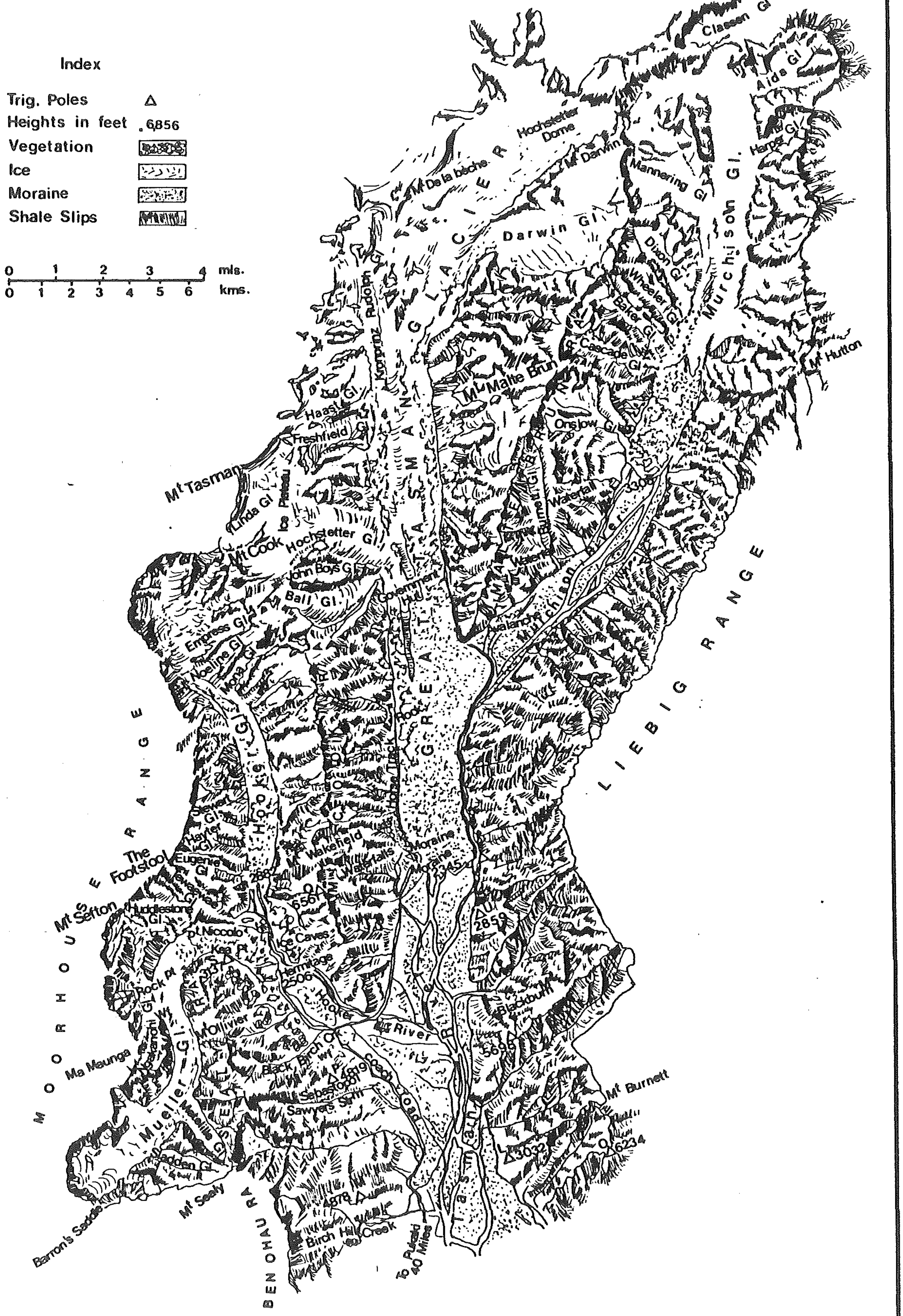
Plan of the **GODLEY** and part of the **SINCLAIR DISTRICTS** by

T. N. BRODERICK , Assistant Surveyor, 1888



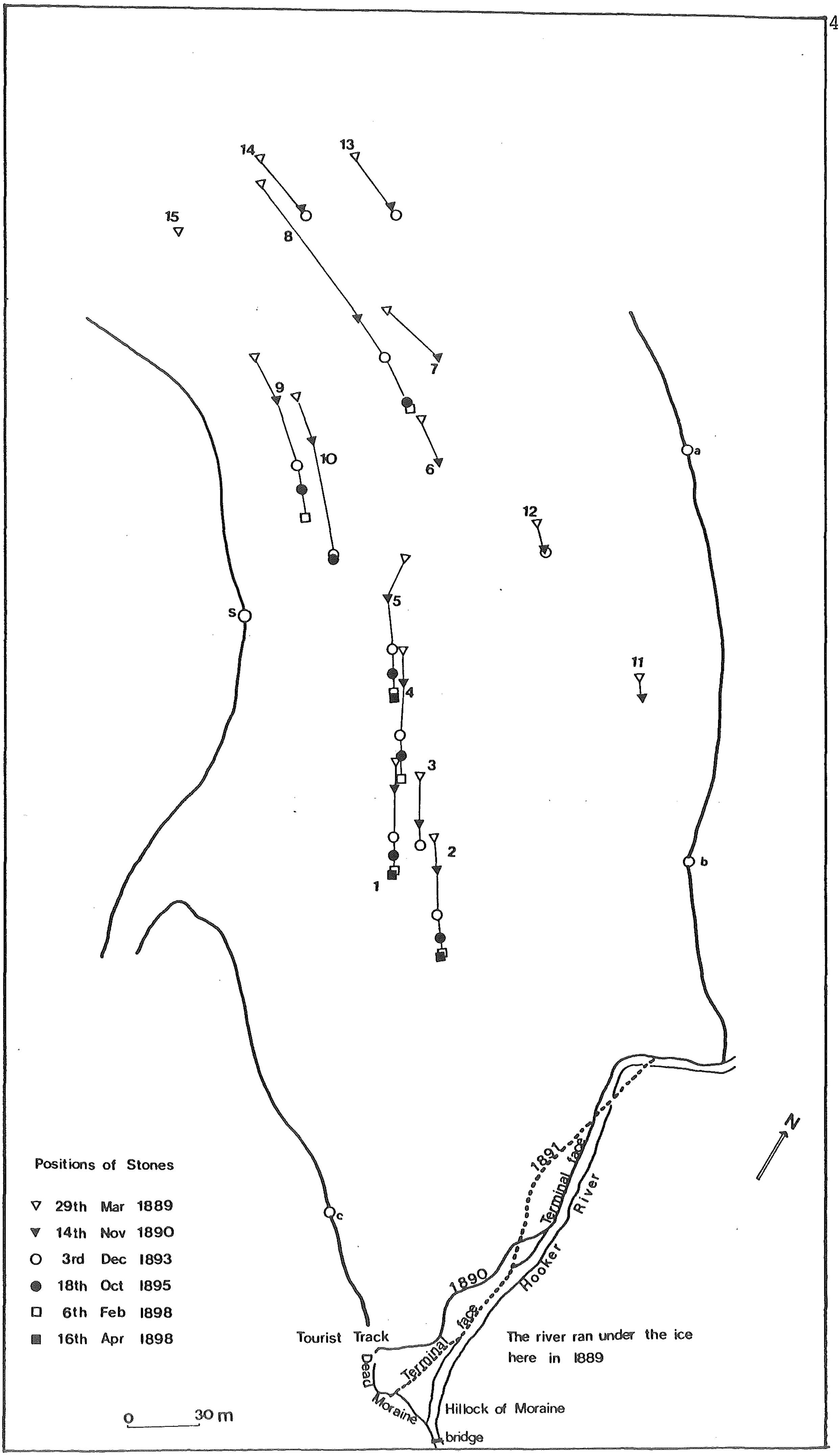
Map of the M^t. COOK GLACIERS, Canterbury, New Zealand

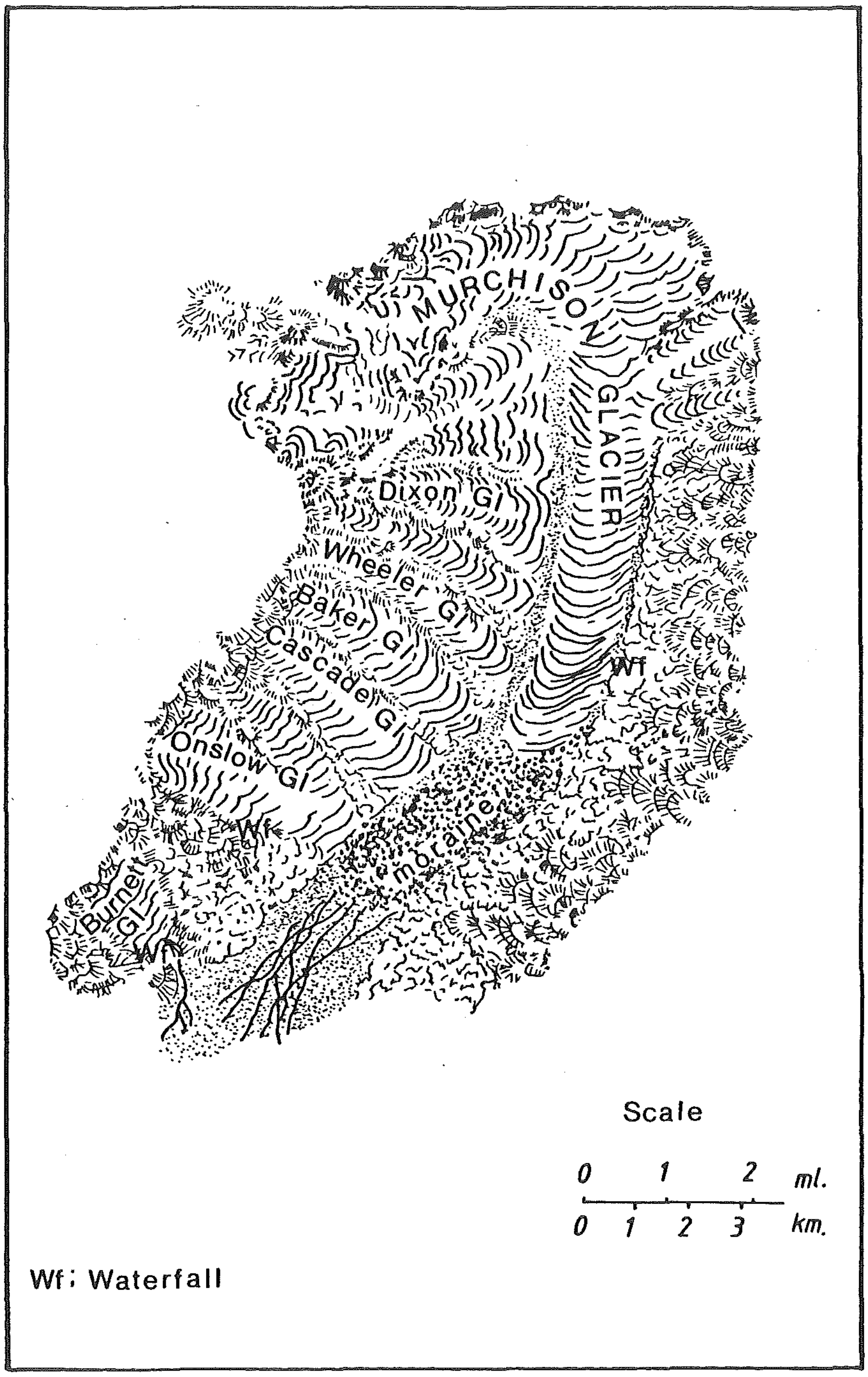
Compiled from Government Surveys by T. N. BRODERICK, DISTRICT SURVEYOR, 1890.
The upper part of the Tasman Glacier is taken from Surveys by D^r. VON LENDENFELD.



H. R. Schmidt, del^t.

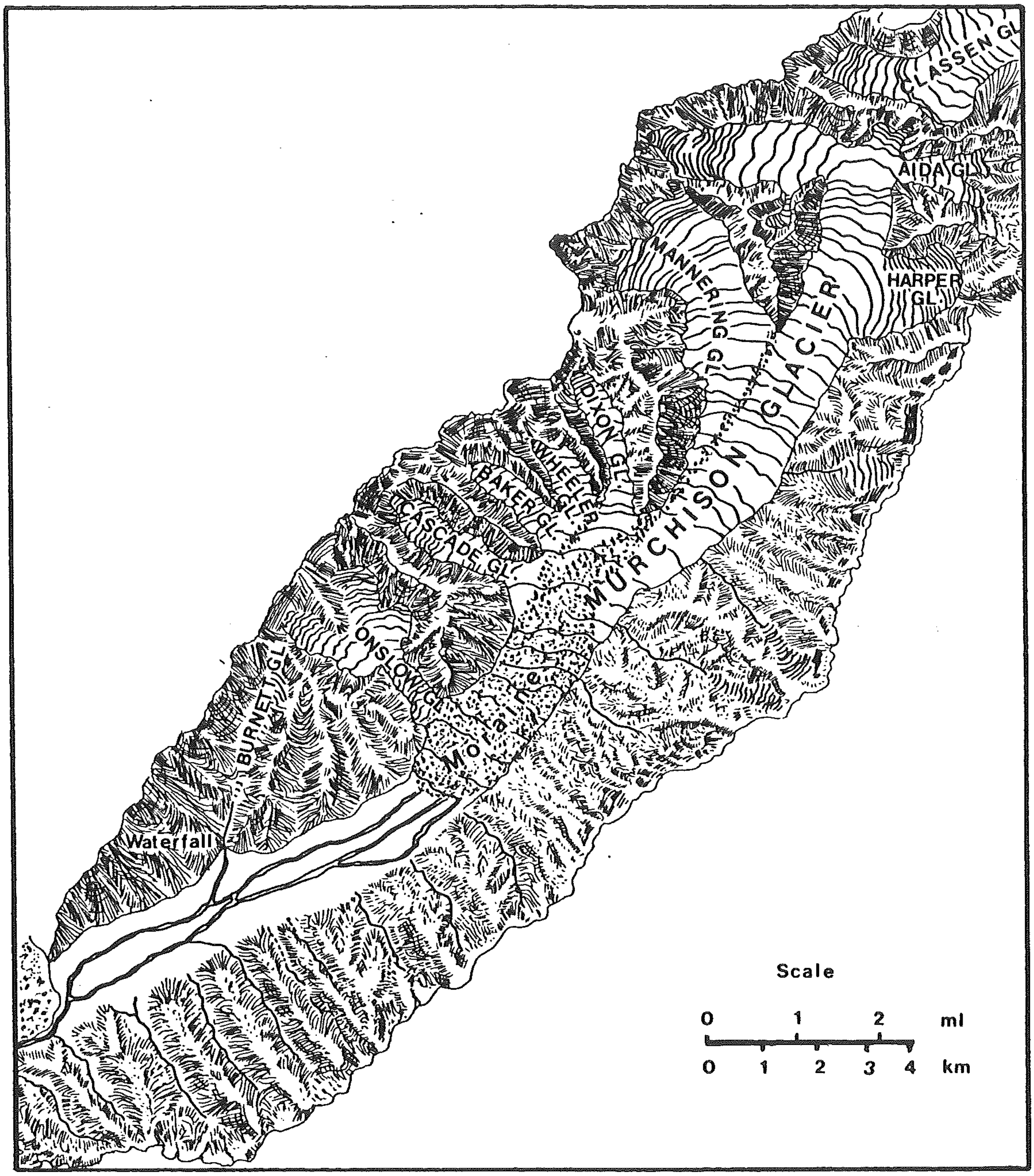
J. H. Baker, Chief Surveyor, Canterbury, N. Z.


14
13
15
8
7
9
10
6
a
12
s
5
11
4
3
2
b
1
N
Positions of Stones
▽ 29th Mar 1889
▼ 14th Nov 1890
○ 3rd Dec 1893
● 18th Oct 1895
□ 6th Feb 1898
■ 16th Apr 1898
c
1891
Terminal face
River
Hooker
1890
Terminal face
Tourist Track
The river ran under the ice here in 1889
Dead Moraine
Hillock of Moraine
bridge
0 30 m



MAP of the MURCHISON GLACIER (1890)

by G. E. Mannering, 1890.

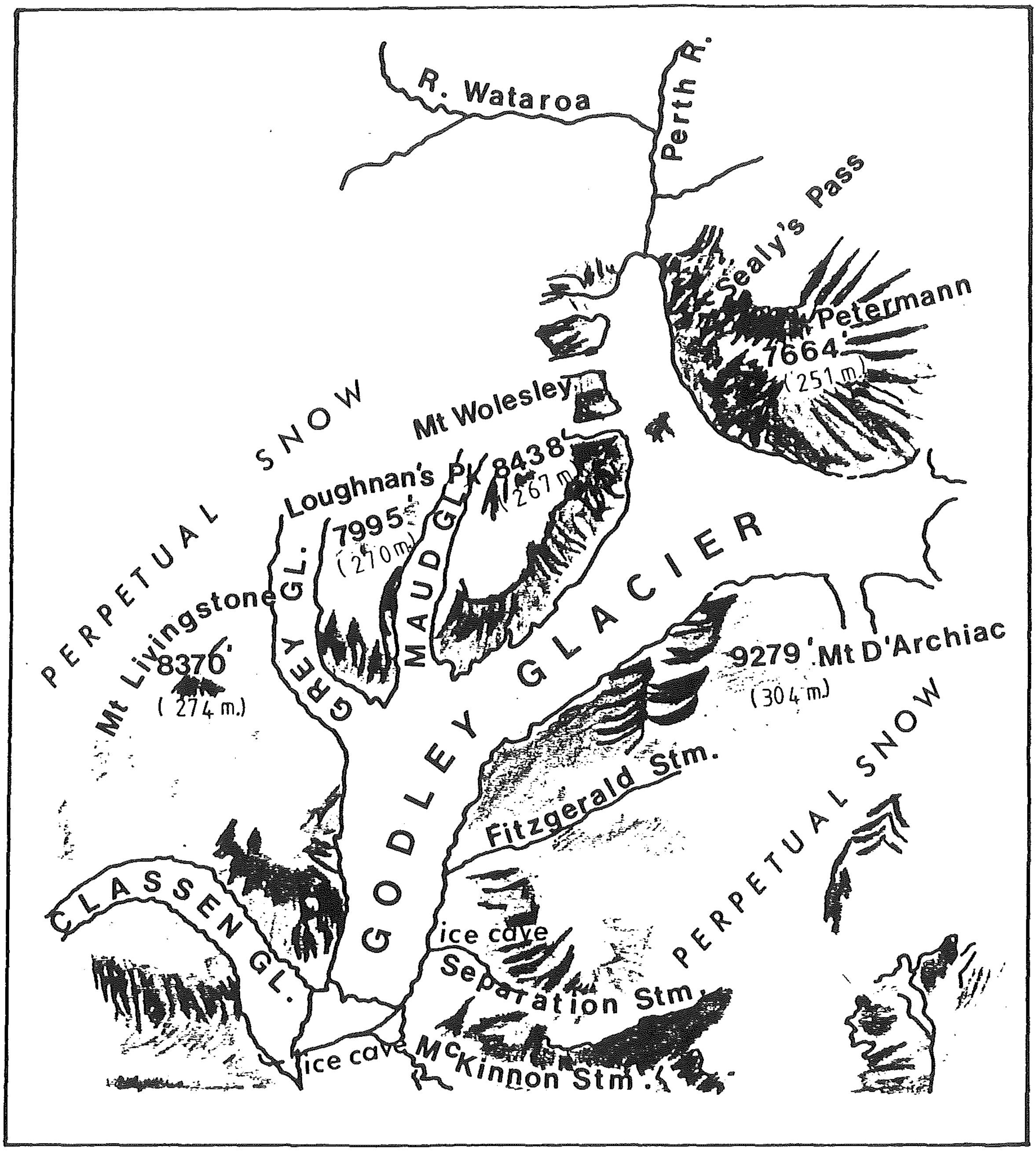


MAP of the MURCHISON GLACIER (1892)

from 'THE CENTRAL PORTION of the SOUTHERN ALPS of NEW ZEALAND'

Compiled from the Government Survey with additions by A. P. HARPER et. al.

PUBLISHED by the ROYAL GEOGRAPHICAL SOCIETY, 1893



SKETCH MAP of the GODLEY GLACIER (1892)

by G. E. Mannering, 1892.

The photographic record from the period 1890 onwards is extensive. A number of photographs have been organised into albums or collections whilst many single photographs remain unclassified and several have no details of the photographer. Moreover the dates of some of the photographs are unspecified and can only be calculated by checking on the dates of the visits made by the people concerned. Photographs in albums sometimes cover several years and so the exact date of the photograph is uncertain.

Broderick, Ross and Inglis all took photographs during the period 1890-91. The Ross Collection[#] includes photographs taken from around the Hermitage (then located at the foot of White Horse Hill) between 1890 and 1914. Broderick photographed the upper Tasman Glacier and views around the Hermitage[*] and Inglis photographed scenes both around the Hermitage and in the upper Godley region. Photographs belonging to Inglis are held in the Kinsey Album[#] which is dated 1895.

Other photographs from that decade are held in the Kennedy Collection[+] 1895 and these include scenes of the Godley Valley by Mannering c.1890 and later work by Hewitt c.1925 and Livingstone c.1931-32. Subsequent work is recorded in numerous albums and collections and these include; the Birch Collection ‹1905› (includes an important photograph by Pringle of the Mueller Glacier)[#], La Trobe Collection ‹1909-13›[*], Harper Albums ‹1891-1934›[*], Frind Album‹1914›[*], Edgar Williams (private collection) ‹1917-18› which records an early expedition to the Godley Valley, Algie Collection ‹1927-28›[*], Scott Albums‹1930-32›[+*], J.T.Paul Collection‹1932›[*], Rose Collection ‹1935›[*], Hewitt Collection ‹1936-37›[+] and the A.C.Elworthy Collection ‹1938›[*].

Following the second world war the photographic record acquired oblique aerial photographs of the region by Odell, 1954 onwards, and subsequently the New Zealand Geological Survey have flown aerial photography reconnaissance flights during the following years; 1954, 1959, 1960, 1965, 1976, 1979 and 1980.[x]

[#] Held in the Alexander Turnbull Library, Wellington, New Zealand

[*] Held in the Hocken Library, Dunedin, New Zealand

[+] Held in the Canterbury Museum, Christchurch, New Zealand

[x] Map archives, Lands and Survey Department, Christchurch, New Zealand

For the remainder of this chapter each valley will be discussed in turn and recent glacier movements described in detail. A short summary will be given at the end of each section in which the timing and magnitude of glacial events are related to known fluctuations in the climatic record.

4.4 MUELLER VALLEY

The pattern of recession shown by the Mueller Glacier over the last 130 years is illustrated in Fig.4.11a. When von Haast visited the area in 1862 A.D. the glacier was approximately 1km forward of its present day position[1]. Von Haast (1879) measured the height of the terminal face of the glacier at 2851' (819m). Today downwasting has reduced the level of the ice to a height of 762m. The lowering of the ice surface despite the overall retreat up-valley, is further confirmed by von Haast's observation of the ice against the Northern moraine:

> "... here the two lateral moraines of which the outer one, standing more than a hundred feet (30m) above the glacier itself, is densely covered with sub-alpine vegetation". (von Haast *loc.cit.*, p.29).

The ice at the present day is over 75m below the outer lateral moraine crest. In 1863 the ice was noted to be resting against the southwestern spur of Mt Cook being separated by only one moraine ridge. By 1888 Hutton (1888) writes that the ice had retreated almost 100m from this position, although the actual ice margin still fluctuated a great deal depending on the volume and course of the Hooker River.

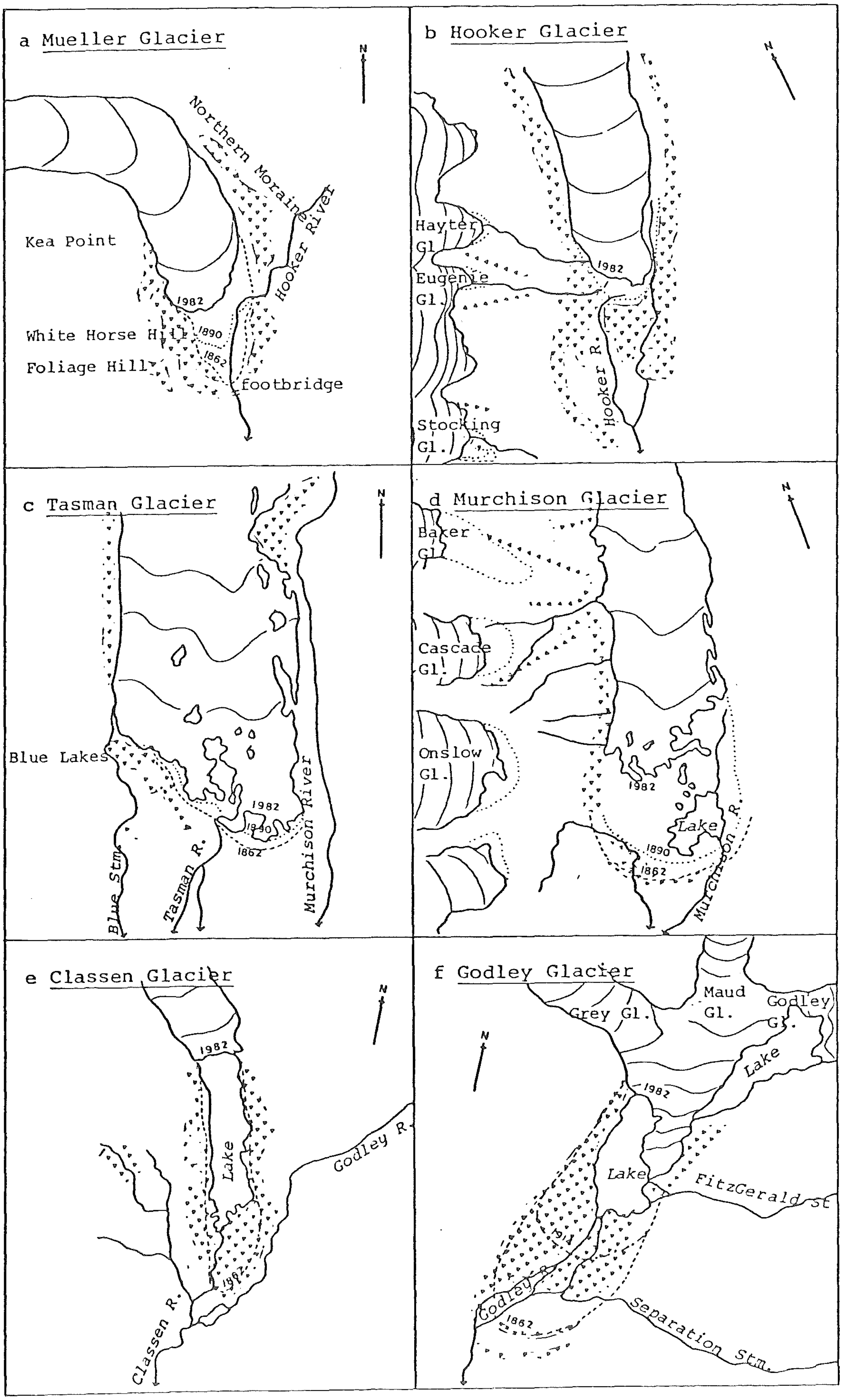
Various accounts of this time describe how the shepherds of Birch Hill Station annually drove their sheep over the glacier utilizing the natural moraine covered ice bridges to do so. The stock would graze on the Hooker and Tasman Valley flats. A typical scene is depicted by Gully in a painting of the Mueller Glacier from von Haast's sketches[2]. The action of the Hooker River and the general retreat of the Mueller Glacier led to the destruction of these ice bridges

---

[1] The present day position of the Mueller Glacier terminus is at grid: S79 761 340 (H36 758 178)

[2] Mt Cook with the Hooker Glacier from the Mueller Glacier, 1862

Figure 4.11 Recent changes to glacier termini, Mt Cook.



at various times. Hutton (1888, p.438) records a flood in 1868 which caused large quantities of ice to be brought down. Green described the situation in 1882:

> "...for years it had been customary to send a mob of about 2000 sheep across the Hooker River to Mt Cook for the summer months, but this year, owing to some ice bridges in the Hooker Glacier[1] having given way, they were unable to cross" (Green 1883, p.157).

The Hooker River next flowed under the Mueller ice in 1885. The summers of 1887 and 1888 brought further collapse of the ice bridges but by July 1888 the Mueller Glacier had begun to advance once again affording access to the Tasman Valley. In 1896 Fitzgerald observed the shepherds from Birch Hill Station as they:

> "...drove their sheep as far as the snout of the Hooker Glacier. The glacier served as a bridge to carry the flock to the other side of the stream where they are left to feed upon the scanty snowgrass during the summer months" (Fitzgerald 1896, p.112).

There was an increasing number of visitors to the Mt Cook region in the 1890's, in particular a group of Government Surveyors. Topographical maps were prepared by Broderick and the Mueller Glacier was surveyed in 1889. Writher, writing to the Chief Surveyor on July 20th 1891, noted how:

> "Near the Hermitage, and about 10 chains (200m) below the terminal face of the Mueller Glacier, a light wire footbridge of 220 feet (67m) span has been thrown over the Hooker River".[2]

This places the Mueller terminus at grid: S79 766 334 (H36 764 174). The glacier is projected to have been about 30m from the site of the footbridge in 1862 (Fig.4.11a) and had retreated about 170m in the intervening thirty years.

The Mueller Glacier terminus is shown in Broderick's field notebook as part of a compass map, dated 11th October 1890[3]. A small moraine is indicated on the map, which is believed to be equivalent to the present day terminal moraine located on the Mueller Glacier floodplain, 150m from the site

---

[1] Probably should read 'Mueller Glacier' which is often regarded as part of the Hooker Valley in some early accounts.

[2] Chief Surveyors Letterbook S641/31 Department of Lands and Survey, Christchurch.

[3] Timaru field notebook no.387, Department of Lands and Survey, Christchurch.

of the footbridge (now referred to as the 1st Swingbridge), at grid: S79 765 335 (H36 763 175). This same moraine is present in two photographs taken later that decade; Kinsey 1895[1] and Ross 1896[2]. The moraine was at one time thought to have been about 35 years old (cf. Burrows 1973a,Fig.13 p.487).

In 1905 the terminal face of the glacier was re-traversed and a slight re-advance recorded:

> "....at the present day the Mueller Glacier has a second outlet. The main stream flows from its terminal face; but a mile (c.1.4km) above this there is an outlet through the southern lateral moraine[3]. Down this channel torrents of water flow in continuous wet weather after the glacier has filled up" (Marshall 1907, p.289).

Pringle's photograph taken in 1905 shows the Mueller Glacier near to the terminus with a thick cover of moraine[4]. The use of a spillway channel to the west of White Horse Hill was again mentioned in 1913 by Fredu du Faur:

> "In fine weather there is a tiny lake at the junction of the Kea Point and the old grass-covered moraine besides which the Hermitage is built. The lake is usually only a few feet deep, and sometimes dries up altogether. The last fortnight's deluge, besides being of considerable volume itself, was a warm rain that had melted the snow in all directions; these conditions caused the lake, which is a well that receives a large portion of the drainage of the Mueller Moraine, to rise about 20 feet, then the pressure of the water burst the bank of the moraine separating the lake from the valley" (Freda du Faur 1915, p.123).

The La Trobe photographs from this time show the Mueller Glacier terminus pressed against White Horse Hill about the same position as it would have appeared to Writher in 1891[5].

---

[1] 'Leibig Range from the top of Mount Ollivier showing the Hermitage' 1895. Kinsey Album p.21, Alexander Turnbull Library,Wellington. ATL 122525½

[2] 'Cook spur and Leibig Range from Sealy Range' 1896. Malcolm Ross Coll. Alexander Turnbull Library,Wellington. ATL 17590¼

[3] Kea Point

[4] T.Pringle 'Mount Cook from the Mueller Glacier' 1905. Birch Coll. Alexander Turnbull Library,Wellington. ATL 6951

[5] La Trobe Album, Hocken Library Dunedin.

The Hooker River had altered its course and appeared to flow along the edge of the ice. A second photograph presumed to be of the same date, shows the old bed of the Hooker River[1].

Glacier recession does not appear to have begun until much later this century. Radcliffe photographed the scene in 1928[2]. Black ice is prominent in the foreground at the terminus (albeit intermittently) since the 1890's. In the 1928 photograph white ice is clearly shown in the middle foreground of the ice face and the Hooker River is either dry or has joined the Mueller melt water channel as only one stream is observed coming from under the ice.

Photographs in the Hewitt Collection[3] indicate downwasting of the ice by the mid-1930's. It is hard to establish if there was any actual retreat by this time. The glacier recession since then has resulted in few glacial deposits on the floodplain except for very recent ice-cored debris mounds opposite the southwestern spur of Mt Cook, grid: S79 761 340 (H36 758 178).

Summary The extremely cold years of 1861-62(Salinger 1979,1982) coincided with the visit to Mt Cook by von Haast who observed the Mueller Glacier in its most advanced state during the last 130 years. Observations suggest that the glacier oscillated annually and changes to the ice face were brought about both by the action of the Hooker River and responses to local climate change by the glacier itself. The flood in 1868 may have been caused by melt water following the severe winter of 1867. 1882 was a warm year. It may be coincidental, but ice bridges across the Hooker River collapsed that year and did not reform again until three years later. There are indications from several sources (Salinger 1979,1982, Dunwiddie 1979, Burrows 1976a, Grinsted & Wilson 1979) that the mid-1880's were cool years (cf. Table 2.3,p.12) and records show that the glacier had readvanced by 1888. The glacier had retreated about 170m from its position in 1862. It appears to have remained in this position for at least thirty years. The low temperature recordings at the

---

[1] La Trobe Album, Hocken Library, Dunedin.

[2] Radcliffe 1928, Alexander Turnbull Library. ATL 7550½

[3] Hewitt Collection 1936-37, Canterbury Museum, Christchurch.

turn of the century are matched by a readvance by the glacier in 1905. The floods recorded for the years 1907 and 1913 were probably caused by conditions associated with the warm Nor'westerly storms and occurred in years with otherwise cold temperatures. The general rise in temperatures towards the end of the 1940's has probably accelerated the glacier recession which had begun in 1862, reached a 'stillstand' around the 1890's and which recommenced towards the end of the 1930's.

4.5 HOOKER VALLEY

There are very few records of the glacier fluctuations in the Hooker Valley and a paucity of reference points in the landscape with which to describe the changes at the terminus. The Hooker Glacier features in the background of several photographs of the Mueller Glacier but few are sufficiently clear to allow assessment of small scale changes to the ice front. The La Trobe collection includes one photograph of the Hooker terminus taken in 1913[1] and from this scene it is clear that the ice was further forward and the ice level higher than at present. Tributary and hanging glaciers in the Hooker Valley have all retreated upslope and the fluctuations of the Stocking Glacier have been particularly well documented by Burrows & Heine (1980). These variations in terminal position are being correlated with climate records, (Heine, Salinger & Burrows in prep.). Burrows & Heine (*op.cit.*) noted that the main periods of glacier advance were around 1890, 1905, 1925, 1945-47, 1949-53 and 1965-69. Marked periods of retreat occurred around 1900-5, 1913-20, 1935-41, 1953-65 and 1969-75.

<u>Summary</u> There are no suitable data concerning the Hooker Glacier with which to make inferences about the response of the main valley glacier to changes in climate during the last 130 years. Response patterns of the Stocking Glacier have been analysed (Heine *et al.*, *op.cit.*) but there is no evidence to suggest that the Hooker Glacier is as sensitive to change as the small hanging glaciers.

---

[1] La Trobe Collection, Hocken Library, Dunedin, New Zealand

4.6 TASMAN VALLEY

The Tasman Glacier terminus was surveyed in 1862 by Julius von Haast (Fig.4.1). The terminus has changed position only very slightly since that time. Baker's map in 1890, (Fig.4.6), shows a point at the terminus labelled 2347' (715m). If the Trig.Point Y[1] at height 2345' (714.7m) on the present day maps is equivalent to the point shown on Baker's map, then it can be assumed that the ice front has retreated just over 600m since 1890. Baker's map differs from earlier maps of the glacier (cf. von Haast 1862 Fig.4.1, von Lendenfeld 1883 Fig.4.2) in that the melt stream flows from the centre of the glacier and not the far eastern side as shown in previous diagrams.

The most noticeable change in the Tasman ice is the extent of downwasting in the last 130 years. Green records ice from the Ball Glacier which was overtopping the high lateral moraines in the Tasman Valley:

> "...bare boulders were piled up into a rampart about sixty feet high over which the ice of the glacier rose in a vertical wall of from twenty to thirty feet. By continually dropping stones from its upper surface onto the top of the moraine it was thus daily, before our eyes, building up the high rampart" (Green 1883,p.199-200).

Elsewhere Green describes how:

> "...the great pile of recent moraine, on which we stood overtopped a rampart of ancient moraine, showing that the glacier, at a period not very remote was smaller than it is at present, oscillations of level being most distinctly recorded, not only here but at various points where we were able to make observations" (Green *loc.cit.*, p.196).

The height of the Tasman ice is depicted in a painting by C.Aubrey of the Blue Lakes in 1888[2]. Independent observations describe breaches in the moraine wall near the terminus caused by the advancing ice.

There are no early photographs of the area as far as is known, and so reference is made to the map record for

---

[1] Grid: S79 827 346 (H36 819 185).

[2] Mr Hyde, Whakatane.

details of glacier change. The accuracy of von Lendenfeld's map (which was used by both Green 1884 and Baker 1890) is questioned by Ross (1892), who examined the changes that had taken place and found that the clear ice, once at a point within 4km of the terminal face, had retreated 6.5km. This marked change was also commented on by Broderick:

> "I found that the place Dr Lendenfeld made of the Tasman in 1883 represents the tongues of ice on the Tasman in such different positions to what they occupied where I made my survey, that I could not reconcile the two at all, supposing the accepted laws of ice motion to be correct. I therefore concluded he had not been very particular and so, I resolved to be more so myself, and so, I put in all the salient features accurately" (Broderick 1897, letter to the Chief Surveyor[1]).

Broderick completed surveys of the Tasman and Murchison Glaciers in 1891 (Topographic maps 60T & 61T)[2]. His surveys were indeed accurate and his constant attention to detail expressed in cartographic and written form is clearly indicated in all his work.

The downwasting of the ice has been best recorded at Ball Hut. Observations by Green (1883) and later by Broderick (1894) describe the ice from the Ball Glacier which was pressed against the main valley lateral moraines. On occasions the ice breached the moraine causing flooding in the vicinity of Ball Hut. Changes to the tributary glaciers upvalley of the terminus do not appear to have been significant at the terminus itself. In 1894 Broderick suggested that the advances of the Ball Glacier would not affect the ice at the terminal face of the Tasman Glacier unless the increased pressures of the advances were sufficient to accelerate the velocity of the whole glacier. Marshall (1907) could find no evidence of an advance at the terminus, and Harper commenting on 45 years of observations noted how:

> "...all the tributary ice streams show considerable shrinkage... the terminal of the Tasman does not appear to have retreated much " (Harper 1935, p.322).

---

[1] Chief Surveyors Letterbook S 4386/21 1897. Department of Lands and Survey, Christchurch.

[2] Map archives, Department of Lands and Survey, Christchurch.

Ross described some glacial activity close to the terminus by the Blue Lake[1] :

> "...a large slip had come down from the moraine exposing clear ice of the glacier, and completely covering the scrub for a distance of about one hundred yards (90m) with moraine accumulation" (Ross 1914, p.32).

This activity might have been related to a minor advance, but there is no record of events elsewhere on the glacier. Harper records that the levels of ice dropped 21m at Ball Hut between 1890 and 1934 and further 24m by 1940 (Harper 1934, 1946). Today the ice is over 90m below the moraine crest(s) which are themselves subsiding and thereby lowering. Fig.4.11c shows the present ice limits of the Tasman Glacier and indicates the approximate extension of ice in 1862, 1890 and the present day. In recent years the terminal ice has shown signs of extensive disintegration and stagnation.

Summary Recession, and more particularly downwasting of the Tasman ice, took place after 1890 and was especially marked towards the end of the 1930's. Advances recorded for the tributary glaciers in the 1890's do not appear to have had any effect on the main valley glacier terminus. The glacier activity in the 1890's at Ball Hut coincides with known low temperature recordings for this time. It seems unlikely that the Tasman Glacier would have commenced downwasting as early as 1890 in view of the recognised cold temperatures and the glacier may well have been advancing at this time. The glacier level has dropped over 45m since the 1940's, a period of general warming in New Zealand.

4.7 MURCHISON VALLEY

The Murchison Glacier was first mapped by Mannering (Fig.4.8) who noted that :

> "...the eastern side shows very little lateral moraine, for the western declivities of the Leibig Ranges do not carry such large quantities of ice as the slopes opposite, and the denudation is consequently not so great" (Mannering 1890, p.359).

---

[1] Ross refers to the original 'Blue Lake' at the head of the Blue Stream shown in a photograph by Ross c.1890-1914 and reproduced in Ross,M. 1930, Wanderlust vol.1 no.1 p.15-30.

A landslip indicated on the 1890 map is again shown on Broderick's map of 1891,(Topographic map 61T), but is not shown by Harper *et al.*(1892), Fig.4.9.

The approximate limits of the ice in 1862 and 1890 are shown in Fig.4.11d. An undated photograph of the Murchison terminus[1] indicates that the ice extended to beyond the Onslow Glacier junction during the last 130 years. The same photograph shows the extent of the Onslow Glacier which in 1892 still flowed into the main valley glacier. Ross noted that:

> "...the Onslow (glacier) nearest the terminal face of the Murchison, is apparently stationary at present. The Cascade and Wheeler contribute nothing to the general stream, and have the appearance of dying out. The Baker and Dixon are advancing without any question, especially the former" (Ross 1892, p,62)

Ross described a lateral moraine in the process of formation on the south side of the Baker, and the presence of an older grass covered moraine, about 60m lower down, which suggested that the glacier had once been much diminished, (Ross *loc. cit.*).

The area was visited by Frind around ‹1914›[2] and later by Algie ‹1927-28›[3], Rose ‹1935›[4], Hewitt ‹1936›[5] and Hall ‹c.1938›[6]. Their photographs record the steady recession of the side valley glaciers. In 1914 the Cascade and Baker Glaciers still joined the main ice stream, but by 1935 only the Wheeler and Dixon glaciers flowed into the Murchison. Today none of the tributary ice streams are actively contributing ice to the main valley glacier. A large frontal glacial lake has formed at the Murchison Glacier terminus and melt water activity is destroying the remaining terminal deposits.

---

1 'Murchison Glacier terminal face and river. Mt Chudleigh and Onslow Glacier' undated and un-named. Alexander Turnbull Library,Wellington ATL 2071½

2 Frind Albums, Hocken Library, Dunedin

3 Algie Collection ‹1927-28›, Hocken Library, Dunedin

4 Rose Collection,‹1935›, Hocken Library, Dunedin

5 Hewitt Collection ‹1936-37›,Canterbury Museum, Christchurch

6 D.O.W Hall Collection ‹c.1938›, Hocken Library,Dunedin

Summary The general recession of the Murchison Glacier is concomitant with climatic observations. It is to be expected that the tributary glaciers would respond faster to climatic changes. The fact that the Baker and Dixon glaciers appeared to be advancing in 1892 can be directly related to the low temperatures recorded at that time. The lack of synchroneity between the tributary glaciers indicates that factors other than temperature variations are important in the glacier front oscillations.

4.8 GODLEY AND CLASSEN VALLEYS

The Godley and Classen Glaciers are consider together. In 1862 the termini of both glaciers were surveyed by Julius von Haast (Fig.4.1). The glaciers were barely 40m apart. Von Haast wrote as follows about the Classen Glacier:

> "...from the fact that several older moraines densely clothed with subalpine vegetation were already half buried in the present terminal moraines of the glacier it was clear to me that the glacier after a period of retreat is now advancing. Travelling over the glacier for several miles I found with very few exceptions it was covered everywhere with a debris load of great thickness" (von Haast 1879, p.20).

The advanced position of both glaciers at this time is shown in Fig.4.11e & f. Fig.4.12 depicts the scene painted by Gully from pencil sketches of von Haast in 1862.

In 1888-89 Broderick surveyed the area and noted the presence of thick scrub and tussock close by the glaciers which were also noted for their thick moraine cover (Fig.4.5). Early photographs of the Godley Valley were taken by Mannering 1890[1] and Inglis c.1895[2]. By 1914 the Godley Glacier had retreated 1km as shown in the photographs taken by Frind[3]. The Separation and FitzGerald Glaciers had also receded considerable distances (up to 3km if early accounts were accurate). Williams (1967) described an expedition to the Godley Valley in 1917 by which time the Godley Glacier had retreated to a position opposite FitzGerald Stream. By 1921, Fletcher considered it "quite evident that the glaciers

---

[1] Kennedy Collection, Canterbury Museum, Christchurch

[2] Kinsey Album, Alexander Turnbull Library, Wellington

[3] Frind Albums, Hocken Library, Dunedin

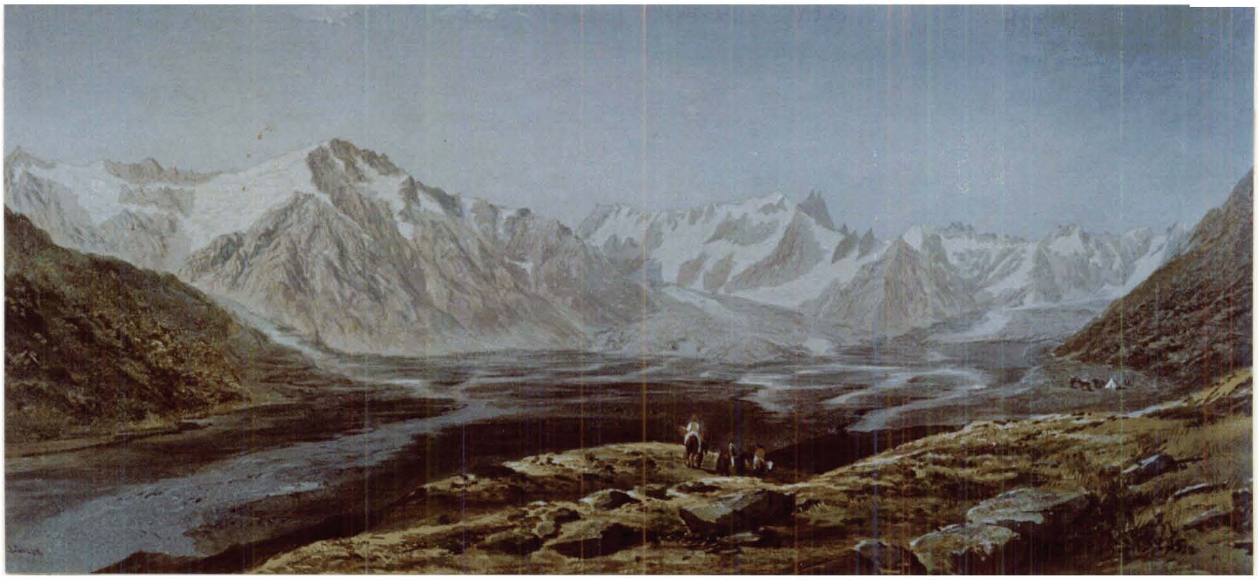


Figure 4.12 Sources of the Godley River, Classen and Godley Glaciers, *Gully, J. 1862.*

had retreated quite considerably" (Fletcher 1921 p.28). According to von Haast (*op.cit.*) the FitzGerald Glaciers[1] had all but joined the main valley glaciers in 1862. By 1921 they had retreated nearly 4km.

Fletcher noted the collapse of ice cliffs at the terminus and in 1924 he observed that:

> "the whole of the eastern side of the Godley Glacier had collapsed and the river instead of flowing underneath the ice, had torn down a gully between the ice and the mountainside" (Fletcher 1925, p.240).

The area was visited by Livingstone in 1931-32 and later by Hewitt in 1935, 1936 and 1939[2]. The glacier terminus is recorded at a position slightly downstream of FitzGerald Stream by Hewitt in the mid-1930's. The ice was over 100m higher than at present. Accounts do not indicate much change to the glacier front position during the period 1914-1939. In contrast, since around 1950 both the Godley and Classen Glaciers have undergone considerable retreat amounting to over 3km in the Godley Valley and over 1km in the Classen Valley.

---

[1] Probably should read 'Separation and Butcher Glaciers'. It is more likely that von Haast was refering to the Separation Valley and the confusion over the correct nomenclature existed in the literature for the next thirty years.

[2] Hewitt Collection, Canterbury Museum, Christchurch

Glacier retreat has been accompanied by spectacular downwasting of the ice level, and this is well marked at the junction of the Maud and Grey Glaciers and the Maud and Godley Glaciers.

Summary The advance of the Classen Glacier which von Haast observed in 1862 coincides with a period of low temperature recordings in New Zealand (Salinger 1979, 1982). Presumably the build up to this advance had occurred some time previous to 1862. The two glaciers have been receding since this time. The Godley Glacier is the better documented with records from 1862, 1888-89, 1890, c.1895, 1914, 1917, 1921, 1922, 1924, 1931-32, 1935, 1936 and 1939 during the early pre-world war II years. Recession appears to have accelerated in recent years and seems to be continuing at the present day.

CHAPTER 5

WEATHERING RIND ANALYSIS

5.1 INTRODUCTION

Rates of weathering rind thickness growth on sandstone clasts of the Torlesse Supergroup are described by Chinn (1981). Rinds are measureable on surface boulders after about 130 years of development. The rind on fine-grained, low grade metamorphic sandstone is comprised of two separate zones;

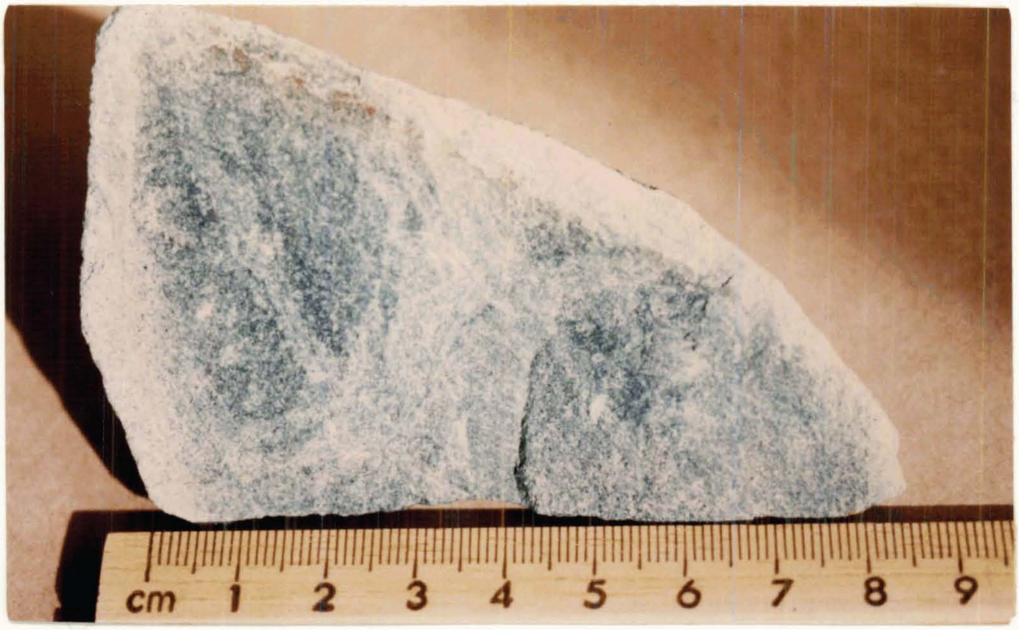
- an outer pink layer increasing in thickness from 0-1mm with age, which grades into
- a prominent whitish zone with a diffuse inner boundary.

On coarse grained rocks an inner dark band of variable thickness is discerned. The rind thickness is defined by Chinn as:

> "the thickness from the boulder surface to the inner limit of the whitish zone" (Chinn 1981,p.36).

An example of rind development on a typical fine-grained sandstone clast is shown in Fig.5.1 below.

Figure 5.1 Weathering rind development on a fine-grained sandstone clast from the Mt Cook region. NB.The ruler shown for scale indicates only the approximate rind width size and was not used for obtaining measurements in this study.



5.2 THE RIND GROWTH CURVE

Rates of rind growth were calibrated using measurements of surface weathering of the clasts on radiocarbon dated deposits. Chinn (1981) described nine radiocarbon dated deposits from the Southern Alps, New Zealand which span the whole of the Holocene period. A tenth site is dated using lichenometric measurements and historical evidence. The details of the ten sampling sites are presented in Table 5.1 and the location of the sites is shown in Fig.5.2a. The weathering rind growth curve described by Chinn (*op.cit.*) is presented in Fig.5.2b.

The dated rind thickness data fits the empirical function:

$$\text{Age(years)} = 1050(\pm 7\%)\ R^{1.23 \pm 0.06}$$

where R is the modal rind thickness in millimetres from fifty or more surface boulders. The standard error of the estimate is ±26% (Whitehouse & Chinn in prep.). The rind growth curve (Fig.5.2b) is established using data from sites located at different distances from the Main Divide and in areas of higher or lower precipitation than at Mt Cook. The weathering rind data do not describe 'total' weathering of the rock surfaces. Measurements are objective enough to enable the collection of similar data between workers, and subsequent comparison of results (Birkeland 1982). Chinn (*op.cit.*) sampled clasts of similar lithology throughout his study in spite of the wide area involved.

The weathering rind curve is not extended beyond c.9000 years. It is extremely difficult to collect a large enough sample on the older surface for two reasons; firstly the rind mode becomes subdued on the older surfaces and secondly there is a marked absence of surface boulders on the older terrain.

5.3 RIND MEASUREMENTS

Each rind count involves the measurement of between c. 30-50 weathering rinds on separate clasts. Only the maximum rind thicknesses were measured using a 15^{x} magnifying hand lens and a graduated steel rule. Rind widths were calculated to the nearest 0.25mm and plotted on a histogram. The modal

Table 5.1

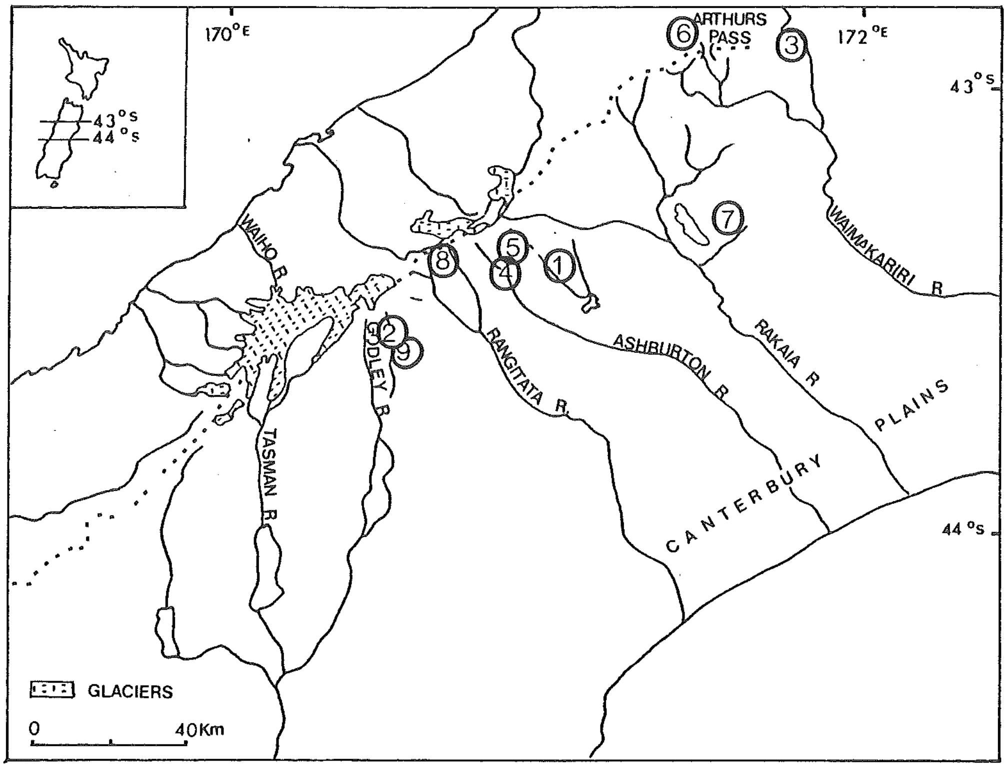
Radiocarbon samples used to construct weathering-rind growth curve, after Chinn (1981)

No.	Lab.No.	Radiocarbon years B.P.	Rind modes mm.	Year sampled	Location	Map Reference	Deposit
1	NZ 688	9520± 95	6.0	1973	Cameron Valley	S73/597743	Outwash[1]
2	NZ 548	8460±120	5.0	1979	Macaulay Valley	S80/212506	Landslide
3	NZ 1824	4020± 90	3.6	1980	Casey Stream	S59/328346	Landslide
4	NZ 1289	5280±105	3.0	1979	South Ashburton R.	S73/575707	Landslide
5	NZ 1880	3030±110	2.0	1978	Cameron Valley	S73/586749	Landslide
6	NZ 4258	2000± 90	2.2	1979	Otira Gorge	S59/050349	Landslide
7	NZ 547	532± 66	0.8	1979	Acheron Valley	S74/145826	Landslide
8	NZ 1901	354± 24	0.4	1979	Clyde Valley	S72/378708	Landslide
	NZ 1902	365± 34					
9	NZ 4914	358± 35	0.4	1979	Macaulay Valley	S80/208523	Landslide
10		c.100	0.2	1979	Cameron Valley	S73/574772	Moraine[2]

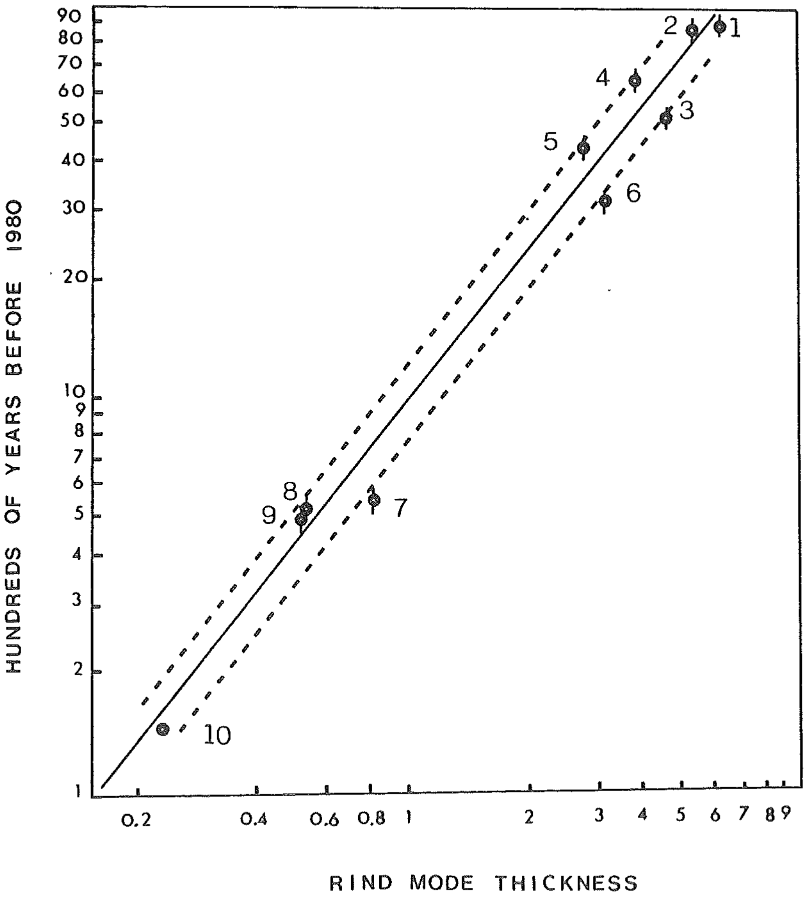
[1] Minimal date for an outwash surface.

[2] Minimal age for a moraine dated principally by lichenometry, (Burrows 1975)

a


170°E
172°E
43°S
44°S
43°s
44°s
ARTHURS PASS
⑥
③
⑦
⑤
⑧
④
①
②
⑨
WAIHO R
WAIMAKARIRI R
RAKAIA R
ASHBURTON R
RANGITATA R
GODLEY R
TASMAN R
CANTERBURY PLAINS
GLACIERS
0
40Km

b


HUNDREDS OF YEARS BEFORE 1980
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
RIND MODE THICKNESS
0.2
0.4
0.6
0.8
1
2
3
4
5
6
7
8
9
1
2
3
4
5
6
7
8
9
10

rind width class is used an indicator of the surface age. Where two or more strong modes are recorded, the oldest mode is assumed to indicate the age.

Sampling was conducted in undisturbed areas. Boulders lying on moraine crests and at the base of moraine slopes were avoided because of the possible influence of exposure and late-lying snow respectively. In addition, sampling of sites near the valley walls and active scree slopes was restricted.

5.4 RESULTS

Within each suite of moraines it was common to observe an increase in rind modal values from the inner to outer moraines. This change in age indicates the approximate duration of the depositional event (Chinn 1981).

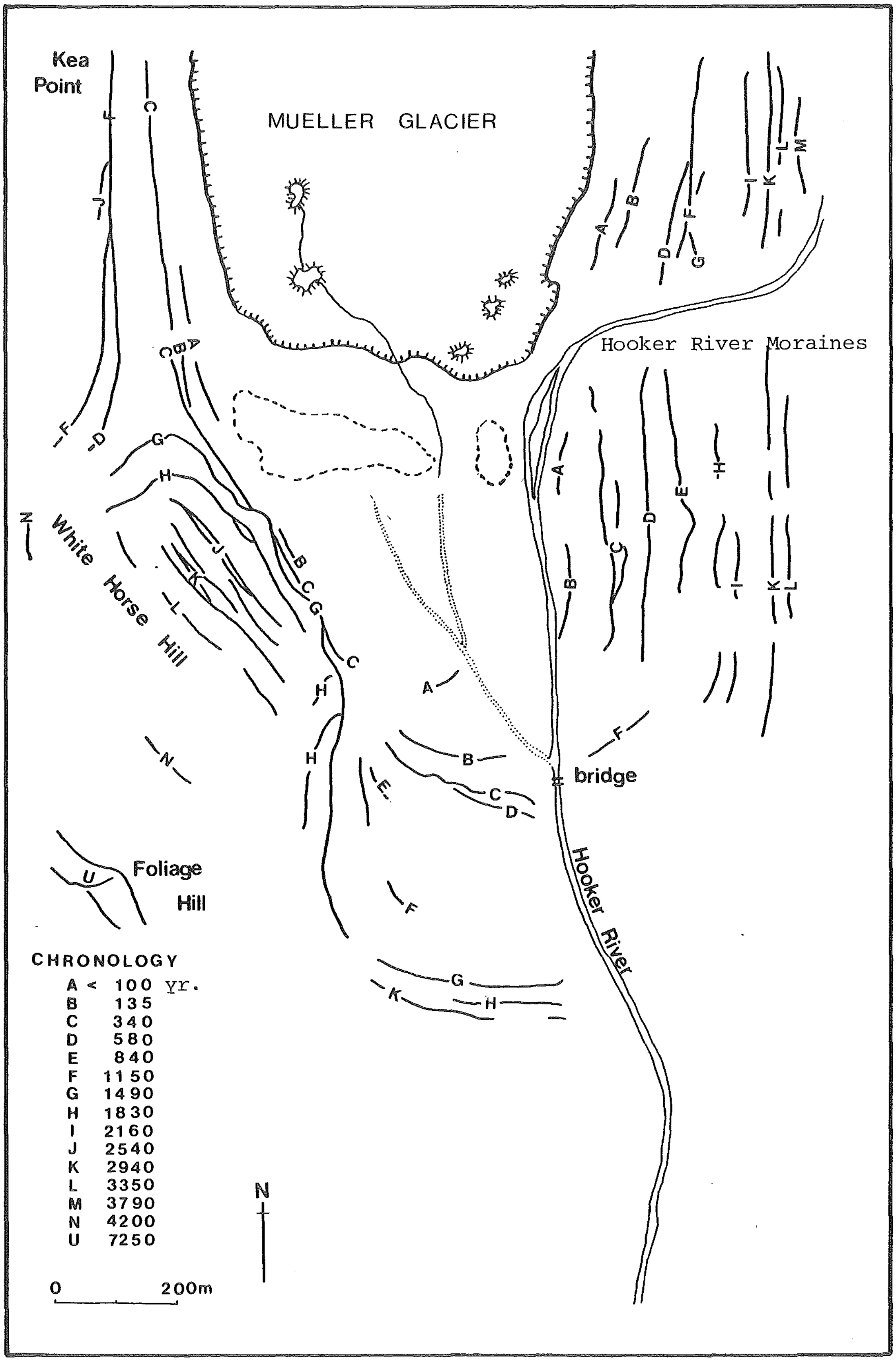
5.4.1 Mueller Glacier

Fifteen different moraine groups are defined at the Mueller Glacier terminus as differentiated by weathering rind thicknesses (Fig.5.3) 35 sites were examined. The results of the weathering rind counts are shown as histograms in Appendix C1-4. Surface ages ranged from less than 100 years old to greater than 7000 years old. Moraines were examined on both sides of the Hooker River. The low inner loop to the west of the 1st swing bridge is comprised of three moraines formed in the last 600 years. The outer loop formed between 3000 and 1500 years ago. Representatives of both these terminal moraine groups are found on the east side of the Hooker River between the two swing bridges.

The inner moraine of the outer loop, the 'G' moraine, is a continuation of the main crest of White Horse Hill. The main ridges of Kea Point and the Northern moraine are both younger, ('F' moraines). The outer slopes of White Horse Hill are dated 3350,2940,2540 and 1830 years respectively. The small 'car park' moraine,'N', is calculated to be over 4000 years old whilst the Foliage Hill complex is dated as about 7250 years old, although it may comprise several differently-aged surfaces.

With the exception of the youngest sites, histograms

Figure 5.3



SKETCH MAP of the MUELLER GLACIER showing the LATERO-TERMINAL MORAINES. CHRONOLOGY BASED ON ROCK WEATHERING RIND THICKNESS.

presented in Appendix C 1-4 indicate a tendency to be skewed to the right. Bi-modal distributions are common (for example G3, H2, K1, N1, U1 and U2). The inclusion of pre-weathered material is indicated at sites C1, D1, G2, H1, H3, K2 and L1.

5.4.2 Hooker Glacier

The weathering rind moraine chronology for the Hooker Valley is shown in Fig.5.4 . The oldest moraines in the Hooker Valley are located on the south side of the Stocking Stream (not shown in Fig.5.4). There were insufficient surface boulders on the deposits to enable an estimate of the rind age for the complex.

A distinct group of moraines, which have formed in the last 600 years, encompass both the retreating glacier and the enlarging floodplain. Downvalley of these moraines the prominent terminal moraine 'H' separates the young moraine deposits from the older established complex. An almost continuous series of dated lateral moraines extends upslope on the valley side walls above the Hooker Glacier. The outermost lateral moraine is dated 3350 years old on the east side and an older outer loop dated over 4000 years old was recorded on the west side.

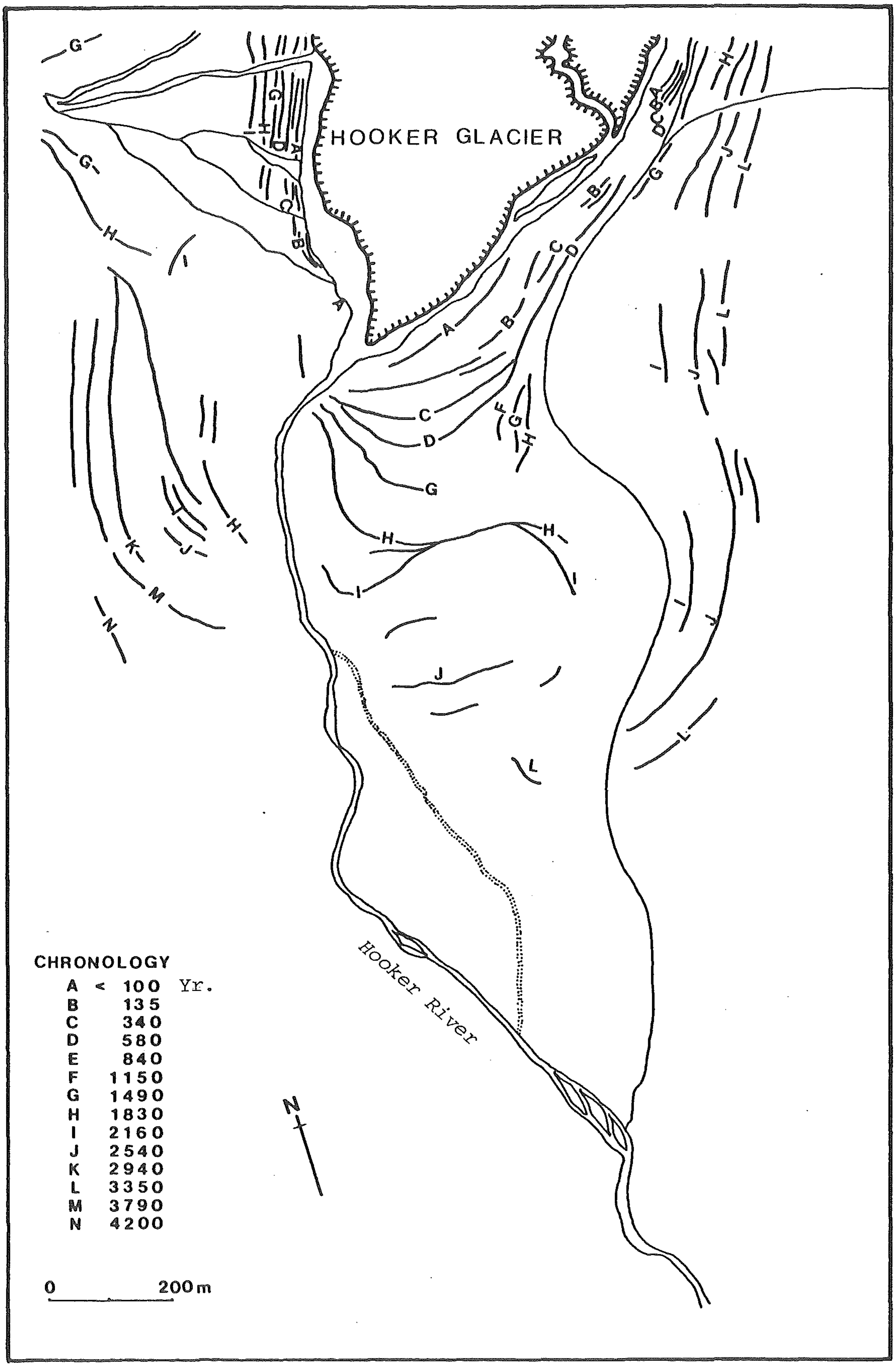
Moraines of the Eugenie Glacier extend down to the Hooker laterals and are dated c.1830 and 1500 years old. They are approximately equivalent in age to the prominent Hooker terminal moraine. A series of younger moraines demarcate the recent recessional positions of the Eugenie Glacier.

A total of 43 sites were sampled in the Hooker Valley and the weathering rind counts are presented as separate histograms in Appendix C5-9. Almost all of the rind counts were positively skewed. A few of the older sites appeared to be bimodal but otherwise the sites selected showed clear unimodal rind distributions.

5.4.3 Tasman Glacier

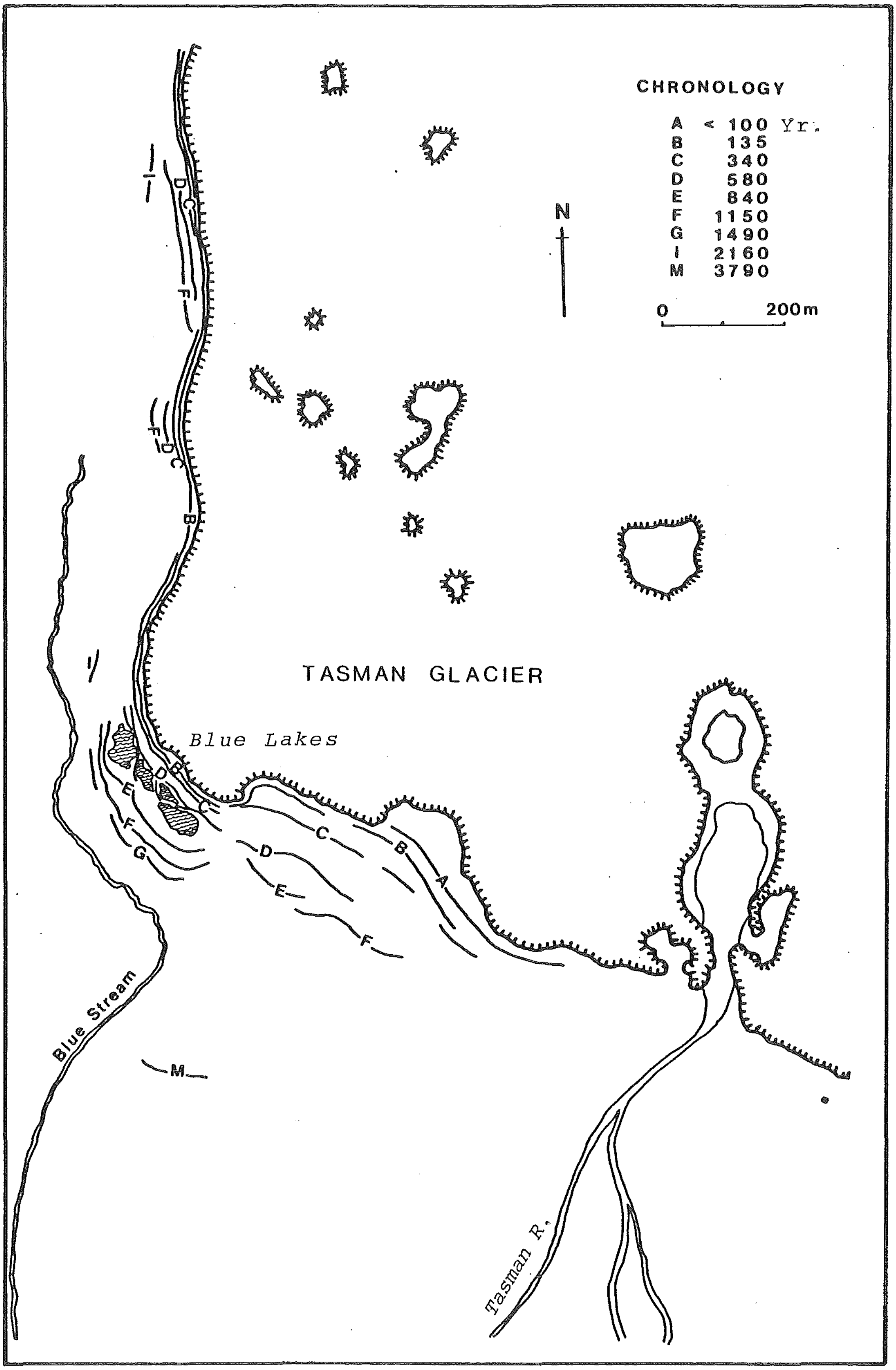
The lateral moraines along the Ball Hut road and the latero-terminal moraines at the Blue Lakes represent periods of glacial deposition which occurred about 3790,2160,1490, 1150,840,580,340 and 135 years ago. The high lateral moraine

Figure 5.4



SKETCH MAP of the HOOKER GLACIER showing the LATERO-TERMINAL MORAINES. CHRONOLOGY BASED ON ROCK WEATHERING RIND THICKNESS.

Figure 5.5



SKETCH MAP of the TASMAN GLACIER showing the LATERO-TERMINAL MORAINES NEAR THE BLUE LAKES. CHRONOLOGY BASED ON ROCK WEATHERING RIND THICKNESS.

is also the youngest and can be traced from the Ball Hut down the Ball Hut road for a distance of 8km back to the terminus near the Blue Lakes (Fig.5.5). The Blue Lakes separate moraines formed 600 years ago from the older deposits. The two high outer moraines at the Blue Lakes (cf.Fig.2.8, p.22) are dated approximately 1150 and 1500 years old. A small remnant terminal moraine located about 400m downvalley of the Blue Lakes is aged c.3790 years.

Recent moraine deposition has occurred further east of the Blue Lakes towards the main glacier terminus. A total of 17 sites were examined and the rind counts are presented in Appendix C 10-11. All the histograms are positively skewed.

5.4.4 Murchison Glacier

No diagram is included for the moraines of the Murchison glacier. It will be recalled that there is very little surviving moraine deposition at the glacier terminus (cf. Fig.2.9, p.23). All of the terminal moraines loops present have formed in the last 340 years. Melt water activity has recently disturbed many of the glacial deposits.

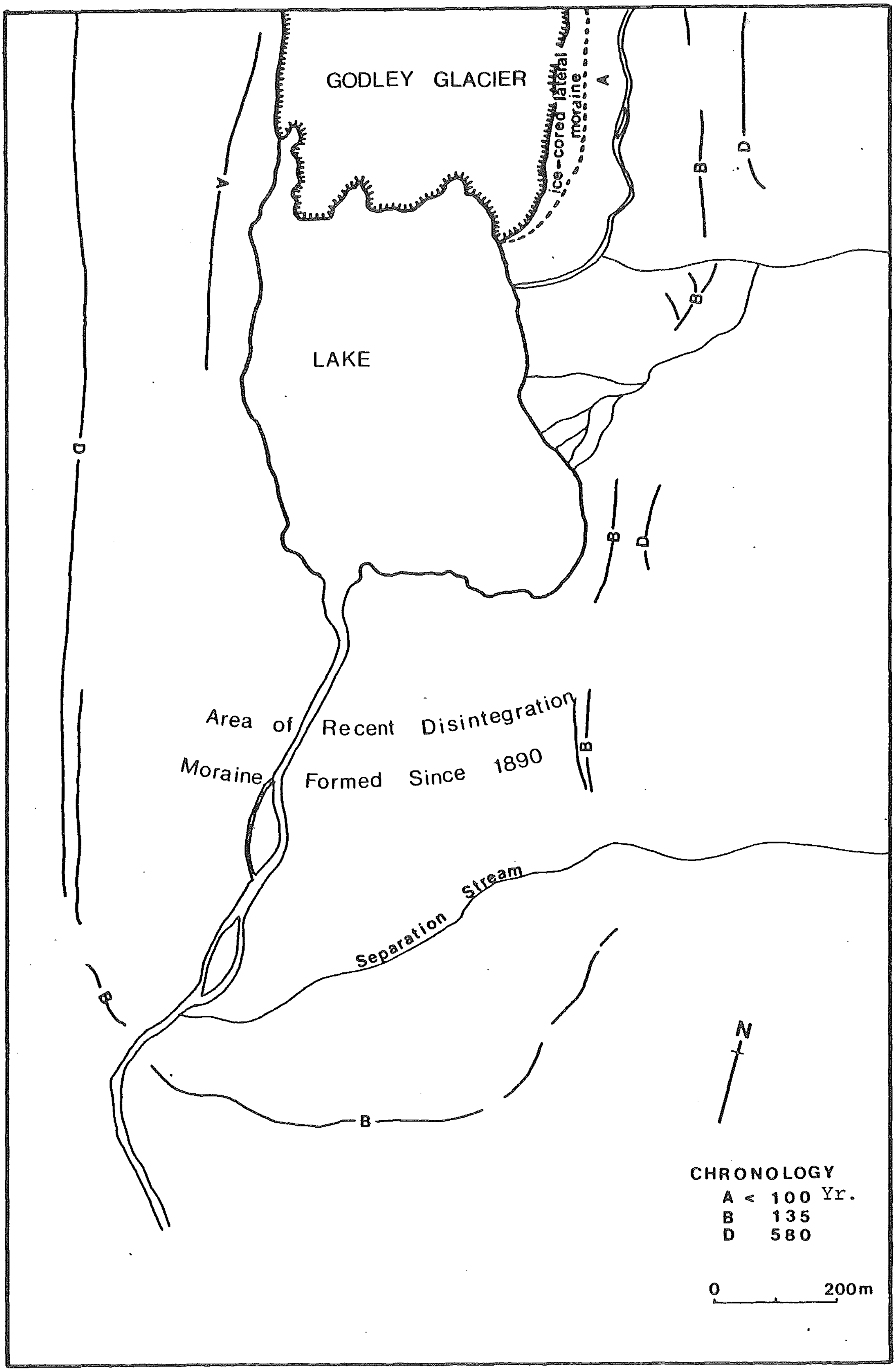
5.4.5 Godley Glacier

There are only very recent moraine deposits remaining in the vicinity of the Godley Glacier, Fig.5.6 (cf. Fig.2.10, p.25). A terminal moraine loop south of Separation Stream formed 135 years ago. Recessional moraines on the north side of the stream mark the retreat of the glacier following its advance downvalley last century. Moraines formed during the last 130 years are deposited at the entrance to Fitz-Gerald Stream on the eastern side of the main valley. A high trim line (cf.Fig.2.10, p.25) formed c.580 years ago. The results of rind counts from 13 sites are presented in Appendix C12.

5.4.6 Classen Glacier

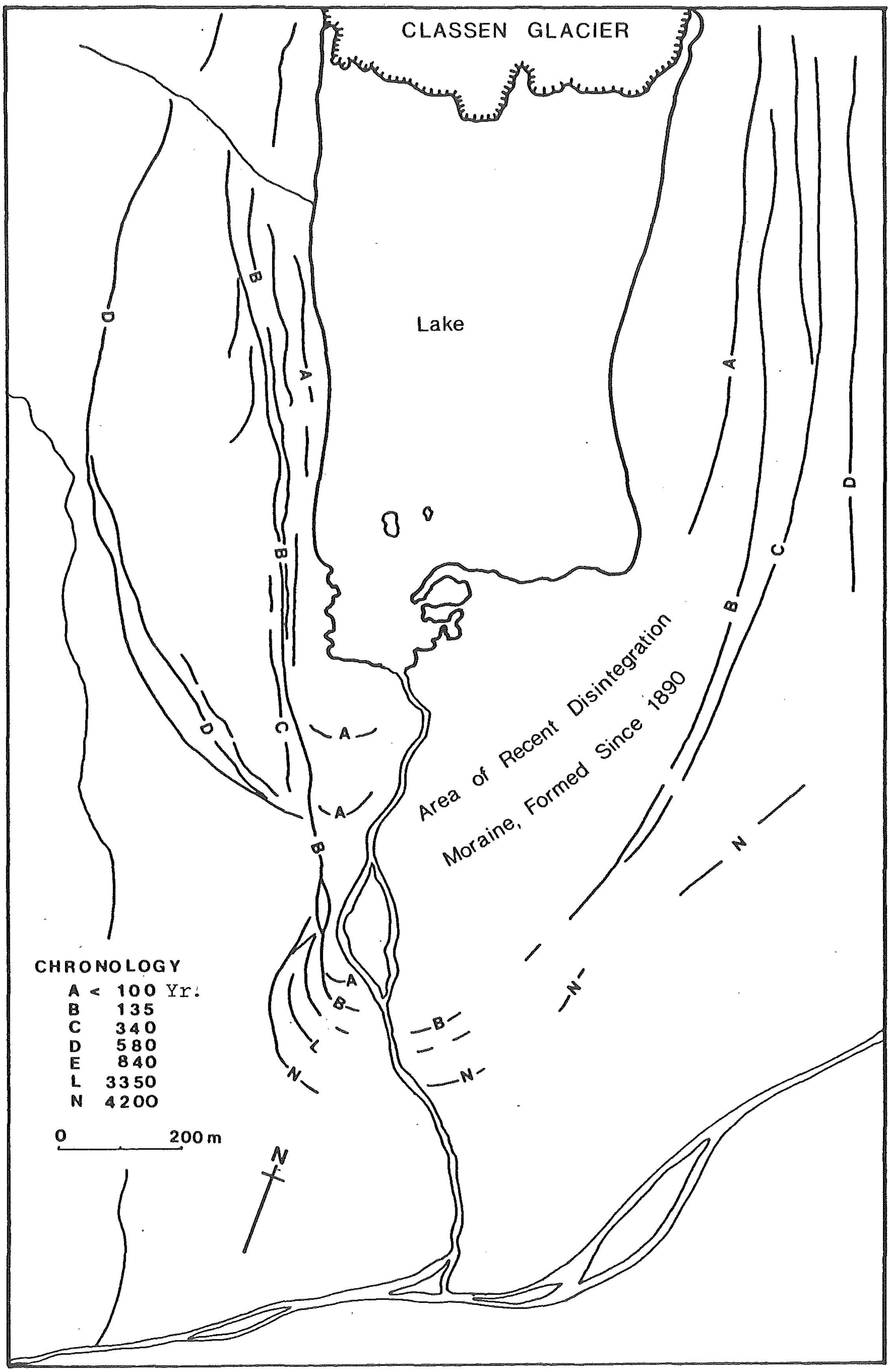
The latero-terminal moraine chronology at the Classen Glacier terminus comprises two distinct moraine groups. A young moraine sequence, less than 850 years old, is aligned

Figure 5.6



SKETCH MAP of the GODLEY GLACIER showing the LATERO-TERMINAL MORAINES. CHRONOLOGY BASED ON ROCK WEATHERING RIND THICKNESS.

Figure 5.7



SKETCH MAP of the CLASSEN GLACIER showing the LATERO-TERMINAL MORAINES. CHRONOLOGY BASED ON ROCK WEATHERING RIND THICKNESS.

next to a very much older moraine set which was deposited c.4200-3400 years ago. The most recent glacial deposits showed no weathering rind development and are subsequently dated as less than 100 years old. Deposits aged 135,340 and 840 years old are present at the terminus. A fourth, recent deposit, aged 580 years, did not extend as far south and forms a wide, bouldery loop shown in Fig.5.7 .

The oldest moraines are at the terminus on both sides of the Classen River. Only two sites were examined on each moraine due to the paucity of surface boulders. Almost every boulder on the outer moraine was cracked open and measured in order to achieve a suitable rind count.

Histograms showing the results of the rind counts are given in Appendix C13-14. Two sites on the 'D' moraine indicate the inclusion of previously weathered clasts, (cf. D1 and D2). The older sites have bimodal distributions.

5.5 DISCUSSION

There is an arbitrary element in the exact dates obtained because of the use of size classes. For this reason the weathering rind method cannot be termed 'absolute' (see Chinn 1981). Theoretically it may be possible to obtain exact size measurements of the rind thicknesses, but such accuracy is unobtainable in the field. The surface dates described from each sequence of valley moraine deposits provides a framework for further discussion and the testing of other dating techniques.

Modal size classes were used in preference to the mean or maximum rind thickness measurements. Table 5.2 presents the approximate age range for each modal size class. The standard error of the estimate is 26% (Chinn 1981). Values of the maximum, average and minimum mean values obtained from the rind counts,(individual results are shown with each histogram in Appendix C1-14), are shown in Table 5.2 as are the number of modal values for each different aged surface which lie above or below the overall mean value obtained from each dated surface. Several sites have been examined on surfaces of similar age in different valleys.The results show that most rind counts from surfaces older than 1150 years were negatively skewed. For individual rind counts

Table 5.2

Analysis of weathering rind thickness data

Ref. No.	Modal[1] Value mm.	Approximate Age[2] and Standard Error, yrs.	$\bar{x}$[3]			Standard Deviation of mean, $\bar{x}$	Total rind count means[4]	
			Max. mm.	Ave. mm.	Min. mm.		Above Rind Mode	Below Rind Mode
A	0.0	100	0.34	0.13	0.05	0.08	11	0
B	0.25	135 ± 35	0.56	0.25	0.16	0.08	12	9
C	0.5	340 ± 88	0.67	0.49	0.39	0.08	4	6
D	0.75	580 ± 150	1.19	0.77	0.35	0.20	9	7
E	1.0	840 ± 218	1.13	0.94	0.78	0.12	3	5
F	1.25	1150 ± 300	1.21	1.07	0.95	0.11	0	9
G	1.5	1490 ± 387	1.64	1.32	1.09	0.17	3	9
H	1.75	1830 ± 476	1.84	1.44	1.15	0.22	1	9
I	2.0	2160 ± 562	1.94	1.64	1.54	0.32	0	5
J	2.25	2540 ± 660	2.25	1.88	1.73	0.19	0	9
K	2.5	2940 ± 765	2.61	2.19	1.85	0.32	1	3
L	2.75	3350 ± 870	2.32	2.14	1.97	0.16	0	6
M	3.0	3790 ± 960	2.92	2.64	2.25	0.26	0	5
N	3.25	4200 ± 1090	3.25	2.94	2.36	0.51	0	3
U	5.0	7200 ± 1870	4.81	4.42	4.03	0.55	0	3

1 Calculated using regular 0.25mm units of measurement

2 Calibrated using rind growth curve (Chinn 1981)

3 Included to demonstrate the variation in individual sample means. Unlike the modal values, the means are usually directly affected by external events and may substantially under or over-estimate the actual period of weathering. For example; surfaces grouped together with modal values of 0.25 (B) exhibit a range of mean values from 0.56 to 0.16mm. Should the same data set be re-grouped according to the mean values then some sites on the same surface would be classed a different age. 12 sites were positively skewed and 9 negatively skewed. Sites with a modal value of 1.5mm (G) similarly include a wide range in sample means. In this instance 75% of sites examined were negatively skewed, as would be expected on older surfaces.

4 The total number of individual rind counts are described using the position of the mean in relation to the rind count mode. On younger surfaces there is a tendency for the sample mean to lie to the right of the sample mode. The distributions are positively skewed. On the older surfaces the means are described as lying to the left of the mode and the distributions are negatively skewed. The two columns describe the variations in the first moment about the mean with an ageing population.

the mean value would not have been a consistent and appropriate indicator of surface age. The average mean values from moraines of the same age, however, correlated strongly with the modal rind values, r=0.996 ($p<0.001$). This correlation gives no indication of the considerable variation indicated on Table 5.2 of mean values from individual rind counts.

Birkeland (1982) described weathering rind thicknesses for a few of the moraines in the Tasman, Hooker and Mueller Valleys. He used the mean rind thickness as his dating parameter but noted no significant difference between mean and modal collective rind values. He concluded that the surface ages of the moraines were older than lichenometric estimates had indicated (cf. Burrows 1973a). The present study indicates a marked discrepancy in the ages of moraines obtained by modal rind measurements as opposed to lichen-dating estimates (Burrows *loc.cit.*). A comparison of the three chronologies (ie. Burrows 1973a, Birkeland 1982 and this study) is shown in Table 5.3 .

The surface age estimates defined by weathering rind analysis from Birkeland (*loc.cit.*) and this study are not consistent. It should be noted that Birkeland paid only a cursory visit to the area and his rind count samples were restricted to two sites in the Mueller Valley, two sites in the Hooker Valley and seven sites in the Tasman Valley. In the Mueller Valley Burrows (*op.cit.*) described a 250-230 year old moraine. Birkeland (*op.cit.*) redated this surface (using only 21 rind counts) as c.690 years whilst results from the present study indicate the moraine to be approximately 1500 years old. An unpublished standard deviation for Birkeland's age estimate was large enough to overlap with both the lichenometric date and the present date(c.1500 year). Birkeland's second sample site in the Mueller Valley was on the previously undated moraine complex called Foliage Hill. Rind thickness measurements in both Birkeland (*op.cit.*) and the present study are similar. The large difference in rind age estimates demonstrates a short-coming of the rind growth curve, which flattens out at this point.

In the Hooker Valley Birkeland (*op.cit.*) recorded

Table 5.3

A comparison of surface age-estimates from three studies of Holocene moraine chronologies in Mt Cook National Park using lichenometric dating (Burrows 1973a), mean weathering rind analysis (Birkeland 1982) and modal weathering rind analysis (this study).

MUELLER GLACIER

Burrows (1973a)	Birkeland (1982)*	this study #
50 yr		135 yr
90 yr		340 yr
130 yr		580 yr
210 -190 yr		840 yr
250 -230 yr	689±400 yr (21)	1490 yr
c.300 yr		1830 yr
c.350 yr		1830 yr
c.450 yr		2540 yr
450 yr		2540 yr
550 yr		3350 yr
c.630 yr		4200 yr
undated	9670±2000yr	7200 yr

HOOKER GLACIER

Burrows (1973a)	Birkeland (1982)	this study
50 yr		135 yr
90 yr		580 yr
230 yr		1490 yr
330 yr		1830 yr
430 yr		2160 yr
530 yr	700±135 yr	2540 yr
730 yr	1190±350 yr (33)	3350 yr

TASMAN GLACIER

Burrows (1973a)	Birkeland (1982)	this study
90 yr		135 yr
130 yr		340 yr
160 yr		580 yr
250 -230 yr	480±150 yr	580 yr
c.330 yr		840 yr
c.360 yr	760±150 yr	840 yr
c.450 yr	1190±180 yr (18)	1150 yr
700 yr	1465±300 yr	1490 yr
830 yr	1000±160 yr	2160 yr
undated		3790 yr

* Wherever possible Birkeland used mean values from rind counts of at least 50 clasts . Rind counts of less than 50 clasts are indicated in parentheses.

Weathering rind thickness age-estimates are accurate to ±26%.

the surface age of two moraines, Table 5.3 . The age-estimates are more inclined to support lichenometric values (Burrows *op.cit.*) than data presented in the present study. The variation in rind width measurements sampled in the present study as shown in Table 5.2 is not sufficiently great to overlap with Birkeland's anomalously 'low' results from the Hooker Valley. This point of discrepancy will be returned to below. Meanwhile it should be noted that there is very close agreement between the two weathering rind studies for the Tasman Valley moraines (Table 5.3).

The age discrepancies obtained by Birkeland (*op.cit.*) and this study may be explained by a number of factors;

i - a difference in operators

ii - a difference in the measuring parameters (mode and mean)

iii - a difference in the size classes used. Birkeland (*op.cit.*) measured to 0.2mm for rinds <1mm, and thereafter he measured to the nearest whole 1mm. In this study, rinds were measured to the nearest 0.25mm throughout.

iv - a difference in the size of rind counts and in the number of sites sampled on each surface. Birkeland (*op.cit.*) was restricted by time and consequently bases his age-estimates on far fewer counts etc. He examined 13 sites as opposed to 95 in the present study for the three valleys.

v - a difference in actual sites. Both workers used descriptions given in Burrows (1973a) to identify some sites and the interpretation of these moraines may have differed.

vi - the inclusion of schistose rock. Birkeland's small sample size in the Hooker Valley may have been insufficient to remove the influence of schistose rocks on his rind count. Alternatively greater sampling in this study may have accentuated this possible error.

The error has probably been shared by both workers, however, because of the more extensive sampling undertaken in this present study it is fair to assume that the age-estimates derived at in this study are the best available. The two weathering rind studies (Birkeland *op.cit.*, and this study) indicate considerable error in the lichen chronology (Burrows *op.cit.*). The lichen control points defined by Burrows & Orwin (1971) were found to be inaccurately dated following examination of the historical record for the Mueller Glacier (cf.4.4, p.52-56). The present chapter records further discrepancy in the age of recent deposits and some examples are given below.

According to Burrows (*op.cit.*) the main crest of White Horse Hill (Mueller Valley) was deposited around 1750 A.D. (230 years ago). He grouped several moraines from other valleys (Hooker and Tasman) with this event. Results from the present study indicate that the crest of White Horse Hill formed nearly 1500 years ago and that the equivalent deposits in the Hooker and Tasman Valleys were deposited c.1500 and c.580 years ago. Similarly the 450 year event noted by Burrows (*op.cit.*) in the Mueller and Tasman Valleys was redated in the present study as c.2540 yr and 1150 yr in the respective valleys.

The rind measurements are consistent on any one surface and must be regarded as more reliable than the lichen chronology described by Burrows (*op.cit.*). Surface age-estimates from the rind width chronology are used as a basic framework for assessing rates of soil and vegetation development on the moraines for the remainder of this study. Inter-valley inconsistencies in the weathering rind chronology should become apparent with further analysis of post-depositional surface modifications under investigation.

CHAPTER 6

SOIL DEVELOPMENT

6.1 INTRODUCTION

The high country yellow-brown earths are characterised by soils with:

> "...greyish-brown to dark greyish-brown topsoils that are loose to very friable when textures are silt loams. Subsoils are brownish-yellow to pale yellow and yellowish brown sandy loams and silt loams, friable to very friable, with weakly developed crumb and blocky structure" (Cutler 1968, p.42).

In soil development environmental factors affect the rate of processes (Jenny 1980, Birkeland 1974). During the elapse of time significant changes, both external and internal occur to the soil system. The present study documents some of those changes which have occurred in a soil development series throughout the duration of the Holocene period in Mt Cook National Park. Soil sample pits are described from three moraine sequences; the Mueller, Classen and Tasman terminal moraines. In addition, one sample pit is described from the Hooker Valley.

The soils to be described below differ from each other in both the time of inception and in the duration of their development. They form what has been termed a 'post-incisive' chronosequence (Vreeken 1975). Soils, in order to constitute parts of a chronosequence , must be monogenetic (Stevens & Walker 1970). Furthermore thay must all have experienced a similar developmental history to that of the oldest member in the sequence up until the time of sampling.

6.2 SOIL FORMATION ON MORAINES

6.2.1 <u>The basic assumptions</u>

It is assumed for the purposes of this study, that climate, parent material, topography, organisms and time have exerted a similar degree of influence on soil development, on the range of surfaces being examined, throughout the Holocene period in the Mt Cook region. Without this assumption, which must be qualified, it would be impossible to consider the soil development on the moraine surfaces as a chronosequence. The assumption is partially met through careful and selective sampling of suitable sites. Only those parameters which might indicate trends indicative of a temporally based soil sequence are used. The analysis presented is not complete but it does incorporate the more significant aspects of soil analysis for this surface age-range. The effects of present day climate are kept uniform by selecting sample pit sites within a small area (less than 4km^2). Climate records suggest that precipitation rates are highest in the Hooker Valley. The Tasman Valley at the Blue Lakes receives less precipitation than the area at the Mueller Glacier terminus. There are no climate data for the equivalent area in the Godley and Classen Valleys. Indications of climatic instability during the Holocene period are made readily apparent by the extent of the moraine deposition. The oscillating climate and its concomitant effect may invalidate the use of the chronosequence concept in this study.

The soils examined share a common parent material, that is, the Torlesse sandstone[1]. The importance of topography in soil development is discussed by Ruhe (1975) and Webb (1976). Webb (*loc.cit.*) found aspect to be important amongst the late-Pleistocene Lake Pukaki moraines. In this study, topographic variations are reduced through selective sampling.

Biotic factors influence and are influenced by the soil. The main consideration is burning, which has been extensive in the Mt Cook region. Although two of the three sequences examined were in areas of known firing, only one sample pit showed any evidence of burning in the site's history.

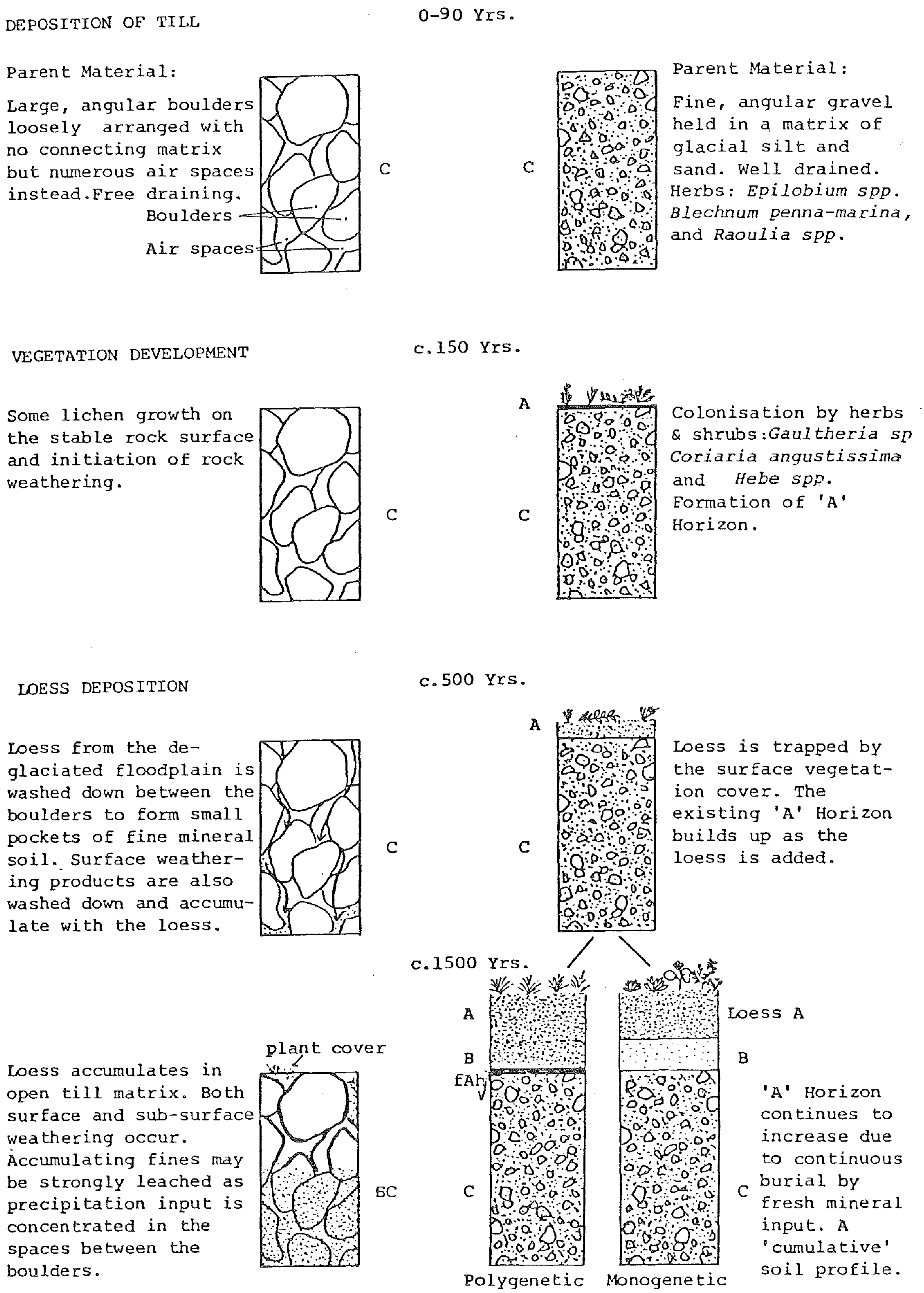
6.2.2 The influence of till matrix and loess input

Till matrix and loess input exert a dominant influence on soil development on the moraines yet neither is constant in time or space. The nature of their influence is

---

[1] It is acceptable to consider the Torlesse sandstone group as uniform lithologically and chemically over wide areas, such as the Mt Cook region, (see sections 2.2.2, p.6 and 5.2, p.62)

Figure 6.1 Influence of till matrix and loess deposition on soil development on moraines.



DEPOSITION OF TILL

0-90 Yrs.

Parent Material:

Large, angular boulders loosely arranged with no connecting matrix but numerous air spaces instead. Free draining.

Parent Material:

Fine, angular gravel held in a matrix of glacial silt and sand. Well drained. Herbs: *Epilobium spp. Blechnum penna-marina,* and *Raoulia spp.*

VEGETATION DEVELOPMENT

c.150 Yrs.

Some lichen growth on the stable rock surface and initiation of rock weathering.

Colonisation by herbs & shrubs: *Gaultheria sp Coriaria angustissima* and *Hebe spp.* Formation of 'A' Horizon.

LOESS DEPOSITION

c.500 Yrs.

Loess from the deglaciated floodplain is washed down between the boulders to form small pockets of fine mineral soil. Surface weathering products are also washed down and accumulate with the loess.

Loess is trapped by the surface vegetation cover. The existing 'A' Horizon builds up as the loess is added.

c.1500 Yrs.

Loess accumulates in open till matrix. Both surface and sub-surface weathering occur. Accumulating fines may be strongly leached as precipitation input is concentrated in the spaces between the boulders.

'A' Horizon continues to increase due to continuous burial by fresh mineral input. A 'cumulative' soil profile.

illustrated in Fig.6.1 . The situations shown are hypothetical and simplified, but they represent field situations encountered in this study. Within each chronosequence examined there are situations where a moraine with extremely bouldery, open till matrix is situated downvalley of a younger, fine-grained till deposit. The latter, for reasons which are made apparent in Fig.6.1, may support a 'more developed' soil profile than the former. These are young circumstances and can be clearly interpreted. The situation might appear more complex in an older moraine sequence where the till matrix has weathered.

Loess is identified by its texture (silty loam grading into a fine sandy loam) and by its distribution (a fine textured mantle deposit of uniform thickness over landforms of variable age, removed from the influences of fluvial deposition), Webb (1976). Loess is present in most high country yellow-brown earths which have developed on the moraine surfaces. It is trapped by the vegetation (on the established, stabilised surfaces) or is washed down between large boulders on the moraine surface. On fine grained loamy parent material the loess quickly helps to build up the 'A' horizon. A bouldery moraine of similar age will posess only a limited soil cover if any at all. Vegetation present on a bouldery till after 150 years is limited to lichen growth. After about 500 years, the vegetation cover is still extremely sparse and restricted to pockets of loess and rock weathering material which may have been washed down between the clasts.

The build up of loess on the fine-grained parent material may result in one of two profile forms: Loess deposition may be steady and continue to enlarge the A horizon to give a 'Loess A' (Webb *op.cit.*). Alternatively the rate of loess input may be too great and result in the eventual burial of the 'A' horizon (fAh). A new 'A' horizon may develop and it too may be eventually buried by the rapid build up of loess. This leads to the formation of a polygenetic soil which cannot be used in chronosequence studies.

The important point to note is that it may take up to 1000 years for the bouldery till matrix to reach the equivalent point of inception in the fine-grained loamy till. The soil coating the boulders in the open till matrix may, however, be extremely well developed due to the concentration of percolating soil water and nutrients between the boulders. This is of importance when preparing samples from bouldery till for analysis.

6.3 SAMPLING

6.3.1 Choice of sites

Sites were chosen from moraine surfaces which had been dated by weathering rind analysis. The moraines from each of the three glacier termini (Mueller, Tasman and Classen) showed the same axial orientation. Within each sequence sites were selected with the same aspect, slope position and, where possible, the same height.

6.3.2 Site descriptions

Fifteen sites were examined in detail. Map references of each sample pit are given with the soil profile descriptions in the following section. Sample pits 1-3 are located in the Tasman Valley. Site 1 is on a c.1150 year old [1] moraine 300m east of Blue Lakes. Site 2 is on the c.3800 year old terminal moraine and site 3 is from an exposure near the 'Wakefield waterfall' [2] dated c.8000 years or older (Burrows 1980, Birkeland 1982).

Sites 4-7 are located at the Classen Glacier terminus. Site 4 is on the 135 year old moraine. Sites 5 and 6 are on the 3350 year old surface, a small enclosed basin. Both sites are located on sloping ground above two small tarns. Site 7 is on the oldest terminal moraine in the valley, dated 4200 years old.

Sites 8-14 are located in the Mueller Valley. Site 8 is on the crest of White Horse Hill (dated c.1150 years old). Site 9 is further downslope on the 1800 year old surface. Site 10 is on the lowermost ridge of White Horse Hill, c.3350 years old. Sites 11 and 12 are located on Foliage Hill which is approximately 7200 years old. Site 13 is from a point in Mt Cook village itself and site 14 is on the lower slopes of Mt Sebastopol from a moraine dated c.8000 yr B.P. (Burrows 1980). Burrows (*op.cit.*) noted that soil development on this

---

1 From hereon (in this chapter) all ages quoted are based on rind thickness measurements derived from this study unless otherwise indicated.

2 cf. footnote 1, p.22.

surface was similar to that on Foliage Hill, the 'car park' moraine and the till exposure near the Wakefield waterfall in the Tasman Valley (site 3).

Site 15 is sampled from the distal slopes of the Northern moraine, Mueller Valley. A young fan has buried an older surface. The site was examined for evidence of a buried soil and is included in this analysis as an example of a polygenetic soil.

6.3.3 Sampling procedures

The location of the sample pits at each site was determined by the presence of surface vegetation and boulders. It was usual to dig several trial pits before selecting the final sample pit. Depths of the pits varied according to the depth of fine textured soil to underlying boulder till material. In fine textured soils volume weight was calculated using a 325cc sample corer. Initially only one volume weight sample was collected from each horizon. Later this was increased to two. All sampling was restricted to what could be reasonably carried out from the site although a helicopter was used to recover soil samples from the Classen Valley.

Soil sampling was organised according to the soil horizon differentiation. Where soil horizons were indistinct or deeper than 10cm, increment sampling at 10cm depths was used. All soil profiles were described in the field according to colour, texture, structure and horizon breaks. The NaF field test for reactive aluminium was used in the field as an indicator of the relative degree of soil development. Details of this test are given in Appendix D. No quantifiable results were obtained from this test.

6.3.4 Laboratory analysis

Measurements of the soil pH were made using 10g of field moist soil in KCl solution and H_2O. Delta pH (ΔpH) was calculated from the difference in these two readings. ΔpH decreases with increased weathering in the soil. Details of the procedure used to obtain values of soil pH are given in Appendix D.

The soil samples were then dried and ground through a 2mm sieve in preparation for further analysis. Care was taken to clean the surfaces of all small clasts present in the soil sample. The % weight of stones larger than 2mm was calculated. Soils were measured for loss on ignition. 5g of oven dried soil were weighed in preheated crucibles and placed in a furnace at 550° for 2 hours. The crucibles were removed and placed in a desiccator until they had cooled. The crucibles were reweighed and loss on ignition measured.

Soils were also measured for % phosphate retention. Phosphate retention is an empirical measure of the ability of the soil to adsorb phosphorous ions rapidly from solution. It is known to increase with depth, a trend which reaches its climax in the 'B' horizons of podzolised high country yellow-brown earths. It can be used as a measure of soil maturity. The procedure adopted for the calculation of % phosphate retention is given in Appendix D .

6.4 RESULTS

6.4.1 Field observations

Site and profile descriptions for the 15 sample pits are given in Table 6.1 . A noticeable feature of all the profiles is the predominance of silty-loam and sandy-loam textures in the A and B horizons. The Classen soils at sites 5,6 & 7 have pronounced Loess A soil horizons. The texture and structure profile forms are classified according to Cutler (1980). Texture profile forms are commonly 'Gradational Negative' (soils becoming progressively coarser with depth) or 'Duplex Negative' (soils which change abruptly within the profile from finer at the top to coarser below). Sites 8 & 10 had 'Gradational Positive' texture profiles, site 5 had a 'Uniform' texture profile and site 15 a 'Variable' texture profile form.

Of the 15 sites examined, 11 sample pits showed 'Isopedal' structured profile forms, that is, soils with the same structure throughout the profile. The immature soil sites had either 'Epipedal' or 'Subpedal' structural forms and site 15 had a 'Hypopedal' structure. These terms are explained in full in Appendix A .

Table 6.1 Site and Soil Profile Descriptions

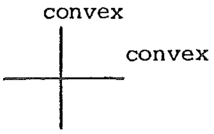
SAMPLE PIT 1 ASPECT S. SLOPE 16° MAP REFERENCE S79 824 357, H36 816 196

SOIL TEXTURE PROFILE FORM Gradational Negative

SOIL STRUCTURE PROFILE FORM Epipedal

VEGETATION COVER *Chionochloa spp., Hieracium praealtum Dactylis glomerata.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^o	0-5	10YR 4/2	Silty fibrous soil with abundant roots. Boundary smooth and clear.
Bg	5-10	10YR 3/2	Fine silty soil. Weakly developed with gravel inclusions. Boundary smooth and clear.
B	10-20	10YR 4/4	Silty loam with gravel. Weakly developed crumb structure. Boundary smooth and clear.
Br	20-30	10YR 5/4	Sandy loam with abundant gravel. Slightly leached horizon with weak crumb texture. Gradual.
Cox	30-40	10YR 5/1	Coarse gravel of parent material.

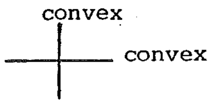
SAMPLE PIT 2 ASPECT SW. SLOPE 24° MAP REFERENCE S79 819 353, H36 812 192

SOIL TEXTURE PROFILE FORM Gradational Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Chionochloa spp., Dactylis glomerata.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
Ah	0-15	10YR 3/2	Fine silty soil, moist and cohesive with weak crumb structure. Boundary smooth and clear.
B	15-30	10YR 5/3	Silty soil, granular structure, well aggregated Boundary gradual.
Bg	30-40	10YR 5/3-5/4	Transitional. Silty-sandy soil mottled appearance. Small subangular sandstone clasts. Gradual.
B	40-50	10YR 5/4	Sand and gravel. Granular. Boundary gradual.
BC	50-60	10YR 5/6-4/4	Fine textured gravel with sandy, poorly aggregated soil. Roots present.

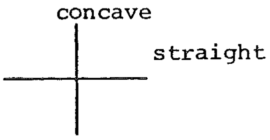
SAMPLE PIT 3 ASPECT SW. SLOPE 34° MAP REFERENCE S79 813 347, H36 807 186

SOIL TEXTURE PROFILE FORM Duplex Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Podocarpus nivalis, Leptospermum scoparium, Phyllocladus alpinus.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
B	10-20	5YR 5/6	Sandy, loessic soil with well developed crumb structure. Abundant roots. Boundary abrupt.
fAh	20-55	7.5YR 5/8	Silty-sand soil, cohesive and well aggregated. Boundary distinct and clear.
B	55-85	5YR 5/6	Sandy soil with angular gravel inclusions. Boundary smooth and clear.
BC	85-110	10YR 5/4	Sandy soil with numerous gravel inclusions. Boundary gradual.
C	110-	10YR 7/1	Strongly cemented, weathered sandstone bedrock.

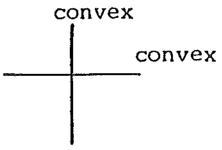
SAMPLE PIT 4 ASPECT S. SLOPE 12° MAP REFERENCE S80 104 582, I35 069 005

SOIL TEXTURE PROFILE FORM Duplex Negative

SOIL STRUCTURE PROFILE FORM Subpedal

VEGETATION COVER *Gaultheria crassa, Blechnum penna-marina, Aciphylla aurea, Wahlenbergia albomarginata, Luzula traversii, Hymenanthera alpina, Muehlenbeckia axillaris.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
AC	0-10	10YR 3/2	Silty-sand ,loose and very weakly developed with many small angular sandstone clasts. Boundary indistinct.
C	10-40	10YR 4/1	Extremely coarse, loose, stony parent material.

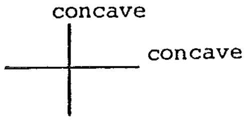
SAMPLE PIT 5 ASPECT N. SLOPE 10° MAP REFERENCE S80 103 580, I35 068 004

SOIL TEXTURE PROFILE FORM Uniform

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Hebe subalpina, Gaultheria crassa, Podocarpus nivalis.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{o}	0-10	10YR 4/2	Sandy loam,organic. Boundary clear and smooth
ABr	10-20	10YR 5/1	Sandy loam. Crumb structure. Boundary gradual.
ABr	20-30	10YR 5/2	Cohesive sandy loam. Boundary clear and smooth.
Br	30-40	10YR 5/2-5/4	Mottled horizon. Sandy, leached soil. Gradual.
B	40-50	10YR 5/4	Sandy loam. Crumb structure. Boundary gradual.
B	50-60	10YR 5/6	Fe rich,fine grained, crumb textured loam. A few boulders present. Boundary gradual.
B	60-70	10YR 5/8	Sandy soil, crumb structure with small angular sandstone clasts. Boundary gradual.
B	70-80	10YR 5/8-4/4	Very stony loam soil. Roots present. Boundary gradual and smooth.
BC	80-90	10YR 5/4-4/4	Bouldery soil,poor texture and boundary gradual.
BC	90-110	10YR 4/4	Weathered parent material.

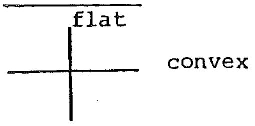
SAMPLE PIT 6 ASPECT S. SLOPE 3° MAP REFERENCE S80 103 579, I35 068 003

SOIL TEXTURE PROFILE FORM Gradational Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Dracophyllum uniflorum, Podocarpus nivalis, Hebe subalpina, Poa spp.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{o}	0-5	10YR 4/2	Fine grained silty soil,boundary clear and smooth.
Br	5-15	10YR 5/1	Fine grained cohesive silty soil. Clear and sharp.
B	15-25	10YR 5/4	Sandy loam,crumb structure,less cohesive. Gradual.
B	25-35	10YR 5/6	Granular sandy ped. Boundary gradual.
B	35-45	10YR 4/4	Fe rich sandy ped. Boundary gradual.
BC	45-55	10YR 4/2	Weathered parent material with fine gravel clasts and sandy matrix. Transitional to C.
C	55-60	10YR 3/3	Weathered parent material. Fine gravel.

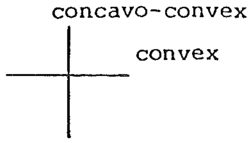
SAMPLE PIT 7 ASPECT S. SLOPE 18° MAP REFERENCE S80 101 578, I35 065 003

SOIL TEXTURE PROFILE FORM Gradational Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Cassinia vauvilliersii, Senecio cassinioides Celmisia spectabilis,Hebe subalpina, Dracophyllum longifolium, Ranunculus lyallii, Gaultheria crassa, Acaena sp.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{O}	0-5	10YR 3/1	Organic rich silty loam. Fine crumb structure. Boundary clear and smooth.
Br	5-10	10YR 6/4	Sandy loam with a few small clasts. Crumb structure Boundary clear and smooth.
B	10-20	10YR 4/4	Sandy with boulders. Poorly cohesive. Gradual.
Box	20-30	10YR 5/8	Sandy with increase in boulders. Sharp and Clear.
Br	30-40	10YR 4/4	Sandy-gravel texture, boulders. Boundary abrupt.
C	40-50	10YR 5/1-5/3	Coarse textured, parent material.

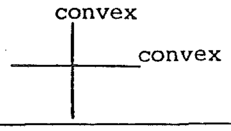
SAMPLE PIT 8 ASPECT SSE. SLOPE 8° MAP REFERENCE S79 755 338, H36 754 177

SOIL TEXTURE PROFILE FORM Gradational Positive

SOIL STRUCTURE PROFILE FORM Subpedal

VEGETATION COVER *Podocarpus nivalis,Hieracium praealtum, Poa colensoi, Agrostis tenuis,Phyllocladus alpinus,Coprosma spp.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A	0-10	10YR 3/1	Sandy loam, abundant gravel,friable. Clear & smooth
E	10-20	10YR 3/1-4/1	Transitional. Sandy loam with small angular gravel. Abundant roots, friable. Boundary gradual & smooth.
BC	20-30	10YR 4/1	Sandy loam with larger gravel components. Very friable. Boundary clear and smooth.
C	30-40	10YR 4/1	Loamy sand with abundant gravel.Loose structure.
Cox	40-50	10YR 4/1	Loamy sand, abundant gravel and loose structure.

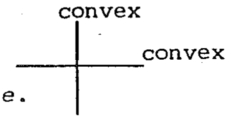
SAMPLE PIT 9 ASPECT SSE. SLOPE 17° MAP REFERENCE S79 755 337, H36 754 176

SOIL TEXTURE PROFILE FORM Gradational Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Poa colensoi, Viola filicaule, Racomitrium lanuginosum, Dracophyllum longifolium,Hydrocotyle novae-zelandiae.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{O}	0-10	10YR 3/1	Silty loam,friable with fine crumb structure. Boundary clear and smooth.
Er	10-20	10YR 5/1-4/4	Sandy ped with mottling. Boundary clear & smooth.
B	20-30	10YR 4/3	Silty - sandy loam,poorly aggregated ped. Gradual.
B	30-40	10YR 4/3-4/4	Sandy non-cohesive. Roots. Boundary irregular.
BC	40-50	10YR 4/2	Sandy with angular small gravel. Friable with roots. Transitional ped.
Cox	50-60	10YR 4/2	Sandy ped,extremely loose and friable with an increase in gravel.
Cox	60-70	10YR 4/1	Sandy with predominantly angular gravel. Loose.

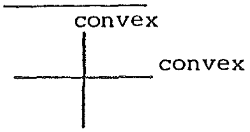
SAMPLE PIT 10 ASPECT SE. SLOPE 20° MAP REFERENCE S79 758 333, H36 758 173

SOIL TEXTURE PROFILE FORM Gradational Positive

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Festuca novae-zelandiae, Hieracium praealtum Dracophyllum longifolium, Podocarpus nivalis, Gaultheria crassa.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{o}	0-10	10YR 4/1	Sandy ped. Nutty structure. Clear and Smooth.
E	10-20	10YR 4/3	Sandy loam, granular and cohesive. Roots. Boundary Gradual and Smooth.
B	20-30	10YR 4/4	Sandy, granular ped with a few roots. Gradual.
B	30-40	10YR 5/4	Sandy, granular with many roots. Gradual.
B	40-50	10YR 5/4	Loamy silt, well developed crumb structure. Sub-angular gravel inclusions. Roots. Boundary gradual.
BC	50-60	10YR 5/4	Loamy silt, weakly developed crumb structure, gravel.

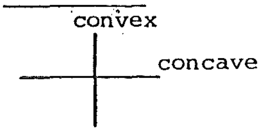
SAMPLE PIT 11 ASPECT S. SLOPE 15° MAP REFERENCE S79 760 327, H36 758 167

SOIL TEXTURE PROFILE FORM Duplex Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Dacrydium bidwillii, Phyllocladus alpinus Poa colensoi.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{o}	0-10	10YR 4/2	Sandy, cohesive ped. Granular. Boundary clear, smooth.
Er	10-20	10YR 5/2	Sandy loam, granular, well developed ped with a few roots. Boundary smooth.
B	20-30	10YR 5/3	Sandy loam with roots. Boundary gradual.
B	30-40	10YR 5/4	Silty loam, crumb structure with gravel. Gradual.
BC	40-50	10YR 5/4	Sandy ped. Loose structure with gravel. Gradual.
Cox	50-60	10YR 4/4	Sandy; friable soil. Abundant sub-angular clasts of the weathered parent material.

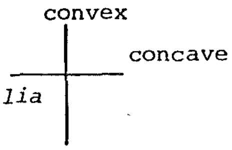
SAMPLE PIT 12 ASPECT W. SLOPE 26° MAP REFERENCE S79 759 326, H36 758 166

SOIL TEXTURE PROFILE FORM Duplex Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Phyllocladus alpinus, Dracophyllum longifolium, Podocarpus nivalis, Ranunculus lyallii, Chionochloa spp. Carmichaelia grandiflora.*

TOPOGRAPHY



HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^{o}	0-10	10YR 3/2	Silty loam, well developed ped, abundant roots. Boundary clear and smooth.
B	10-20	10YR 4/2	Silty loam crumb structured ped. Cohesive. Roots. Boundary Gradual.
B	20-30	10YR 4/2	Silt-loam with weak crumb structure, very loose and friable with roots and rock clasts. Abrupt & smooth.
B	30-40	10YR 4/4	Coarse sandy textured ped, abundant roots and clasts. Boundary Gradual and Wavy.
B	40-50	10YR 4/4	Coarse sandy ped, weak crumb structure, weathered clasts of parent material. Gradual and Indistinct.
BC	50-60	10YR 5/4	Sandy loose and friable with roots and clasts. Gradual.
Cox	60-70	10YR 5/4	Weathered parent material.

SAMPLE PIT 13 ASPECT W. SLOPE 5° MAP REFERENCE S79 764 307, H36 762 150

SOIL TEXTURE PROFILE FORM Gradational Negative

SOIL STRUCTURE PROFILE FORM Isopedal

VEGETATION COVER *Pittosporum anomalum, Griselinia littoralis, Phyllocladus alpinus, Rubus schmedliodes.*

TOPOGRAPHY
concave
concave

HORIZON	DEPTH cm	COLOUR	DESCRIPTION
O	0-10	10YR2/2	Fine silty litter layer. Boundary gradual.
A^o	10-15	10YR 3/2	Very fine silty loam, abundant roots and gravel. Boundary abrupt and smooth.
E	15-20	10YR 5/2	Fine textured,friable silty loam. Sharp and smooth.
Iron Pan		5YR 4/8	2cm deep, extremely compact and impervious.
Bg	20-30	10YR 5/4	Sandy gleyed horizon with mottling. Gradual.
B	30-40	10YR 4/4	Sandy ped, weak crumb structure, Gradual.
B	40-50	10YR 3/4	Sandy with fine gravel. Loose. Boundary gradual.
B	50-60	10YR 3/4	Sandy with abundance of gravel.
Cox	60-70	10YR 4/1	Weathered parent material. Boulders.

SAMPLE PIT 14 ASPECT S. SLOPE 15° MAP REFERENCE S79 763 299, H36 763 142

SOIL TEXTURE PROFILE FORM Gradational Negative.

SOIL STRUCTURE PROFILE FORM Isopedal.

VEGETATION COVER *Dacrydium bidwillii, Phyllocladus alpinus, Podocarpus nivalis, Gaultheria crassa, Aciphylla aurea.*

TOPOGRAPHY
convex
convex

HORIZON	DEPTH cm	COLOUR	DESCRIPTION
A^o	0-15	10YR 3/2	Organic rich silty loam,cohesive. Clear and smooth.
Obh	15-25	7.5YR 2/0	Buried charcoal layer. Organic. Sharp and smooth.
B	25-40	10YR 7/6	Sandy cohesive ped with a few roots. Clear & smooth.
B	40-50	10YR 6/6	Sandy loam ped with granular structure,Gradual.
B	50-60	7.5YR 5/6	Sandy,moderatelt developed,roots. Boundary gradual.
B	60-70	7.5YR 5/6	Sandy weakly developed ped with gravel. Gradual.
BC	70-100	10YR 5/6	Sandy, becoming increasingly coarser with roots and weathered parent material and clasts.

SAMPLE PIT 15 ASPECT SW. SLOPE 4° MAP REFERENCE S79 755 356, H36 754 194

SOIL TEXTURE PROFILE FORM Variable texture.

SOIL STRUCTURE PROFILE FORM Hypopedal

VEGETATION COVER *Chionochloa flavescens, Hieracium praealtum Ranunculus lyallii, Dracophyllum uniflorum*

TOPOGRAPHY
concave
concave

HORIZON	DEPTH cm	COLOUR	DESCRIPTION
O	0-10	10YR 4/1	Cohesive humus layer with abundant roots, Boundary clear and smooth.
Er	10-20	10YR 5/3	Silt-loam,gleyed.Crumb structure. Gradual.
EB	20-30	10YR 5/4	Coarse sandy loam,loose and friable. Sharp and clear.
B	30-40	10YR 6/3	Silt loam with angular clasts. Clear and smooth.
BC	40-50	10YR 4/1	Silt loam with abundant small angular clasts. Extremely loose and friable.

The sample pits are organised into 4 groups with regard to the field observations. These are as follows:

- -Group 1,surface age 135yr site 4
- -Group 2,surface age 1150-1830yr sites 1,8,9 & 15
- -Group 3,surface age 3350-4200yr sites 2,5,6,7 & 10
- -Group 4,surface age 7000-8000yr sites 3,11,12,13 & 14

Group 1 This group is characterised by a soil with minimal degree of pedogenesis. The AC horizon derives all its textural and structural characteristics from the underlying parent material. A coarse sandy matrix combines with unweathered clasts of the sandstone parent material.

Group 2 Within this group distinct soil horizon differentiation is described with A,Bg or E, B,BC and Cox horizons being identified. Textures are predominantly sandy-silty loams and a high percentage of clasts were present in the B and C horizons.

Group 3 The 'Loess A' horizon is the chief characteristic of this group, which contains high country yellow-brown earths with local development of podzolisation. Silt-sandy loams predominate.

Group 4 The final group contains the podzolised high country yellow-brown earths. Sandy-silt loams predominate throughout. Horizons are well differentiated. Clasts of parent material are frequently completely weathered. In sample 14 a charcoal layer was noted and at site 13 an iron pan formation described. The stratigraphy of site 3 is uncertain. A rich organic horizon is interposed between two apparently similar 'B' horizons the lower of which rests on strongly cemented grey weathered till.

6.4.2 Chemical analysis

Results of the laboratory analyses are presented in Table 6.2 . The table includes a summary of the field observations. Threshold values of the soil properties are different, and rates of change vary. The individual properties examined will be discussed separately. The influence of some variables may be eclipsed by others, and thus appear to have no relation to the development of the soil chronosequence.

Table 6.2

Laboratory analyses of the soil chronosequence

Ref. no.	Age[1] yr.	Horizon mm.		Colour/Texture[2]		B.D.[3] g/cc	% wt. >2mm	pH H2O	pH KCl	pH Δ	% P.[4] ret.	% LoIg.[5]
1	1150	0-5	A^{o}	10YR4/2	Si		2.8	5.2	3.8	1.4	29	17.9
		5-10	Bg	10YR3/2	Si+Grv							
		10-20	B	10YR4/4	SiLo+Grv		2.4	5.4	3.7	1.7	21	7.1
		20-30	Br	10YR5/4	SaLo+Grv		19.5	5.5	4.0	1.5	54	3.6
		30-40	Cox	10YR5/1	Grv		34.9	5.6	4.4	1.2	45	1.6
2	3790	0-15	Ah	10YR3/2	Si		0.0	5.6	3.9	1.7	36	11.3
		15-30	B	10YR5/3	Si		3.1	5.6	3.8	1.8	56	7.2
		30-40	Bg	10YR5/3-4	SiSa		21.4	5.6	4.0	1.6	62	4.3
		40-50	B	10YR5/4	Sa+Grv		27.4	5.7	4.1	1.6	56	5.6
		50-60	BC	10YR5/6	Sa+Grv		34.3	5.7	4.1	1.6	69	5.9
3	7000	10-20	B	5YR5/6	Sa		16.3	5.4	4.0	1.4	62	5.5
		20-55	fAh	7.5YR5/8	SiSa		4.6	5.6	4.2	1.4	91	8.1
		55-85	B	5YR5/6	Sa+Grv		19.8	5.7	4.1	1.6	79	5.4
		85-110	BC	10YR5/4	Sa+Grv		23.2	5.7	4.1	1.6	38	3.5
		110-	C	10YR7/1	Grv		22.0	5.7	4.3	1.4	21	1.2
4	135	0-10	AC	10YR3/2	Grv+SaSi		46.0	5.3	4.1	1.2	9	9.2
		10-40	C	10YR4/1	Grv		64.0	5.9	4.3	1.6	4	0.8
5	3350	0-10	A^{o}	10YR4/2	SaLo	0.8	0.0	4.6	3.5	1.1	28	17.2
		10-20	Abr	10YR5/1	LoSa	1.4	8.0	5.3	3.9	1.4	17	3.3
		20-30	Abr	10YR5/2	LoSa	1.4	6.0	5.4	4.0	1.4	10	3.0
		30-40	Br	10YR5/2	Sa	1.3	21.o	5.2	3.6	1.6	30	3.1
		40-50	B	10YR5/4	SaLo	1.3	10.0	5.1	3.5	1.6	49	5.1
		50-60	B	10YR5/6	Lo	1.3	44.0	5.2	3.6	1.6	61	10.6
		60-70	B	10YR5/8	Sa+Grv		68.0	5.2	3.7	1.5	63	6.2
		70-80	B	10YR5/4	Sa+Grv		55.0	5.4	3.9	1.5	54	4.8
		80-90	BC	10YR5/4	Grv+Sa		65.0	5.5	4.2	1.3	36	2.8
		90-110	C	10YR4/4	Grv		62.0	5.6	4.5	1.1	18	0.4
6	3350	0-5	A^{o}	10YR4/2	Si	1.0	14.0	5.2	3.7	1.5	31	17.1
		5-15	Br	10YR5/1	Si	1.6	9.0	4.3	3.7	0.6	29	2.9
		15-25	B	10YR5/4	SaLo	1.2	1.0	4.6	3.5	1.1	52	9.5
		25-35	B	10YR5/6	Sa	1.1	13.0	4.6	3.7	0.9	54	8.4
		35-45	B	10YR4/4	Sa	1.3	11.0	4.7	3.8	0.9	50	4.7
		45-55	BC	10YR4/2	Sa+grv		60.0	5.1	3.9	1.2	47	4.4
		55-60	C	10YR3/3	Grv		67.0	5.4	4.1	1.3	27	3.3
7	4200	0-5	A^{o}	10YR3/1	SiLo		0.0	5.1	3.4	1.7	25	15.4
		5-10	Br	10YR6/4	SaLo		21.0	4.8	3.3	1.5	25	6.0
		10-20	B	10YR4/4	Sa+Grv		50.0	4.9	3.5	1.4	72	20.4
		20-30	Box	10YR5/8	Sa+Grv		52.0	4.8	3.6	1.2	82	12.8
		30-40	Br	10YR4/4	Sa+Grv		62.0	5.2	3.9	1.3	52	4.8
		40-50	C	10YR5/1	Grv		70.0	5.7	4.2	1.5	37	2.4

---

[1] Age estimates from weathering rind analysis (this study)

[2] Si=silty, Sa=sandy, Lo=loamy, Grv=gravel

[3] Values from one or two volume weight samples only(BD=bulk density)

[4] % Phosphate retention, mean of replicate samples

[5] Loss on Ignition

Table 6.2 cont..

Ref. no.	Age[1] yr.	Horizon mm	Colour/Texture[2]	B.D.[3] g/cc	% wt. >2mm	pH H2O	pH KCl	pH Δ	% P.[4] ret.	%[5] LoIg.
8	1450	0-10 A	10YR3/1 SaLo+Grv	0.5	3.0	5.2	3.8	1.4	23	8.8
		10-20 E	10YR3/1 SaLo+Grv	1.0	15.0	5.3	3.7	1.6	20	4.7
		20-30 BC	10YR4/1 SaLo+Grv		52.0	5.7	4.1	1.6	14	2.1
		30-40 C	10YR4/1 LoSa+Grv		63.0	5.9	4.3	1.6	9	1.4
		40-50 Cox	10YR4/1 LoSa+Grv		64.0	6.1	4.4	1.7	10	1.0
9	1830	0-10 A^o	10YR3/1 SiLo		4.0	5.3	3.7	1.6	32	7.4
		10-20 E	10YR5/1 Sa		2.0	5.3	3.8	1.5	38	4.8
		20-30 B	10YR4/3 SaLo		14.0	5.6	4.1	1.5	47	4.1
		30-40 B	10YR4/3 Sa		52.0	5.7	4.2	1.5	44	3.6
		40-50 BC	10YR4/2 Sa+Grv		52.0	5.7	4.4	1.3	33	2.7
		50-60 Cox	10YR4/2 Sa+Grv		62.0	6.0	4.7	1.3	36	3.5
10	3350	0-10 A^o	10YR4/1 Sa	0.6	0.5	5.1	3.5	1.6	32	13.2
		10-20 B	10YR4/3 SaLo	0.7	0.0	5.0	3.6	1.4	62	8.3
		20-30 B	10YR4/4 Sa	0.5	0.1	4.9	3.9	1.0	65	6.2
		30-40 B	10YR5/4 Sa	0.8	0.4	5.3	3.9	1.4	56	5.4
		40-50 B	10YR5/4 LoSa		2.0	5.3	3.9	1.4	53	4.7
		50-60 BC	10YR5/4 LoSi		1.0	5.3	3.9	1.4	47	3.5
11	7200	0-10 A^o	10YR4/2 SaLo		1.0	4.7	3.3	1.4	44	1.2
		10-30 B	10YR5/4 SaLo		0.9	5.0	3.7	1.3	68	6.8
		30-50 BC	10YR5/4 Sa+Grv		11.6	5.2	3.9	1.3	76	7.2
		50-70 C	10YR5/4 Sa+Grv		33.9	5.3	3.9	1.4	72	6.7
12	7200	0-10 A^o	10YR3/2 SiLo	0.8	0.9	4.5	3.3	1.2	42	9.6
		10-20 B	10YR4/2 SiLo	0.8	0.1	4.8	3.5	1.3	54	5.8
		20-30 B	10YR4/2 SiLo+Grv	0.7	0.1	4.9	3.8	1.1	69	5.8
		30-40 B	10YR4/4 Sa+Grv	0.7	0.8	4.9	3.8	1.1	65	5.5
		40-50 B	10YR4/4 Sa+Grv	0.7	2.6	4.9	3.9	1.0	60	4.6
		50-60 BC	10YR5/4 Sa+Grv		46.3	5.0	4.0	1.0	72	6.0
		60-70 Cox	10YR5/4 Grv							
13	?	0-10 O	10YR2/2 Si		0.0	4.2	3.1	1.1	13	80.1
		10-15 A^o	10YR3/2 SiLo		1.5	4.3	3.2	1.1	50	10.1
		15-20 E	10YR5/2 SiLo		5.0	4.5	3.5	1.0	49	7.5
		Iron Pan	10Yr4/8 Imperv.							
		20-30 Bg	10YR5/4 Sa		1.8	4.7	3.8	0.9	66	8.1
		30-40 B	10YR5/4 Sa		20.6	4.8	4.0	0.8	67	8.2
		40-50 B	10YR3/4 Sa+Grv		59.0	5.0	4.2	0.8	81	8.1
		50-60 B	10YR3/4 Sa+Grv		58.0	5.1	4.4	0.7	67	5.1
		60-70 Cox	10YR4/1 Grv		56.5	5.2	4.4	0.8	47	2.7
14	8000	0-15 A^o	10YR3/2 SiLo		0.0	5.1	3.7	1.4	59	17.4
		15-25 Obh	7.5YR2/1 Si(charcoal)		1.6	5.0	3.7	1.3	57	9.1
		25-40 B	10YR7/6 Sa		0.0	5.1	3.8	1.3	63	4.1
		40-50 B	10YR6/6 SaLo		0.0	5.1	3.9	1.2	70	4.1
		50-60 B	7.5Yr5/6 Sa		9.0	5.3	4.2	1.1	86	10.0
		60-70 B	7.5YR5/6 Sa+grv		9.4	5.1	4.1	1.0	94	15.8
		70-80 BC	10YR5/6 Sa		13.0	5.3	4.2	1.1	96	6.3
		80-90 BC	10YR5/6 Sa		35.4	5.4	4.4	1.0	96	6.3
		90-100BC	10YR5/6 Sa		38.0	5.3	4.4	0.9	93	9.0
15	1150	0-10 O	10YR4/1 Sa	0.9	0.0	4.9	3.6	1.3	34	1.3
		10-20 Er	10YR5/3 SiLo	1.2	0.4	5.1	3.9	1.2	19	2.1
		20-30 EB	10YR5/4 SaLo	0.9	2.0	5.1	3.9	1.2	29	3.2
		30-40 B	10YR6/3 SiLo		46.0	5.3	3.9	1.4	74	6.7
		40-50 BC	10YR4/1 SiLo+Grv		52.0	5.4	4.0	1.4	64	5.8

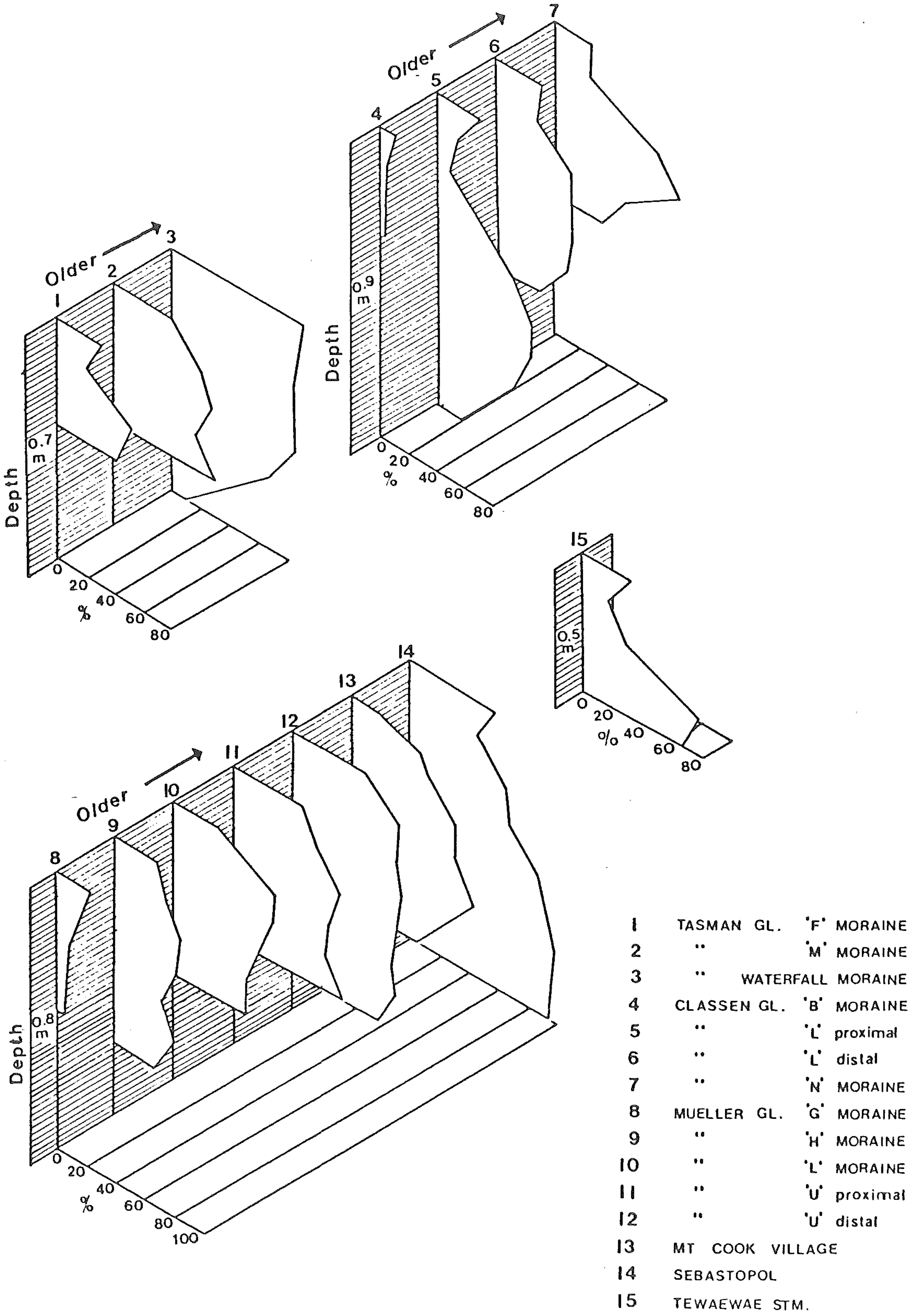
Bulk density Determination of bulk density was extremely difficult due to the nature of the substrate. An accurate value could not be gained from loose,gravelly peds, nor from crumbly,fibrous horizons. No bulk density measurements were obtained from BC and C horizons. Data is presented from 6 sample sites. Values vary more with soil texture than with surface age. Estimates of bulk density ranged from 0.5-1.6 g/cc. The values reached a maximum in the upper 'B' horizon.

% weight of stones <2mm Stones are important in that they dilute the soil with completely inactive material, (Miller 1968). Partially weathered clasts derived from the parent material constitute up to 70% of the subsurface horizons. The percentage weight of stones in the surface horizons is highest in the youngest soils (46% at site 4) and decreases with increased weathering of the clasts, loess input and humus accumulation to yield values of 0.0% (sites 2,5,7,13,14 & 15).

Soil pH Soil pH values dilute with intensive leaching and accumulation of humus. The variations in pH from horizon to horizon within each profile reflect the nature of some of the processes operating in the system. pH values decrease with depth. A sharp increase in soil reaction is recorded by some strongly leached B horizons. Surface pH (H2O) drops from 5.3 on the 135 year old surface to 4.7-4.5 on the 7200 year old surface. Values of pH are inconsistent. Soil surface values show an increase on surfaces up to c.4000 years old, thereafter values of pH decline in the A horizon. Subsurface values suggest a build up in surfaces aged 2000 years and younger, followed by a gradual decline. The differences are not sufficient to regard pH as a successful discriminator of age.

% Phosphate retention % phosphate retention is a measure of the anion adsorption of the soil colloids. Values recorded are as low as 4% at site 4 (c.135 years old) and reach a maximum of 98% at site 14 (c.8000 years old). The increase in % phosphate retention is most clearly shown in the B Horizons during the first 4000 years of development and in the BC horizons in older soils. Values of % phosphate retention increase abruptly at texture breaks in the soils

Figure 6.2 % Phosphate retention as a function of depth and time.



1	TASMAN GL. 'F' MORAINE
2	" 'M' MORAINE
3	" WATERFALL MORAINE
4	CLASSEN GL. 'B' MORAINE
5	" 'L' proximal
6	" 'L' distal
7	" 'N' MORAINE
8	MUELLER GL. 'G' MORAINE
9	" 'H' MORAINE
10	" 'L' MORAINE
11	" 'U' proximal
12	" 'U' distal
13	MT COOK VILLAGE
14	SEBASTOPOL
15	TEWAEWAE STM.

where fresh accumulating loess rests on weathered parent material (sites 5.6.7 & 15). A similar trend is shown in the profile from site 13 where % phosphate retention increases rapidly below the iron pan at a depth of 20cm. The change in % phosphate retention with time and depth in a soil chronosequence is illustrated in Fig.6.2 .

% Loss on ignition The amount of organic matter in the soil system is controlled by the availability of phosphorus, and rapidly builds up to reach a maximum value in the Ah horizon within the first 200 years (Walker & Syers 1976). Thereafter the changes in the carbon content of the soil are a reflection of vegetation and environment and do not appear to be age-related.

6.5 DISCUSSION

The analyses undertaken for this study were selected from among those criteria judged to be best suited to describing a Holocene soil sequence. I am conscious that this study is not exhaustive. Rather I have abstracted a number of soil properties and used them to describe a whole soil system. Such an approach has obvious limitations. The study was limited in respect to the difficulties of sampling the till. The inadequacies of the field sampling are best exemplified by the restrictions imposed on bulk density sampling. In spite of these various difficulties, some of the results are of use in defining the relative age-development of surface soils on the moraines. Arising from this study are two main points of discussion:

- To what extent does the input of loess affect the monogenetic status of the soils being examined ?
- What physical and chemical soil properties usefully describe the relative age differences within a soil chronosequence ?

It is problematical as to whether some of the soils examined in the course of this study are monogenetic. All of the soils are affected by the input of loess. This input is variable in both space and time. The situation was simplified in Fig.6.1 where it was suggested that:

i- where loess input was so great as to overwhelm the existing soil development and bury the soil profile, the resulting soil profile would be polygenetic, otherwise

ii- loess input could be steadily accumulated and assimilated in the soil profile without altering the monogenetic status of the soil.

There is, however, a third category where:

iii- a soil may have the physical appearance of a monogenetic soil yet have a chemical composition more closely aligned with that of a polygenetic soil.

Site 15 in the Hooker Valley is an example of a polygenetic soil, and it was included in this study as such. It is evident from the physical appearance of the soil profile that there have been two phases of deposition separated by a period of erosion. The abrupt break in the sequence is also evident in the chemical analysis where values of % phosphate retention increase markedly below the erosion surface from 29% to 74%. A similar trend was observed for site 7 and to a lesser extent at sites 5 and 6. All three sites have a pronounced Loess A horizon, although this was not interpreted as a texture break, let alone a developmental break in the field. Equivalent soil development in the Tasman (site 2) and Mueller (site 10) Valleys shows no evidence of a hiatus in either the chemical of physical properties in soils of about 3000-4000 years old. The input of loess is reduced in the eastern valleys of the Mt Cook region. The increase in % loss on ignition, at depths specified in Table 6.2, at sites 5, 7 & 14 is characteristic of a buried humus podzol and contributes further to the suggestion that the soils at the Classen terminus may not be strict mono-sequences.

The second point of discussion refers to the success of the different procedures adopted for assessing relative age differences between the sites. At any one point in a sequence of developing soil surfaces there is considerable heterogeneity in the processes at work. The most useful transformations for defining a chronosequence are those which take effect from the beginning of soil formation and which reach a steady state in the oldest members of the sequence. Stevens & Walker (1970) noted that each soil component tends towards dynamic equilibrium at different rates and that few components reach an apparent steady state at the same time if at all. Birkeland (1981) was able to differentiate between two young moraine surfaces at the Mueller Glacier terminus using soil descriptions of pH and organic carbon. He used age-related criteria which effectively described soil developmental change on recently formed surfaces. Different criteria are required when examining a chronosequence spanning several thousand years. The present study found that % phosphate retention most adequately defined the increasing maturity in the soil system. Low % phosphate retention values correspond to a lack of amorphous aluminium and iron compounds and indicate low maturity in the system. A value of 9% was obtained from soil on a 135 year old surface. With increasing age (c.1000-1800 year old moraines) phosphate retention values rose to 20-30% in the subsurface horizons. The values continued to rise. On the c.7200 year old surface (Foliage Hill) phosphate retention measured 70-76% in the subsurface horizons and values from sites 3 & 14 exceeded 90% in the B and BC horizons. Both these surfaces had originally been correlated with Foliage Hill(c.7200 years),(Burrows 1980), but show closer similarity in age to Birch Hill moraines (c.10000-11000 yr) for which similar % phosphate retention values were obtained by Webb(unpubl.). A similar age-related sequence of phosphate retention was described for a sequence of terrace soils near Reefton (Campbell 1975). The surfaces ranged from 1000 to 130 000 years. The usefulness of soil development as a relative age indicator is supported by many similar studies overseas (Crocker & Major 1955, Crocker & Dickson 1957, Tisdale & Fosberg 1966, Goldthwait *et al.* 1966, Ugolini 1968). A comparison,with these studies, of the approximate rates of development is not feasible due to the many differences in environmental controls.

Regional patterns of soil development in the Mt Cook region approximate the weathering rind model (chapter 5). Soil development on the crest of White Horse Hill (c.1500yr) is similar to soil development on the outer slopes of the Blue Lakes(c.1150yr) and similar soil development is recorded from the 3350 and 3790 year old moraines in the Tasman, Mueller and Classen Valleys. The results confirm the general

CHAPTER 7

VEGETATION DEVELOPMENT

7.1 INTRODUCTION

The present study examines the primary succession on the moraines in Mt Cook National Park. The surfaces examined were dated using weathering rind analysis (chapter 5). Moraine sequences between 0-4200[1] years were sampled. This is a much greater time scale than most comparable studies outside of New Zealand which tend to be restricted to sequences of 500 years or less (Cooper 1923, 1931, 1939, Crocker & Major 1955, Lawrence 1958, Tisdale, Fosberg & Poulton 1966, Stork 1963, Wright 1980, Birks 1980). The moraine environment influences the pattern and rate of change in plant development, and therefore requires special consideration.

7.1.1 The pattern of plant succession on moraines

According to Stork (1963) vegetation studies of morainic deposits in other parts of the world show that colonization, competition and development of the vegetation occur in the same way everywhere. She refers to the work of Lüdi, who described the sequence as follows:

"Übereinstimmend ist an allen Gletschervorfeldern als Erstbesiedlung eine zufällige Mischung von Arten der Umgebung,welche auf einem absolutem Rohboden zu keimen und zu wachsen vermögen.Übereinstimmend ist auch,dass in diesen ersten Stadien die Blütenpflanzen und die Moose voneinander unabhängig wachsen, also nicht etwa die Moose den Blutenpflanzen vorausgehen müssen oder umgekehrt. Wohl aber sind die Moose wirksame Humusbildner,die verhältnismässig rasch eine erste Anreicherung an dunklem Humus bewirken, meist in Form einer ganz dunnen Decke,die den Boden auch festigt und später für bestimmte Blütenpflanzen als Keimbett dienen kann.Übereinstimmend ist ferner der spätere Vorgang

A common feature of all glacier forefields is the accidental mixture of colonising species from the surroundings which are able to germinate and grow on pure mineral soil. In the first stages the angiosperms and mosses grow independently with,for instance, the mosses preceding the flowering plants or vice versa.But certainly the mosses are effective humus producers(builders) and give rise,relatively quickly to the first accumulations of dark humus,generally in the form of a very dark thin cover which also consolidates the soil and later can serve as a germination medium for certain flowering plants. Another common feature is the later process of selection according to site (s), which leads to the develop-

---

[1] All surface dates cited are derived from the weathering rind chronology (this study) unless otherwise stated.

> der Aussonderung nach Standorten, der zur Ausbildung besonderer Pflanzengesellschaften führt...Für die Weiterentwicklung ist sehr wichtig die Oberflächengestaltung: steile Hänge besiedeln sich sehr langsam, weil die Feinerde immer wieder ausgespült wird: flache Lagen oder Mulden sind viel günstiger und kommen rascher zu dichterer Besiedlung."
> (Lüdi 1958, p.401-2)

> ment of particular plant communities ...
>
> Surface forms are very important for the further development: steep slopes are populated very slowly, because the fine material is washed out again and again; flat positions or depressions are more favourable and are more quickly and more densely populated."
> Translated: P.Haase, 1982.

It is assumed, in the present study, that the pattern of vegetation on surfaces which are stable both physiographically and climatically but which differ in age of formation and period of exposure, is the result of predictable changes with time. This is simplistic. The vegetation responds not to time per se, but to changes in stress, and to environmental and floristic gradients. The use of vegetation development as a relative age-indicator presupposes that all change occurs in a similar fashion, rate and direction throughout the sequence of similar substrates etc on the different aged deposits. Two temporal indices are examined:

i- the rate of colonization of a bare surface, &

ii- the rate of change in the succession

The former is recorded directly on the most recently exposed surfaces. The latter is described from a spatial sequence. The inital conditions for seedling establishment may be heterogeneous and their influence may persist over a very long period of time. Nevertheless trends should become apparent in which "immature", "maturing" and "mature" species assemblages are discernible.

The objectives of this study, therefore, are to determine the changes in plant development in a chronosequence at sites in the East Hooker and Classen Valleys.

7.2 SITE SELECTION

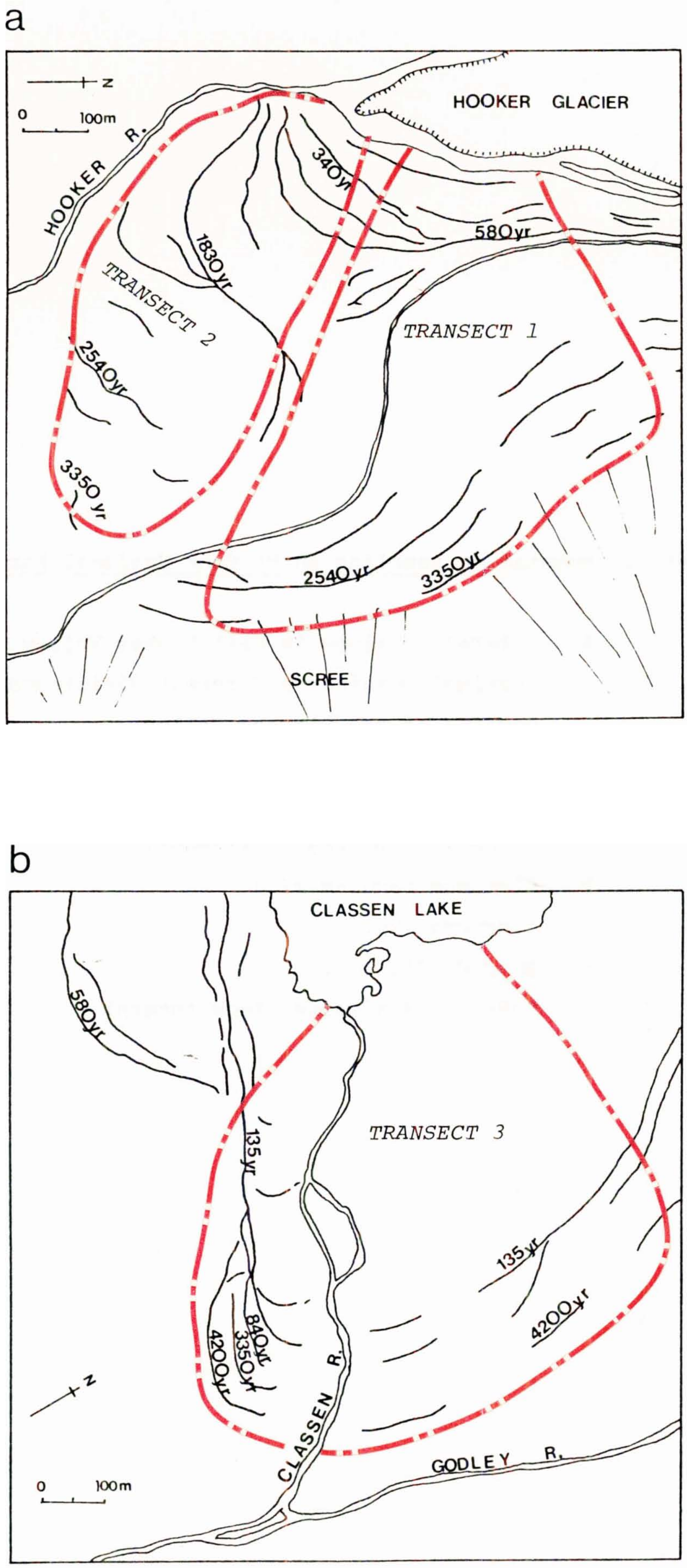
7.2.1 East Hooker Valley

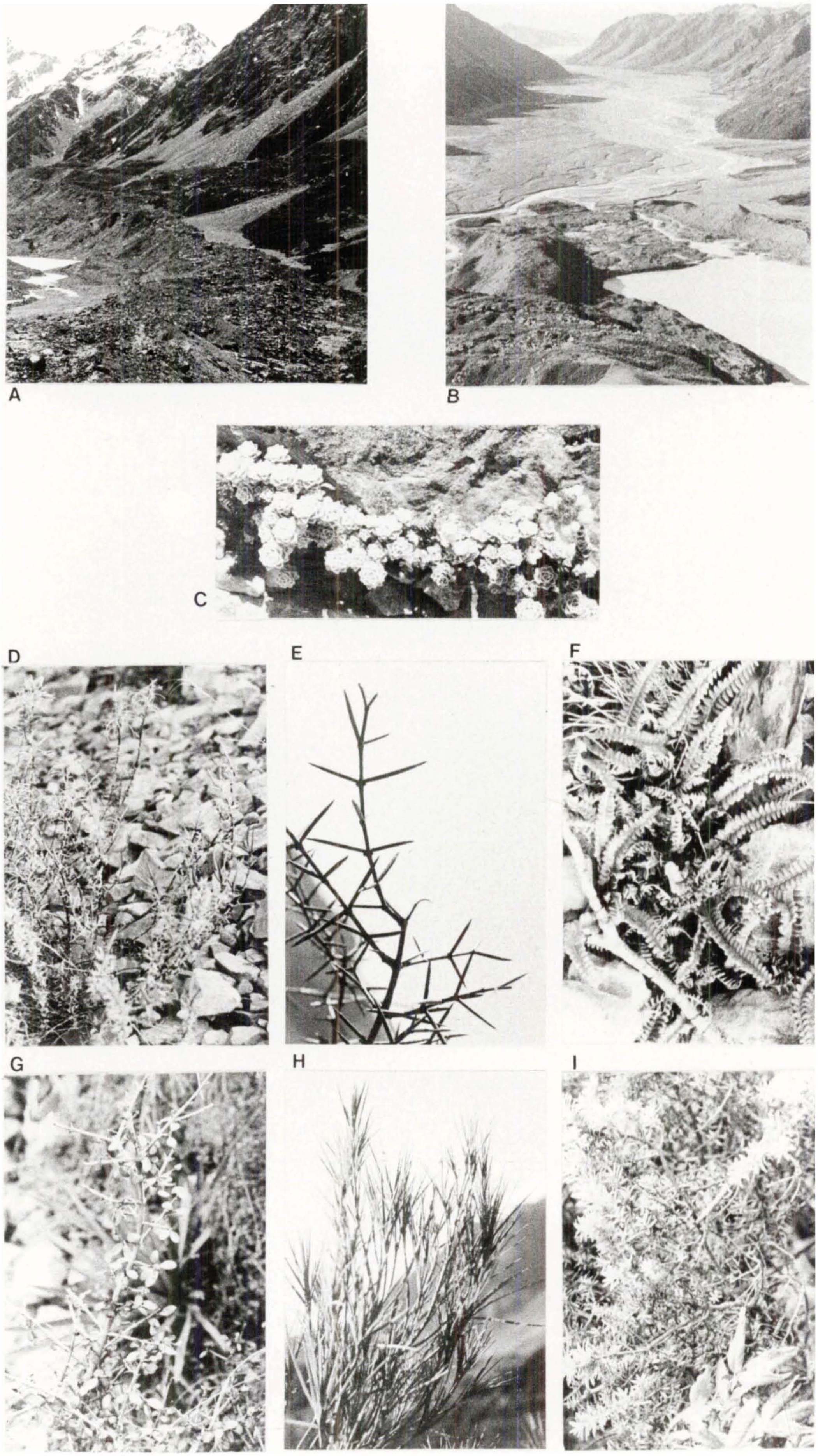
Within the east Hooker Valley the vegetation is only locally disturbed. According to Wright 1884 (Fig.4.4, p.44) the only area to have been burnt in recent historical time was the 'Island' south of the main terminal moraine. Burrows (pers.comm. 1982) remarked on the presence of charcoal on an east Hooker Valley lateral moraine approximately level with the Hooker glacier terminus. Written accounts mention grazing in the Hooker Valley until the end of the last century (4.4, p.52-54). Avalanches are common in the valley as well as several active scree slopes. A sequence of eleven separate glacier front positions are discernible from within the period 3400-0 years (Fig.5.4, p.71). Two sample belt transects were examined which cut across the moraine sequences. The two surveys will be referred to as Transect 1 and Transect 2 (Fig.7.1a). Transect 1 incorporates the lateral moraine sequence (Fig.7.2A). It extends south-east from the glacier snout and covers an altitudinal range of approximately 300m (850m-1140m). Transect 2 extends downvalley for a distance of 800m and incorporates the terminal moraine sequence including the area commonly referred to as the 'Island'. The oldest moraines in both sequences support medium height scrub (<2m). The younger surfaces support low scrub (<1m) and tussock grassland, and the youngest sites, immediately adjacent to the glacier, support low lying herb communities (<0.3m)

7.2.2 Classen Valley

The dated Classen moraine sequence is discontinuous. Four dated surfaces are less than 1000 years old and these are juxtaposed against two very much older surfaces, dated 3350 and 4200 years old (Fig.5.7, p.75). According to Wilson (1976), an area close to the Classen terminus was burnt as recently as c.1930 A.D. Broderick noted extensive burning on the Sibbald Range and stunted scrub with a few snow grass tussocks close by the Classen Glacier when he mapped the area in 1888 (Fig.4.5, p.45). In addition he noted the presence of sheep and cattle grazing right up to the glacier. The vegetation of the glacier forefield and the terminal moraines is examined within one transect, Transect 3 (Fig.7.1b, Fig. 7.2B). The two older moraines support snow tussock grassland and medium height scrub which contrasts strongly with the incompletely closed plant cover and herb field on the younger surfaces.

Figure 7.1 Positions of Transects 1, 2 and 3.




A
B
C
D
E
F
G
H
I

7.3 SAMPLING

A standard plot size of $4m^2$ was used throughout the study for description within subjectively selected uniform stands of vegetation. The plot size was chosen to conform with the minor topographic variations on the moraines. A smaller quadrat might have been inadequate to encompass the pattern created by the presence of individuals of relatively large size (eg.*Dracophyllum* spp.,*Chionochloa* spp.) whilst an area too large would include heterogeneous conditions. The quadrats were positioned as follows:- from a known point on the moraine ridge the plot was located a random number of paces along the crest and a random number of paces down the slope. If the number of paces exceeded the distance of the ridge length or slope, a further value was sought. Each plot on each moraine was located by reference to the known starting position. All taxa of vascular plants, bryophytes and lichens occurring in the plots were recorded. Identification of species was made using the Field Guide prepared by Wilson (1978) and Allan (1961). Cover abundance of all plants and bare ground was estimated visually using five groups: <20%, 20-40%, 40-60%, 60-80%, >80%. Species absent from the plot but occurring in close proximity to the plot were noted. Each plot was given a reference number. Habitat features were recorded, namely aspect, slope and moraine age (as determined by weathering rind analysis in this study). Soil development on moraines in the Classen Valley is described in Chapter 6. The soil development was only briefly examined in the Hooker Valley and was not included in the earlier study of soil chronosequence development in the Mt Cook region. A total of 56 quadrats were recorded in Transect 1, a further 33 quadrats in Transect 2, and 84 quadrats in Transect 3.

7.4 VEGETATION ANALYSIS

The data were analysed using Principal Components Analysis (PCA) and Reciprocal Averaging (RA). Both aim to extract a number of axes which define the underlying structure of the relationships of species with one another and with habitat variation. PCA has been criticised for its inability to cope with increasing diversity within a sample set. PCA involves a number of subjective decisions the most significant of which is the assumption that relationships between vegetation and the environments are linear, (Gauch & Whittacker 1972, Gauch *et al.* 1977). RA is more tolerant of sample diversity but posesses two drawbacks: The first is the 'arch effect' which is simply a mathematical artefact corresponding to no real structure in the data and which arises because the second axis of RA is constrained to be independent of it, (Hill & Gauch 1980). The second is the inability to preserve ecological distance. These two problems can be corrected for by Detrended Correspondence Analysis (DCA), (Hill & Gauch 1980). A computer programme to do this was not available in New Zealand at the time of writing.

7.5 RESULTS

The results of the vegetation sampling from each individual plot are presented in Appendix E 1-9. Cover abundance is tabulated. Details of vegetation development on the different aged surfaces is presented for each transect separately. Taxonomic nomenclature is according to Allan (1961). The nomenclature of plant communities follows Wilson (1976).

7.5.1 Vegetation description

A Transect 1 The numbered series of plots begin close to the glacier terminus. Plots 1 and 2 describe the youngest site examined. The surface is <100 years old and is colonised sparsely with a few individuals notably of: *Epilobium melanocaulon, Blechnum penna-marina* and *Raoulia* spp. Bare ground is a feature in all the early plots and is commonly recorded as occupying more than 80% of the quadrat area (cf.Appendix E). Plots 2-8 exhibit a more continuous plant cover referred to as a mid-seral community[1]. The early colonists are replaced or exceeded in importance by a few low herbs. The most persistent of these taxa on

---

[1] Each of the plant community groups described by Wilson (1976) will be underlined in the text as shown.

the 100-180 year old surfaces were; *Racomitrium lanuginosum* and *Luzula colensoi*. Plots 6, 7, 8 & 13 supported Festuca short tussock. This plant community was characterised by the introduction of *Blechnum penna-marina, Celmisia walkeri, C.hectori, Anisotome flexuosa, Wahlenbergia albomarginata, Pimelea traversii* and *Gentiana corymbifera*. The woolly moss, *Racomitrium lanuginosum*, continues to be important with *Muehlenbeckia axillaris* and *Cyathodes fraseri* contributing to the ground cover either in the plots or adjacent to the sites chosen. Plots 6, 7 & 8 were sampled on a 580 year old moraine. Plot 13 was from a surface 1800 years old. Subsequent plots were all sampled on surfaces older than 1000 years.

Quadrats 9-12 were sampled from a small latero-terminal moraine complex which is encircled by two ephemeral streams. The moraines are 1150-1490 years old. The soil was recorded as an immature podzol with gleying in the B horizon. The moraine surfaces were characterised by a *Chionochloa flavescens* grassland. Apart from the presence of *C.flavescens*, a number of other species were recorded; *Pimelea traversii, Myrsine nummularia, Gaultheria crassa, Ranunculus lyallii, Aciphylla aurea, Coprosma rugosa, Hebe subalpina, Hymenanthera alpina* and *Podocarpus nivalis*. In addition four plants were noted for their earliest appearance in the moraine sequence, and these were; *Phyllocladus alpinus, Cassinia vauvilliersii, Pseudopanax colensoi* and *Ranunculus lyallii*.

Subsequent plots were sampled from the high lateral moraines where variation in aspect and altitude may account for differences in the vegetation development (Fig.7.2A). Plots were sampled from proximal and distal moraine slopes separately. There are four main lateral moraine ridges. The lowest dates from c.2160 years ago. The surface is colonised by subalpine short scrub . The vegetation is <1.5m high and is dominated by three main species; *Podocarpus nivalis, Gaultheria crassa* and *Celmisia coriacea*. The ground cover is composed of several species; *Myrsine nummularia, Lycopodium fastigiatum, Acaena* spp., *Celmisia petiolata, Hebe macrantha, Hebe treadwellii, Racomitrium lanuginosum* and *Parahebe decora*. *Olearia nummularifolia, Celmisia petiolata, Myrsine nummularia* and *Hebe treadwellii* are all present for the first time in the sequence.

The second highest lateral moraine ridge is dated as c.2500 years. Quadrats 16-32 were sampled from the westward facing slopes which supported a shrubland on moraine community. The principal taxa are: *Aciphylla aurea*, *Olearia moschata*, and *Dracophyllum longifolium*. The ground cover was comprised of *Gaultheria crassa*, *Celmisia coriacea*, *Coprosma rugosa*, *Hebe subalpina*, *Anisotome haastii*, *Gentiana corymbifera*, *Luzula colensoi* and *Olearia nummularifolia*. In disturbed sites (quadrat 22) *Aristotelia fruticosa*, *Geum parviflorum*, *Muehlenbeckia axillaris*, *Taraxacum magellanicum*, *Viola filicaule* and *Celmisia walkeri* were recorded.

On the same surface facing east, the vegetation cover reverted to a *Chionochloa flavescens* seral shrubland. Associated with the tussock are *Olearia nummularifolia*, *Aciphylla aurea* and *Dracophyllum longifolium*. An extensive list of additional herbs and shrubs accompanies the four dominant taxa; *Podocarpus nivalis*, *Celmisia coriacea*, *Coprosma rugosa*, *C.parviflora*, *C.rigida*, *Gaultheria crassa*, *Phyllocladus alpinus*, *Anisotome haastii*, *Olearia moschata*, *O.nummularifolia*, *Racomitrium lanuginosum*, *Pseudopanax colensoi*, *Cardamine debilis*, *Cassinia vauvilliersii*, *Chionochloa pallens*, *Coriaria angustissima*, *Cyathodes fraseri*, *Dracophyllum kirkii*, *D. uniflorum*, *Hebe macrantha*, *H.subalpina*, *H.treadwellii*, *Hymenanthera alpina*, *Myrsine nummularia*, *Parahebe decora*, *Polytrichum juniperinum*, *Ranunculus lyallii*, *Senecio bennettii* and *Wahlenbergia albomarginata*.

The third highest lateral moraine is less extensive than those above and below. It is about 3000 years old and supports a subalpine medium-height scrub. On both sides of the moraine, which is at most c.3m in relief, *Chionochloa flavescens*, *Dracophyllum longifolium*, *Coprosma rugosa* and *Hebe subalpina* are common.

The highest lateral moraine was deposited over 3300 years ago and now supports two distinct plant communities; subalpine medium-height scrub and *Hoheria* scrub. Plots were located on the western facing slopes only as the distal moraine side was partially buried by slope wash material and scree. The subalpine medium-height scrub was dominated by

Dracophyllum uniflorum, Coprosma rugosa, C.rigida, Chionochloa flavescens, Hymenanthera alpina, Cassinia vauvilliersii and *Racomitrium lanuginosum*. The Hoheria scrub was dominated by; *Hoheria lyallii* in association with *Racomitrium lanuginosum, Hymenanthera alpina, Chionochloa flavescens, Dracophyllum longifolium, Cyathodes fraseri, Cassinia vauvilliersii, Hebe subalpina, Pseudopanax colensoi, Coprosma rigida, C.rugosa, Ranunculus lyallii, Celmisia petiolata* and *Phyllocladus alpinus*.

B Transect 2 The vegetation development on the terminal moraines in the Hooker Valley is presented in detail in Appendix E3-4. Plots were positioned on the youngest surfaces initially, and subsequent plots were examined on the outer, older moraines. Quadrats 1-4 describe the surface vegetation on moraines which have formed in the last 135 years, (new moraine). Bare ground predominates with a sparse, but varied assemblage of herbs and low shrubs. These include: *Ourisia caespitosa, Polytrichum juniperinum, Raoulia* spp., *Epilobium* spp., *Blechnum penna-marina, Luzula colensoi, L.rufa, Racomitrium lanuginosum, Wahlenbergia albomarginata, Hymenanthera alpina, Trifolium repens, Geum parviflorum, Lycopodium fastigiatum* and *Hieracium praealtum*.

The 340, 580 and 1490 year old surfaces are all dominated by shrubland on moraine communities with an increase in plant cover and height and a decrease in bare ground with age. The principal taxa on all three surfaces are; *Hieracium praealtum, Gaultheria crassa, Lycopodium fastigiatum, Geranium sessiliflorum, Aciphylla aurea, Hydrocotyle novae-zelandiae, Celmisia walkeri, Gentiana corymbifera, Hebe subalpina, Coprosma rigida, Olearia nummularifolia* and *Ranunculus lyallii*.

The main terminal moraine, c.1830 years old, supports *Chionochloa flavescens* shrubland on the north-facing slope and seral medium-height scrub on the older, south facing slope. The difference in age between the two slopes (c.300 years) indicates a halt in recession of the glacier shortly after depositing the moraine thereby delaying the stabilisation of the proximal moraine surface. The *Chionochloa* *flavescens* shrubland, apart from the tussock, is also dominated by: *Racomitrium lanuginosum, Luzula rufa, Viola filicaule, Aciphylla aurea, Anisotome haastii, Pimelea traversii, Gentiana corymbifera, Hebe subalpina, Coprosma rigida, C. rugosa, Ranunculus lyallii, Myrsine nummularia, Podocarpus nivalis* and *Cardamine debilis*. This species assemblage contrasts markedly with the *Dracophyllum longifolium*-dominated seral medium-height scrub on the lee side of the moraine. Additional species on the south facing slope include: *Hymenanthera alpina, Gaultheria crassa, Luzula rufa, Geum parviflorum, Plantago novae-zelandiae, Parahebe decora, Chionochloa flavescens, Aciphylla aurea, Gentiana corymbifera, Celmisia coriacea, Hebe subalpina, Coprosma rigida, C.rugosa, C. parviflora, Podocarpus nivalis, Myrsine nummularia, Phyllocladus alpinus, Pseudopanax colensoi, Cassinia vauvilliersii* and *Polystichum vestitum*. The vegetation on the distal slope is about 1.5-2.5, tall. The slope is strewn with large boulders which are partially concealed by the vegetation.

The 'Island' is the area immediately downvalley of the main terminal moraine. It is a flat, poorly drained area, and was burnt at some point prior to 1884 A.D. The changed nature of the vegetation is a result of both the burning and the poor drainage. Soils in this area are shallow and gleyed, resting directly on parent material. A number of small tarns characterise the terrain. A steep slope rim at the southern end of the 'Island' plateau separates the area from the low *Dracophyllum-Olearia* dominated flats. *Chionochloa flavescens* seral shrubland covers the general area of the 'Island'. The dominant species present are: *Olearia* spp., *Celmisia coriacea, Aciphylla aurea, Dracophyllum longifolium, D.kirkii, D. uniflorum, Racomitrium lanuginosum, Pimelea traversii, Hebe subalpina, Coprosma rigida* and *Gaultheria crassa*. Locally, around the tarns and hollows, *Celmisia petiolata* and *Ranunculus lyallii* are very common. The outer slope of the 'Island' is dominated by tall *Dracophyllum* scrub with a rich ground cover of *Blechnum* spp., *Lycopodium* spp., *Polystichum* sp., *Racomitrium lanuginosum, Celmisia* sp., *Parahebe decora,* and *Hypochoeris radicata*. This is in contrast to the open, tall *Dracophyllum-Olearia* scrub on the Hooker flats opposite the Stocking Stream. The scrub is unvarying with similar ground cover throughout. The most common taxa present include: *Coprosma rigida, Olearia nummularifolia, Racomitrium lanuginosum, Ranunculus lyallii, Hydrocotyle novae-zelandiae, Celmisia petiolata, C.walkeri, Blechnum fluviatile, Pygmea pulvinaris, Colobanthus buchananii* and *Anisotome haastii*. The 'Island' formed about 2540 years ago and the *Dracophyllum* flats formed c.3350-2540 years ago. Both surfaces appear to have been much modified by surface drainage patterns and more recently by grazing and fire.

C <u>Transect 3</u> An extensive deglaciated forefield in front of the Classen lake, which was exposed less than 60 years ago, is described by plots 1-17. The plots were randomly selected from the lake shore outwards. The surface is characterised by chaotic accumulations of dumped moraine only 1-2m in height above the surrounding floodplain. Lichens had begun to colonise the more stable surface boulders and the fine textured alluvium of the floodplain was colonised by small herbs. The area of the floodplain and the surrounding moraines is shown in Fig.7.2B. Recent moraine surfaces are relatively barren in contrast to the silty floodplain which is more readily inhabited by pioneering plants. The early colonising species included: *Blechnum penna-marina, Racomitrium lanuginosum, Epilobium* spp., *Gaultheria depressa, G.crassa, Parahebe lyallii, Luzula rufa, Viola cunninghamii, Cyathodes fraseri, Ranunculus cheesemanii* and *Raoulia* spp. . *Muehlenbeckia axillaris* and *Parahebe lyallii* were especially dominant on the flats adjacent to the plots sited on the moraines. The outer edge of the floodplain is probably as much as 100 years old, as shown by the increase in lichen size (see chapter 8).

A prominent terminal moraine, about 5m high, at the edge of the flood plain, is dated about 135 years old. The incompletely closed plant cover is described by quadrats 18-27. *Racomitrium lanuginosum* and *Blechnum penna-marina* replaced by *Gaultheria crassa, Coriaria angustissima, Muehlenbeckia axillaris* and *Lycopodium fastigiatum*. Several new species make their first appearance: *Wahlenbergia albomarginata, Acaena inermis, Dracophyllum kirkii, Olearia nummularifolia, Cassinia vauvilliersii, Hebe subalpina, Celmisia coriacea* and *Hieracium praealtum*. *Olearia ilicifolia*, one of the rarest plants in the Park, but which is very abundant further west across the Main Divide, was found growing by the lake shore on the southern side. Details of the vegetation sampling from these and other quadrats in the Classen Valley are presented in Appendix E6-9.

The vegetation on the 340 and 580 year old moraines was not examined. Both these moraines are not well formed at the terminus (Fif.7.1b) and are dated from sites further upvalley. The 840 year old moraine is described by quadrats 28-37. Two plant communities were distinguished; a closed plant cover and *Cassinia* shrubland. The former plant association comprises; *Olearia nummularifolia, Hymenanthera alpina, Celmisia coriacea, Rumex acetosella, Podocarpus nivalis, Aristotelia fruticosa* and *Dacrydium bidwillii*. Associated with these shrubs is a dense ground cover assemblage comprising; *Blechnum penna-marina, Gaultheria depressa, Viola cunninghamii, Cyathodes fraseri, Raoulia* spp.,*Epilobium* spp. and *Muehlenbeckia axillaris*. The *Cassinia* shrubland is dominated by;*Cassinia vauvilliersii, Aciphylla aurea, Poa* spp., *Dracophyllum longifolium* and *Hebe subalpina* with the addition of five new species at this stage in the sequence; *Gentiana corymbifera, Pimelea traversii, Celmisia gracilenta, Senecio cassinioides* and *Geranium microphyllum*.

The more recent Holocene glacier advances reached as far forward as the earlier advances such that the two sets of deposits, young and old, rest adjacent to each other, and in some places overlap. The *Gaultheria-Dracophyllum* scrub and the *Gaultheria crassa- Chionochloa* grassland contrast strongly with the earlier plant communities on the younger surfaces. Both plant associations are dominant on the 3300 year old moraines. Apart from the obvious plant species indicated by the group names, a number of other distinctive taxa are present. In the *Gaultheria-Dracophyllum* scrub also present are: *Cyathodes fraseri, Racomitrium lanuginosum, Muehlenbeckia axillaris, Aciphylla aurea, Celmisia coriacea, Hebe subalpina, Cassinia vauvilliersii* and *Coprosma ciliata*. Within the *Gaultheria crassa- Chionochloa* grassland the *Dracophyllum* species are of reduced importance and *Chionochloa pallens* and *C.flavescens* accompany an increase in *Gaultheria crassa*.

Quadrats 48-84 were all sampled on the 4200 year old moraine on both sides of the Classen River. A number of distinctly individual plant communities were detected and the quadrats are grouped as follows; Quadrats 48-54 *Dracophyllum* scrub, Quadrats 55-63 *Dracophyllum-longifolium* scrub, Quadrats 64-84 *Cassinia-Senecio* tall scrub.

The *Dracophyllum* scrub is dominated by; *Dracophyllum longifolium, D.uniflorum, D.kirkii, Cassinia vauvilliersii, Coprosma ciliata, C.parviflora, Aristotelia fruticosa, Hebe treadwellii, H.subalpina, Podocarpus nivalis* and *Senecio scorzoneroides*. This is distinguished from the *Dracophyllum longifolium* scrub in which *Hypochoeris radicata, Dracophyllum kirkii, Brachycome sinclairii, Celmisia walkeri, Craspedia* sp. large and *Cyathodes fraseri* assume greater importance. *Dracophyllum uniflorum, Gaultheria crassa, Aristotelia fruticosa, Coprosma parviflora, Podocarpus nivalis* and *Senecio scorzoneroides* are all absent. Within the third plant group *Senecio cassinioides* and *Cassinia vauvilliersii* are dominant. A complex and varied ground cover includes shrubs: *Pimelea traversii, Cyathodes fraseri, Coprosma ciliata, C.pumila, Dracophyllum longifolium, Olearia nummularifolia, Podocarpus nivalis, Hebe treadwellii, Hymenanthera alpina* , herbs: *Aciphylla aurea, Celmisia coriacea, C.lyallii, Anisotome aromatica, Ranunculus lyallii, R.cheesemanii, Geranium microphyllum, Viola cunninghamii* and ferns: *Hypolepsis millefolium, Blechnum penna-marina*. In all three plant communities the scrub is tall, over 2m in places, and dense. Both the 3350 and 4200 year old surfaces have gley-podsolised high country yellow-brown earths with a deep Loess A horizon. It was suggested in Chapter 6 (cf.6.5, p.100) that these soils are not monogenetic. The non-uniform development may have influenced the vegetation pattern.

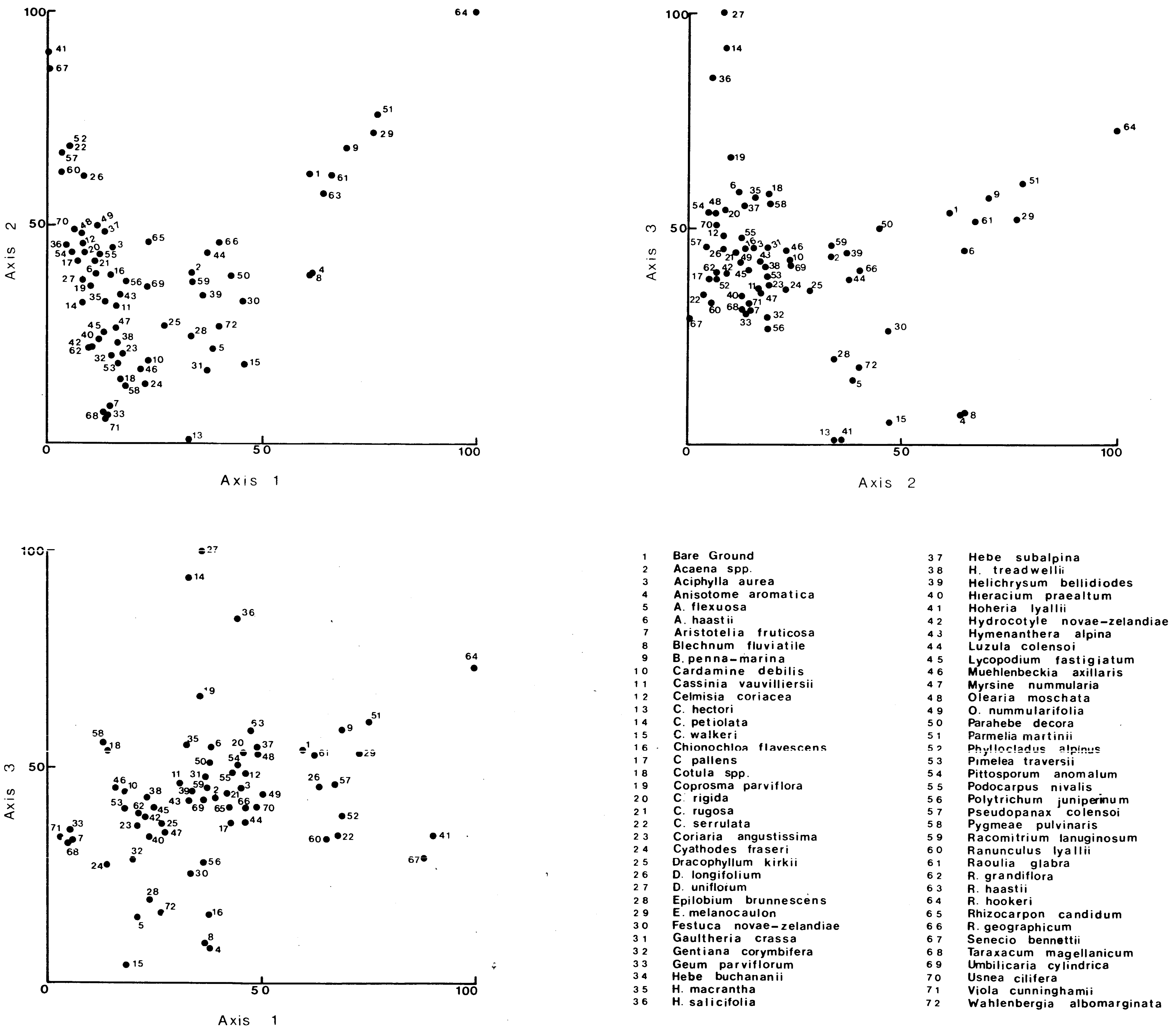
7.5.2 Ordination

The results of both the field measurements and the ordination are summarised in Table 7.1 . Ordinations resulting from the Reciprocal Averaging method, as outlined by Hill (1973) were found to be more suitable for describing the vegetation and habitat variation than Principal Components Analysis.

The results of the species and quadrat ordination for Transects 1 and 3 are presented in Figs.7.3, 7.4, 7.5 and 7.6. The plant development within Transect 2 had been too greatly disturbed to be meaningfully interpreted by these means.

The vegetation and quadrats are arranged along three axes and a comparison of the first two axes shows the optimum sorting of the data. The 'arch effect' discussed in section 7.4,(p.108-9) manifests itself in an inverted form. Both species and quadrats are arranged along this 'V' shaped horseshoe effect which is possibly a response to one main gradient (Dr N.Mitchell, Auckland University, pers. comm. 1981). This principal gradient is interpreted as being related to the ages of the moraine surfaces, and therefore to 'time'.

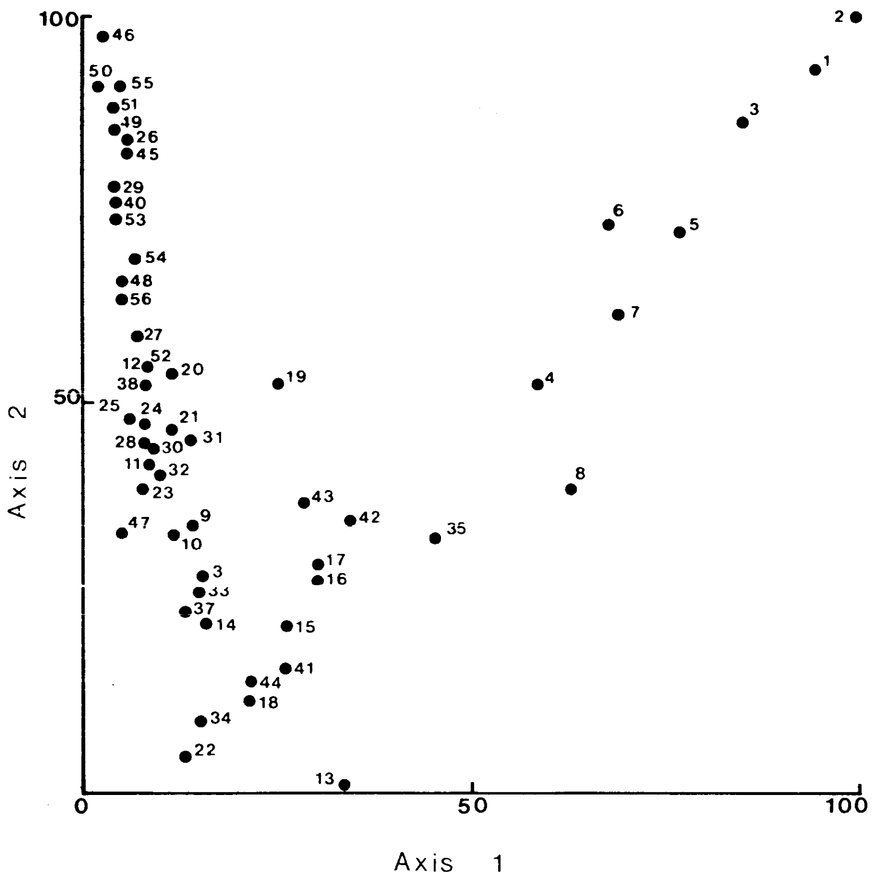
Communities that are particularly well described by the ordination include the *Hoheria* scrub, subalpine medium-height scrub, *Celmisia walkeri* scrub, mid-seral community and bare ground in Transect 1, new moraine and shrubland on Transect 2 and new moraine, *Cassinia-Poa* shrubland, *Gaultheria- Dracophyllum* scrub, *Cassinia-Senecio* tall scrub and *Dracophyllum* scrub along Transect 3.

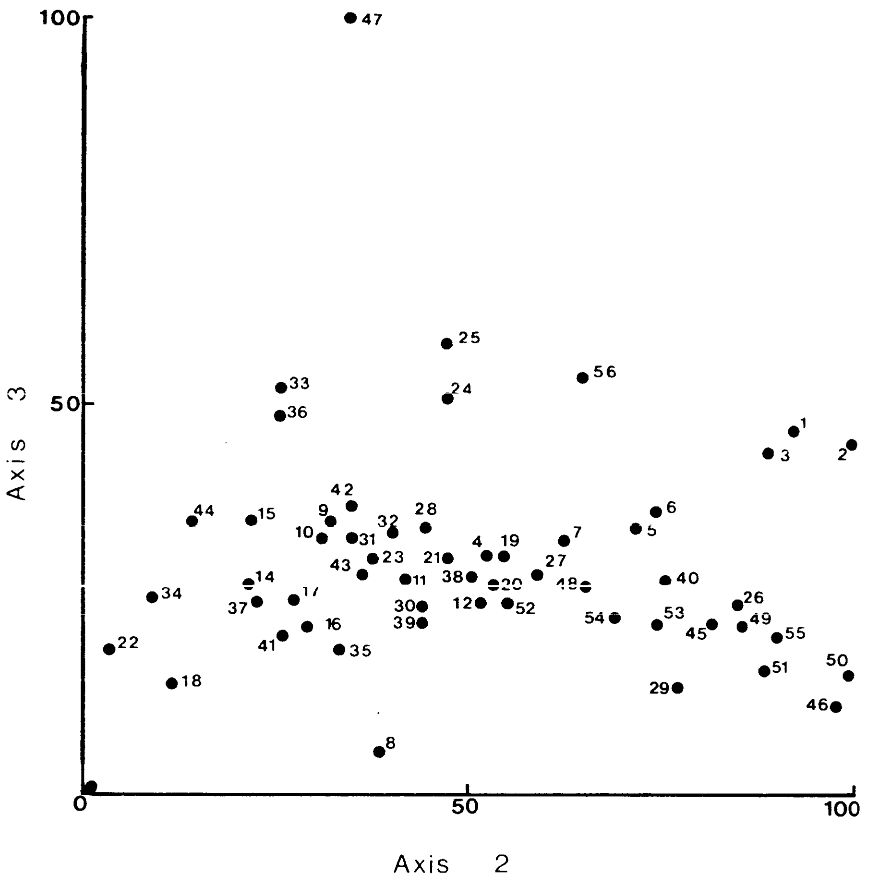


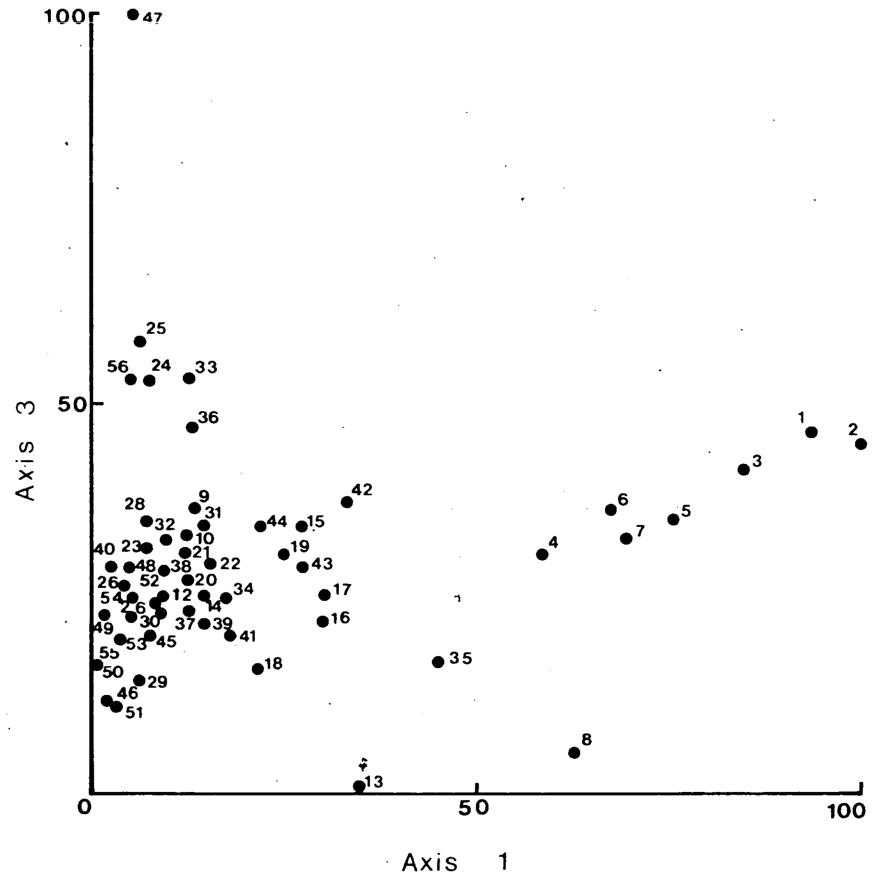
1	Bare Ground	37	Hebe subalpina
2	Acaena spp.	38	H. treadwellii
3	Aciphylla aurea	39	Helichrysum bellidiodes
4	Anisotome aromatica	40	Hieracium praealtum
5	A. flexuosa	41	Hoheria lyallii
6	A. haastii	42	Hydrocotyle novae-zelandiae
7	Aristotelia fruticosa	43	Hymenanthera alpina
8	Blechnum fluviatile	44	Luzula colensoi
9	B. penna-marina	45	Lycopodium fastigiatum
10	Cardamine debilis	46	Muehlenbeckia axillaris
11	Cassinia vauvilliersii	47	Myrsine nummularia
12	Celmisia coriacea	48	Olearia moschata
13	C. hectori	49	O. nummularifolia
14	C. petiolata	50	Parahebe decora
15	C. walkeri	51	Parmelia martinii
16	Chionochloa flavescens	52	Phyllocladus alpinus
17	C pallens	53	Pimelea traversii
18	Cotula spp.	54	Pittosporum anomalum
19	Coprosma parviflora	55	Podocarpus nivalis
20	C. rigida	56	Polytrichum juniperinum
21	C. rugosa	57	Pseudopanax colensoi
22	C. serrulata	58	Pygmeae pulvinaris
23	Coriaria angustissima	59	Racomitrium lanuginosum
24	Cyathodes fraseri	60	Ranunculus lyallii
25	Dracophyllum kirkii	61	Raoulia glabra
26	D. longifolium	62	R. grandiflora
27	D. uniflorum	63	R. haastii
28	Epilobium brunnescens	64	R. hookeri
29	E. melanocaulon	65	Rhizocarpon candidum
30	Festuca novae-zelandiae	66	R. geographicum
31	Gaultheria crassa	67	Senecio bennettii
32	Gentiana corymbifera	68	Taraxacum magellanicum
33	Geum parviflorum	69	Umbilicaria cylindrica
34	Hebe buchananii	70	Usnea cilifera
35	H. macrantha	71	Viola cunninghamii
36	H. salicifolia	72	Wahlenbergia albomarginata

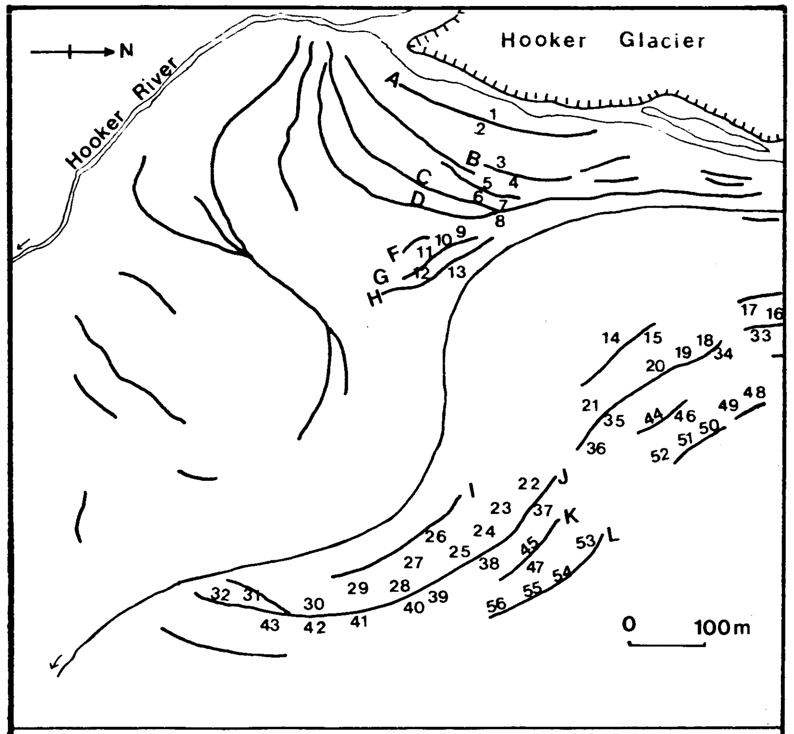
ORDINATION OF SPECIES

Figure 7.3 Ordination of species,Transect 1.





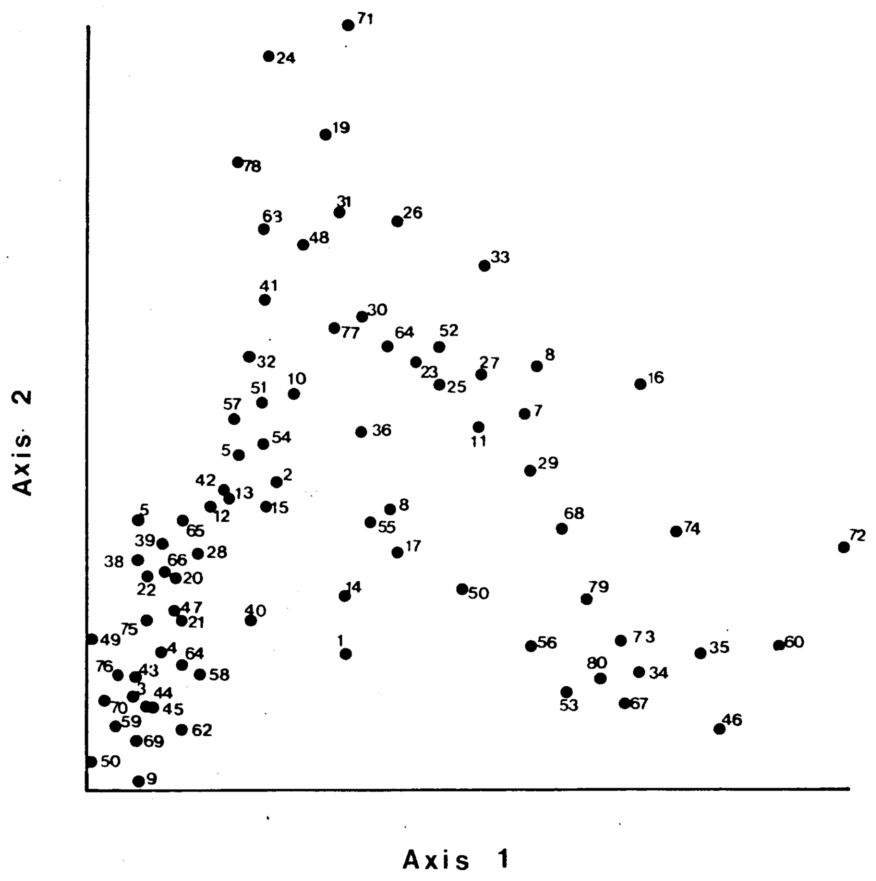


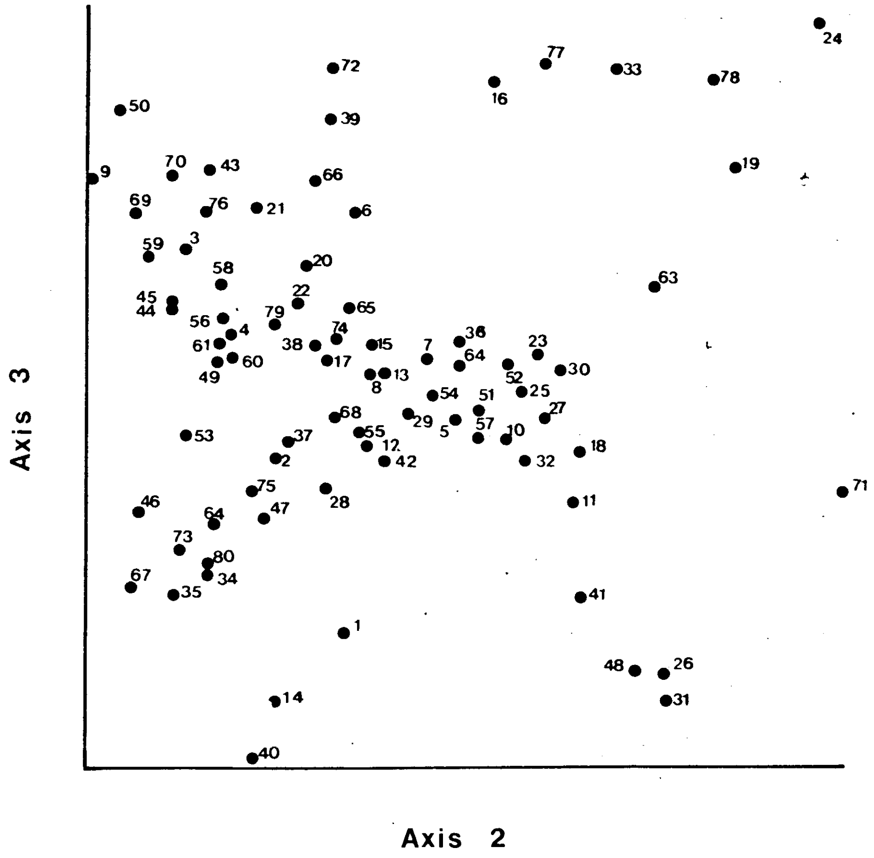


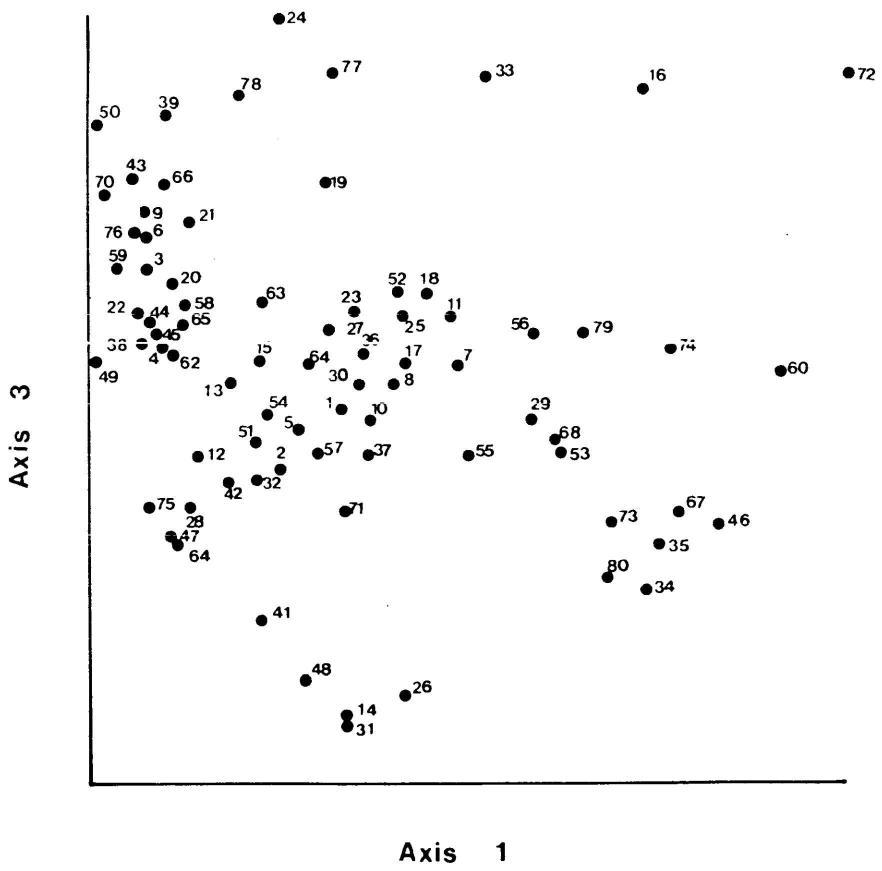
Location of Sampling Sites on East Hooker Moraines

ORDINATION OF SITES

Figure 7.4 Ordination of sites,Transect 1



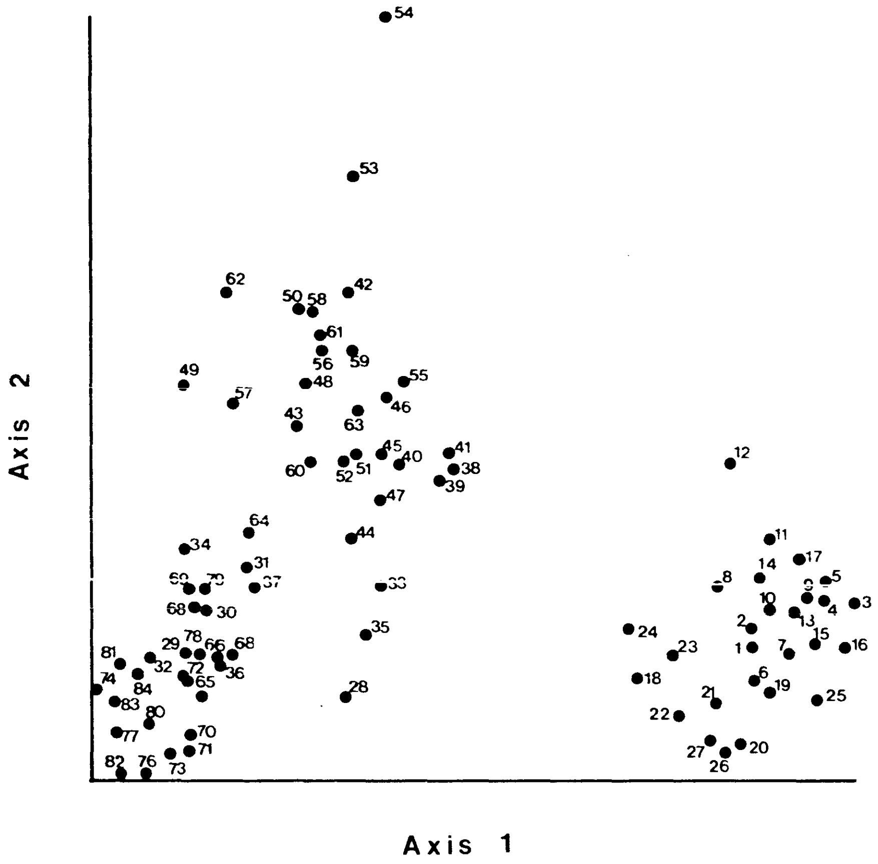


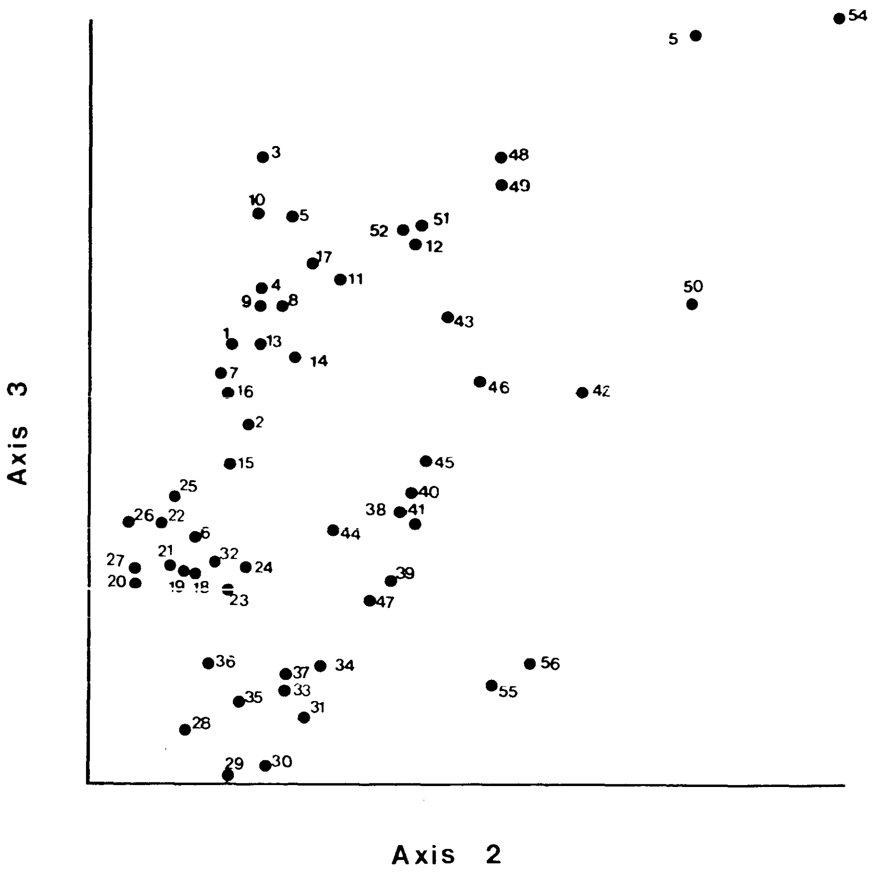


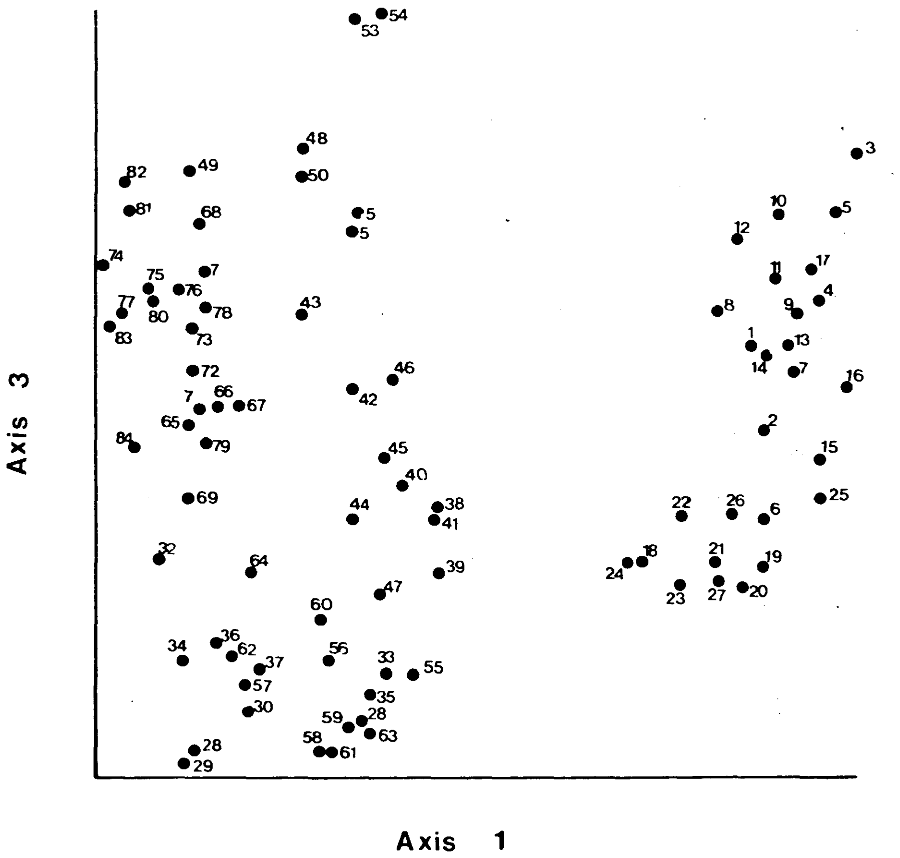
1	Acaena inermis
2	Aciphylla aurea
3	A. scott-thompsonii
4	Anisotome aromatica
5	Aporostylis bifolia
6	Aristotelia fruticosa
7	Asplenum flaccidum
8	Blechnum penna-marina
9	Brachycome sinclairii
10	Carex spp.
11	Carmichaelia grandiflora
12	Cassinia vauvilliersii
13	Celmisia coriacea
14	C. gracilenta
15	C. lyallii
16	C. petiolata
17	C. walkeri
18	Chionochloa flavescens
19	C. pallens
20	Coprosma ciliata
21	C. parviflora
22	C. pumila
23	C. rigida
24	C. serrulata
25	Coriaria angustissima
26	Craspedia sp. lge.
27	Crepis axillaris
28	Cyathodes colensoi
29	C. fraseri
30	Dacridium bidwillii
31	Dracophyllum kirkii
32	D. longifolium
33	D. uniflorum
34	Epilobium spp.
35	Forstera sedifolia
36	Gaultheria crassa
37	G. depressa
38	Gentiana corymbifera
39	Geranium microphyllum
40	G. sessiliflorum
41	Hebe ciliolata
42	H. subalpina
43	H. treadwellii
44	Helichrysum bellidiodes
45	H. filicaule
46	Hieracium praealtum
47	Hymenanthera alpina
48	Hypochoeris radicata
49	Hypolepsis millefolium
50	Lachnagrostis richardii
51	Leptopteris fragilis
52	Leucogenes grandiceps
53	Luzula rufa
54	Lycopodium fastigiatum
55	Muehlenbeckia axillaris
56	Myosotis macrantha
57	Olearia ilicifolia
58	O. nummularifolia
59	Ourisia caespitosa
60	Parahebe lyallii
61	Phormium cookianum
62	Phyllocladus alpinus
63	Pimelea traversii
64	Poa sp.
65	Podocarpus nivalis
66	Polystichum vestitum
67	Prasophyllum colensoi
68	Racomitrium lanuginosum
69	Ranunculus cheesemanii
70	R. lyallii
71	Raoulia glabra
72	R. haastii
73	Rhizocarpon geographicum
74	Rock
75	Rumex acetosella
76	Senecio cassiniodes
77	S. schorzonoroides
78	Usnea cilifera
79	Viola cunninghamii
80	Wahlenbergia albomarginata

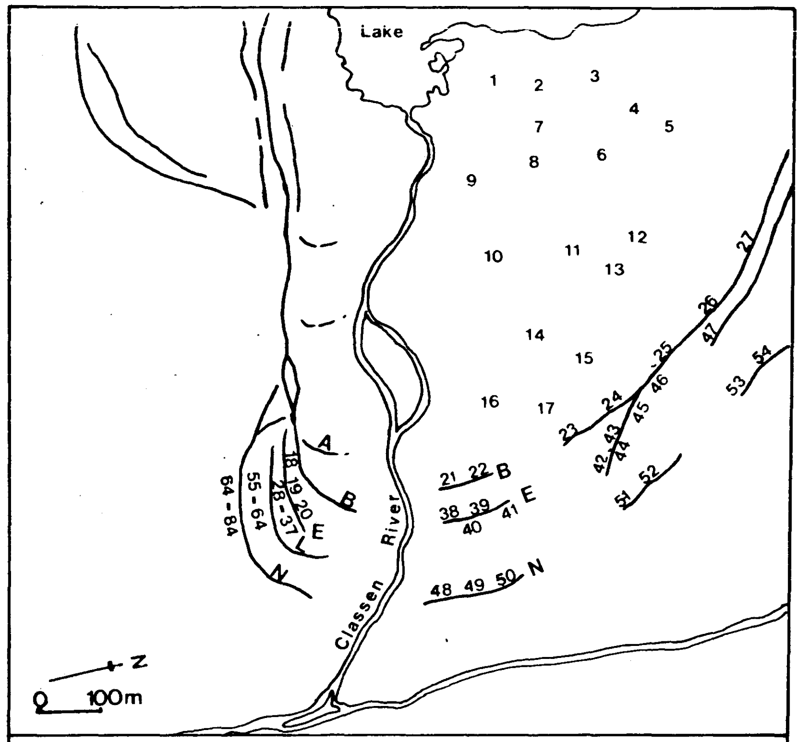
ORDINATION OF SPECIES

Figure 7.5 Ordination of species, Transect 3









Location of Sampling Sites on Classen Gl. Moraines

ORDINATION OF SITES

Figure 7.6 Ordination of sites,Transect 3

7.6 DISCUSSION

With the exception of the vegetation of small tarns, avalanche chutes, ephemeral drainage channels and ice spillways, which occupy restricted areas of the Hooker and Classen Valley moraines, the vegetation growing on the moraines can be grouped on floristic criteria alone into 21 plant communities. Individual surfaces may support several separate plant communities. The general successional pattern on the Holocene glacial surfaces exposed during the last 4200 years is summarised in Table 7.1 and in Appendix E[10]

Plant species colonising the youngest surfaces were similar throughout the study area. Chance factors are important in the dispersal of the propagules and their subsequent establishment. The importance of chance was noted earlier by Stork (1963), Crocker & Major (1955), Given & Soper (1975) and Birks (1980). In addition the variation in terrain will influence the success of the seedling in its establishment and eventual growth. As Tisdale & Fosberg noted:

> "Differences in topography and aspect and in the texture of soil parent material all exert an influence which is striking on the younger moraine and still detectable on the oldest" (Tisdale & Fosberg 1966, p.522).

Crocker & Major noted the importance of site variability on patterns of plant colonisation:

> "There is an areal pattern of soil profile formation which partially reflects the areal pattern of pioneer plant establishment. This is at first largely related to factors outside our system depending upon such things as the location and state of the neighbouring ecosystems, the pre-adaption of the disseminules, and the accidents of dispersal" (Crocker & Major 1955, p.446).

The variation in vegetation on the surfaces examined in the Hooker Valley was noted by Rowley (1966). She suggested that these local changes in plant community structure might be due to the size texture of the mineral soil and also the climatic variation within the Hooker Valley. The effect of surface soil cover and the texture of the parent material is strongly marked. On surfaces with stony parent material the initial herbfield community shows a tendency to develop into shrubland, whilst less bouldery surfaces support *Festuca* short tussock. Particularly bouldery moraine in the Classen Valley has remained sparsely colonised after a period of over 500 years since deposition.

A number of studies have related the changes in plant cover to soil development on moraines(Crocker & Dickson 1957, Olson 1958, Stevens 1968, Tisdale, Fosberg & Poulton 1966 and Jacobsen & Birks 1980). The soil develops rapidly in the initial period of colonisation with a marked build up of organic matter and organic bound phosphorus, accompanied by a drop in pH. Values for soil development change on two recent moraines in the Mueller Valley were presented by Birkeland (1982). If the values for the moraine age are corrected with data from the present study, it can be shown that the surface soil pH drops from 5.4 to 4.8 on surfaces aged 340 and 580 years respectively. Percentage organic matter and organic bound phosphorus increase from 3.4-11.4 and 17-64 over a similar time period. Measurements of these soil variables on older surfaces show very little change from the amounts recorded on the 580 year old moraine which indicates relative stabilisation of the pH and organic content after about 600 years.With the exception of the extremely bouldery surfaces, all the moraines support a closed plant cover with either shrubland or grassland after 1000 years of stabilisation.

The general pattern of succession in the moraine sequence is the progression from bare ground ⟶ herbfield ⟶ grassland or shrubland ⟶ seral grassland or shrubland ⟶ low scrub ⟶ tall scrub. Where shrubland reverts to grassland, or short tussock ⟶ tall tussock, the succession pattern has experienced some form of disturbance, Appendix E.[10] Fire induced *Dracophyllum* scrub has developed from seral medium height scrub in the Hooker Valley, but in the Classen Valley *Dracophyllum* scrub has developed without the occurrence of widespread burning. In Westland, Wardle (1980) describes *Dracophyllum longifolium* scrub dominating surfaces formed during the seventeenth and eighteenth centuries. The time period required to reach a particular stage in the plant succession on the West Coast is, however, greatly reduced. Burning and repeated disturbance due to glacier fluctuations may account for the slow rate of vegetation change in the Mt Cook region. Burning affects all areas directly or indirectly because ultimately it interrupts the availability of seedlings and the input of new species to the region from elsewhere.

The diversity of plant cover on all surfaces restricts the general usage of 'indicator' species for separate aged moraines or habitats. A few exceptions can be made, for example; damp or poorly drained sites are dominated by *Celmisia petiolata, Gunnera dentata, Ranunculus lyallii* and *Senecio bennettii*. *Ranunculus lyallii,* a palatable plant, is also suggestive of an area with reduced ungulate grazing. *Celmisia walkeri, C.hectori, C.haastii, Ranunculus sericophyllus* and *Pernettya alpina* are associated with areas of late lying snow. Two species are common in avalanche paths; *Poa cockayniana* and *Hypolepis millefolium*. *Anisotome flexuosa* is found in areas with thin, poorly drained soil. Several species are abundant on recently burnt surfaces. These include; *Phormium cookianum, Aciphylla aurea, Celmisia coriacea, C.lyallii, C.petiolata* and *Gaultheria crassa*.

No individual species were found to be age-specific. Burrows(1973a) noted the presence of *Dacrydium bidwillii* on older moraines in the Mueller Valley (Foliage Hill, car park moraine and Sebastopol moraine) and suggested that the species was restricted to surfaces of a similar age. The distribution of *D.bidwillii* is more general than he suggested and plants were observed on the 3300 year old moraine in the Classen Valley. The use of lichen growth as a biological relative-age indicator is discussed in the following chapter.

The general pattern of vegetation development is similar in all areas examined (Table 7.1) Species diversity is greatest in the early maturing sites, namely the shrubland and grassland communities. The most advanced plant development examined was on surfaces about 4000 years old. What further development takes place on these deposits will depend on the stability of the environment. The formation of new surfaces as the glaciers retreat indicates the continuing change at the present day to the environment which will have repurcussions throughout all of the habitats described above.

CHAPTER 8

LICHENOMETRIC DATING

8.1 INTRODUCTION

The technique of lichen dating was pioneered by Beschel who referred to its potential in dating rock surfaces (Beschel 1961) and who later described its application to measuring the age of recent moraines (Beschel 1973). The basic premise of lichenometry is that the diameter of the largest lichen thallus growing on a moraine or other surface is proportional to the length of time that the surface has been exposed to colonisation and growth. Data on lichen growth rates can enable estimates to be made of both the age of a thallus and the period of exposure of a substrate.

Use of lichenometry for establishing moraine chronologies has had some success (Benedict 1967, Anderson & Sollid 1971, Denton & Karlèn 1973a) but has met with considerable criticism (Jochimsen 1973, Carroll 1974). It has been described as a useful reconnaissance tool by Denton & Karlèn (1973a) who also found that where an accurate time sequence was known, lichen measurements proved to be both sensitive and consistent. As a field technique it has the advantage that measurements are relatively simple and easy to obtain. Several factors do, however, limit the applicability of the technique. The need for local calibration is paramount. Benedict (1967) in defence of lichenometry, noted that objections to lichen-dating have frequently arisen from studies in which the method has been badly abused.

Lichens provide a measure, albeit a minimum value, of how long the substrate has remained immobile and undisturbed. Lichen growth may be interrupted or terminated by sudden slope movements, the encroachment of a thick vegetation cover or the redistribution of loess which alternatively covers or exposes the rock surface.

By careful sampling and the selection of suitable lichens, independent studies have shown that there is a case for accepting lichen dating as a valid technique. Beschel

(1973) described how it is invaluable for dating closely spaced, recent events for which other techniques may, for various reasons, not be appropriate.

8.2 SELECTION OF LICHEN SPECIES

Lichen species are selected on a number of criteria. Firstly they should be easily identifiable. Secondly, their habit needs to be morphologically suitable for radial growth measurements. Thirdly, they should be early colonisers of fresh rock surfaces. When a number of closely spaced young surfaces are to be dated, fast growing lichen species are selected. Conversely, on older surfaces, slower growing species are used. Fourthly, lichens with a preference for specific substrates or environmental conditions which would restrict their distribution are disregarded.

Species of the *Rhizocarpon* genus have frequently been chosen for lichenometric dating. The most commonly reported of these yellow-green crustose lichens is *R.geographicum* L (DC). The taxonomy of the *Rhizocarpon* group is extremely complex (Runemark 1956). The problematic existence of several morphologically very closely related species has led to this lichen often being reported as *R.geographicum* agg. (Matthews 1974) or as *R.geographicum sensu lato* (Andrews & Webber 1964). Dr D.Galloway (pers.comm.1982) recognises three yellow-green species in New Zealand: *R.geographicum, R.superficiale* and *R.viridiatrum.*

The likelihood of being able to distinguish between the different taxa within the yellow-green *Rhizocarpon* group in the field is extremely low. The present study refers to those lichens sampled as *Rhizocarpon* spp. . Although the earlier studies in the Mt Cook region specifically referred to *R.tinei* (Tornab) Run. (Burrows & Lucas 1967) and *R.geographicum* (Burrows & Orwin 1971) when dealing with the yellow-green variety, it is almost certain that they were sampling *R.geographicum* agg. . The genus *Rhizocarpon* also includes both black and white species. Burrows & Lucas (1967) measured *R.candidum* and this was the most useful lichen on the older surfaces.

8.3 MEASUREMENT OF THE LICHEN THALLUS

No one aspect of lichenometry has received as much attention as the question regarding sampling. A review by Lock,Andrews & Webber (1979) attempted to resolve the situation and they proposed a method which would standardise the procedure. They noted that Beschel's failure to define adequately his sampling techniques forced many workers to invent their own, and most did, (Lock *et al., loc.cit.*).

The most commonly used sampling parameter for lichenometry is the diameter of the nearly circular thallus. A number of studies describe the use of the long or short axes of oval thalli when no circular thalli were to be found. According to Lock *et al.* (*op.cit.*) the optimum measurement is the diameter of the largest circle (hereafter referred to as DLC) that can be inscribed in a lichen shape. The DLC is measured using vernier calipers.

In spite of the large number of studies using lichen dating very few studies exist concerning the nature of lichen growth, in particular the deviation from a perfect circular shape to give an oval thallus. This has not deterred workers from measuring the long or short axes of oval thalli and, in so doing, possibly overestimating or underestimating the rate of lichen growth and thereby incorrectly estimating the ages of the surfaces from a calibration curve drawn up from circular thalli.

In the present study the 'Indirect' method (Lock *et al. op.cit.*) of growth curve determination was used. This simply refers to the use of measurements of the diameter of the largest lichen growing on a surface of known age. In contrast to 'Direct' measurements eg. photogrammetric determinations, the Indirect values are more practicable as they minimise the effect of short term fluctuations and they are completed in one field season.

Determinations of the radial growth rate (cm/yr) are described. The DLC was recorded for the largest lichen on the first 400 greywacke boulders. All the boulders used exceeded 0.5m^3 in size. The sample size was designed to include a size-frequency analysis of the DLC lichen population. Proximal and distal slopes were examined separately.

8.4 SIZE FREQUENCY HISTOGRAMS

Farrar (1974) described size-frequency histograms to investigate lichen growth rates and succession on dated surfaces. Two earlier studies on glacial moraines had already developed the idea of size-frequency plots of lichen populations (Benedict 1967, Anderson & Sollid 1971). Their explanation of the population data was restricted to interpretations of the homogeneity or otherwise of the populations.

Farrar (*op.cit.*) proposed that at least 100 thalli per species at any one site should be sampled and that the area examined be as uniform as possible. She presented a number of hypothetical histograms. In any population the frequency of thalli in a particular size class is proportional to the rate of colonisation when that size class was established and inversely proportional to the growth rate in that class. Because measurements in the present study were of the DLC, the interpretation of the size-frequency histograms requires careful attention.

8.5 SITE SELECTION

Lichen growth rates are closely related to environmental and climatic conditions both at the time of colonisation and during the subsequent lifespan. An appreciation of those factors limiting the growth of the thallus is important to field studies.

Benedict (1967) noted seven factors: rock type, exposure to abrasion, shading, temperature, moisture, stability of the substrate and length of the growing season. Jochimsen (1973) described a similar set of environmental factors and concluded that, overall, environmental factors influence the life of lichens and precipitation is not solely responsible for their growth. Orwin (1972) studied the effect of environment on assemblages of lichens growing on rock surfaces in New Zealand. She found that the main cause of variation was the response of the lichen to the rock aspect providing the most favourable moisture conditions. Orwin noted, however that the dominant *Rhizocarpon* species, (*R.geographicum s.l.*) revealed no specific preference for any one aspect. She suggested that this species had a high degree of tolerance for harsh conditions.

Despite Orwin's assurances I chose to restrict sampling of the moraines in the Mt Cook region to distal and proximal slopes except at the Mueller Glacier terminus where no distinction was made. This was in contrast to earlier work by Burrows & Orwin (1971) who did not distinguish between the two slopes. I later rejected measurements from the proximal slopes as they were unreliable. Proximal slopes in the area sampled tended to face north and were predominantly less stable.

In their review of lichenometry Lock *et al.*(1979) discussed the numerous approaches to sampling. They described suitable sampling and recording procedures and it is worthwhile to list the most critical items as emphasized by these authors themselves:

a - The diameter measured should be that of the largest inscribed circle (DLC).

b - Fixed area searches are preferred to fixed time or exhaustive ones.

c - The mean of the five largest thalli should be more representative of the relative surface age than the single maximum.

d - The application of multi-parameter methods, where time permits is to be preferred to the use of lichenometry alone.

8.6 ESTABLISHING LICHEN CONTROL POINTS

The location of the lichen control points for each glacier (measurements were obtained from the Classen, Mueller and Tasman Glacier termini) are indicated in Figs.8.1, 8.2 & 8.3 . The moraines at all three glacier termini have been tentatively dated using rock weathering rind thickness and historical records (this study). Locally the vegetation and soil development have been examined for supplementary evidence of differences in surface age. Detailed descriptions of the sites are given in Gellatly (1982). The moraines examined at the Classen Glacier terminus lie south of the Classen River adjacent to the Eade Memorial Hut and on the basis of rock

Figure 8.1 Location of lichen control points at the Classen Glacier terminus.

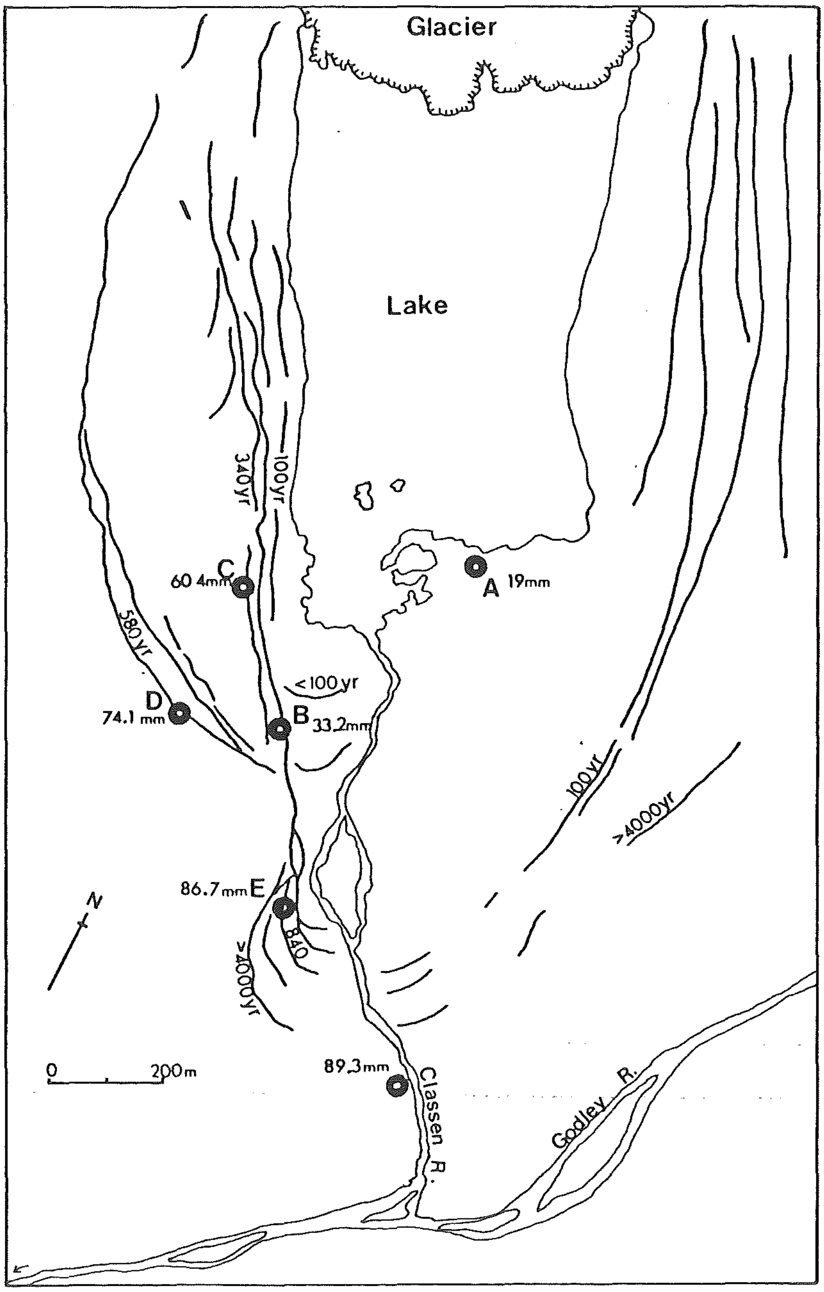


Figure 8.2 Location of lichen control points at the Mueller Glacier terminus.

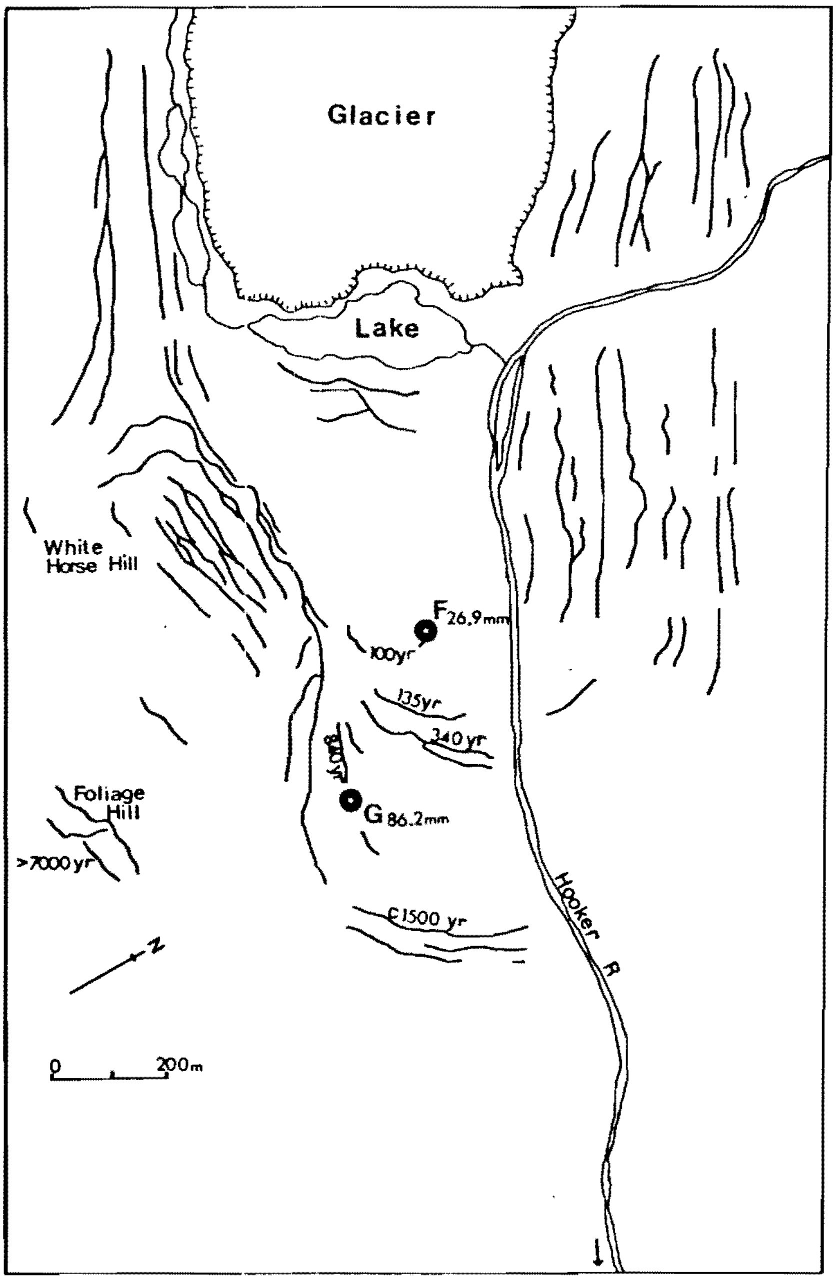
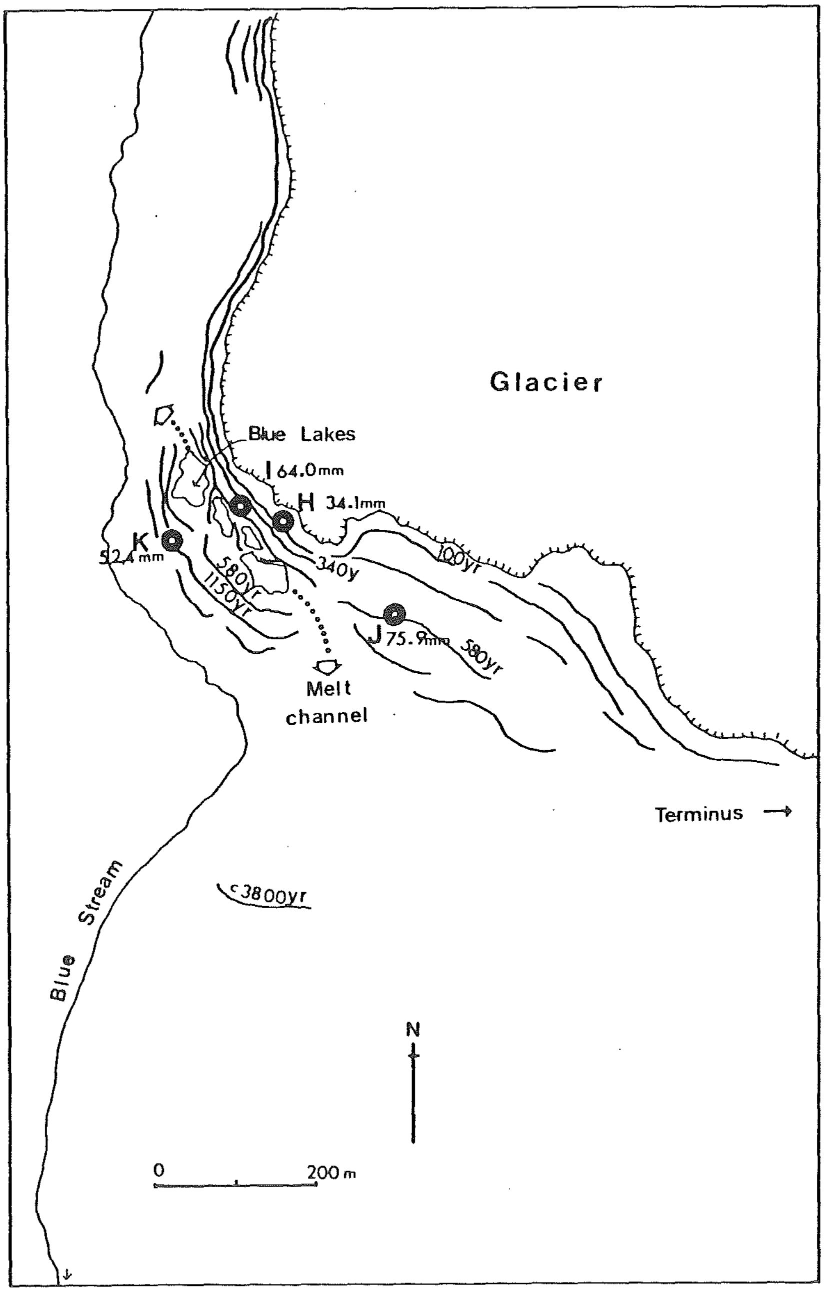


Figure 8.3 Location of lichen control points at the Tasman Glacier terminus.



weathering rind dates and historical dating lie in the range from c.4000-0 years. The moraines near the Blue Lakes were examined from the Tasman terminus and these varied in age from c.3300-0 years. Lichens were measured on the 840 and <100 year old moraines at the Mueller Glacier terminus.

8.7 RESULTS

8.7.1 The lichen growth curve

A lichen growth curve is constructed using the maximum DLC measurement of the largest *Rhizocarpon* thallus on each dated surface. Two curves are presented, one from the Classen Valley and the other from the Tasman Valley. As only two points were measured at the Mueller Glacier terminus no attempt was made to construct a growth curve for the Mueller Valley. The two curves are shown in Fig.8.4 . Also shown is the corresponding growth curve described by Burrows & Orwin (1971).

The largest lichen thallus measurement and the modal size-frequency class are indicated in Table 8.1 . Table 8.2 presents the recalibrated values from the work by Burrows (1973a). The lichen measurements have been recalibrated using the corrected surface age (that is,the surface age assessed through the use of weathering rind thickness). In this way it is possible to compare further the present study with earlier work (Burrows *op.cit.*) and evaluate the use of DLC, (see section 8.8).

The lichen growth curves for the Tasman and Classen Glacier moraines shown in Fig.8.4 are non-linear. The "lichen factor", ie. the diameter of 100 year old lichens, (Beschel 1956) is 33-34mm and was consistently recorded at the Classen, Mueller and Tasman termini.

Measurements from the proximal slopes in the Tasman and Classen Valleys were smaller and less consistent than those from the distal slope sites, Table 8.3 . Many of the lichens growing on the older surfaces were damaged and some were clearly senescent, a feature noted by Burrows & Orwin (1971) and Burrows (1973a). Lichen thalli on the oldest surfaces at the Tasman and Classen termini were smaller than thalli on the younger moraines and so the lichen growth curves were not extended beyond a thousand years.

Figure 8.4 The lichen growth curve for *Rhizocarpon* spp. on glacial moraines in Mt Cook National Park.

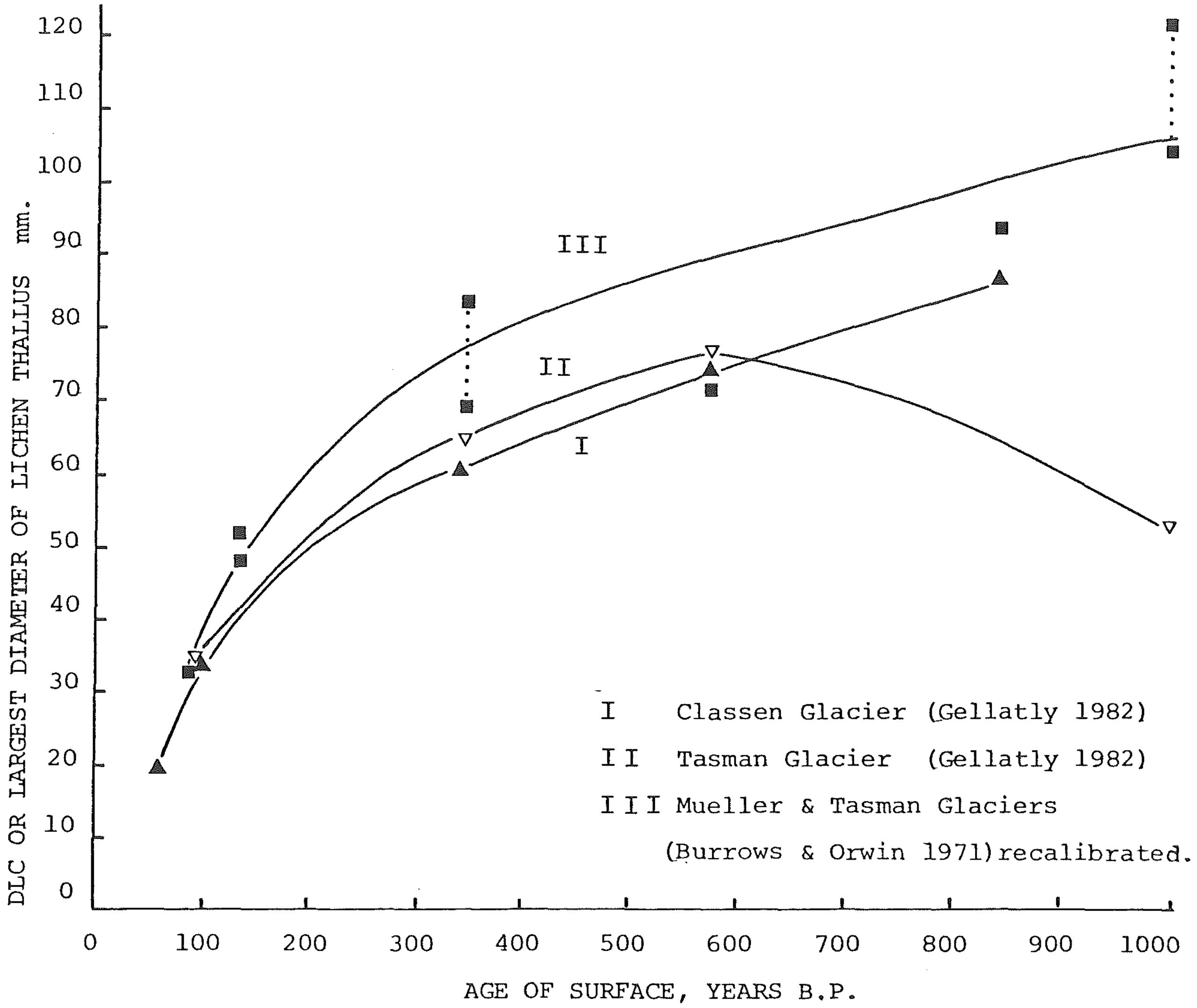


Table 8.1

Measurements of the maximum DLC for lichen thalli at the Classen, Tasman and Mueller Glacier termini and modal-size frequency class values for the Classen and Tasman Glacier termini.

	CLASSEN		TASMAN		MUELLER
Surface age yr.	Lichens mm.	Modal size frequency	Lichens mm.	Modal size frequency	Lichens mm.
<60	19.0	0-5	-*	-	-
90	-	-	-	-	26.9
100	33.2	15-20	34.1	15-20	-
340	60.4	10-20	64.0	25-30	-
580	74.1	35-40	75.9	20-25	-
840	86.7	25-30	-	-	86.2
>1000	-	-	52.4	30-35	-

* A dash (-) means that no data were collected.

Table 8.2

Measurements of the largest diameter of *Rhizocarpon geographicum* thalli at the Tasman and Mueller Glacier termini recorded by Burrows (1973a). Values are recalibrated with corrected surface age estimates.

	TASMAN	MUELLER
Surface age yr.	Lichens mm	Lichens mm.
<100	-*	23.0
100	-	33.0
135	48.0	48.0,51.0
340	-	68.0, 84.0
580	71.0	-
840	94.0	-
>1000	-	104.0, 122.0

* A dash (-) means that no data were collected.

Table 8.3

A comparison between maximum thalli size on the proximal and distal slopes of moraines at the Classen and Tasman Glacier termini.

	CLASSEN		TASMAN	
Surface age yr.	Proximal slope mm.	Distal slope mm.	Proximal slope mm.	Distal slope mm.
<60	19.0	19.0	-*	-
100	36.6	33.2	26.3	34.1
340	29.2	60.4	38.4	64.0
580	54.7	74.1	43.5	75.9
840	65.6	86.7	-	-
>1000	-	-	40.4	52.4

* A dash (-) means that no data were collected.

8.7.2 Size-frequency analysis

From the 400 measurements of DLC recorded at each site a size-frequency analysis is presented, Fig.8.5 . The shape of the size-frequency histograms are interpreted using theoretical models developed for sampling of the whole lichen colony (Farrar 1974). The distributions are all unimodal. The modal size class increases with distance from the glacier and with age of the moraine surface, Table 8.1 . The absence of measurements of lichen thalli in the smaller size classes must not be interpreted as meaning that no new lichens are colonising those surfaces since the sampling was restricted to measurements of the largest lichen per boulder.

Of particular note is the relation of the largest lichen (DLC) recorded on each surface to the remainder of the histogram. The maximum DLC have a very low occurrence and are frequently considerably larger than the other lichens. The individual histograms are described separately;

Classen Glacier

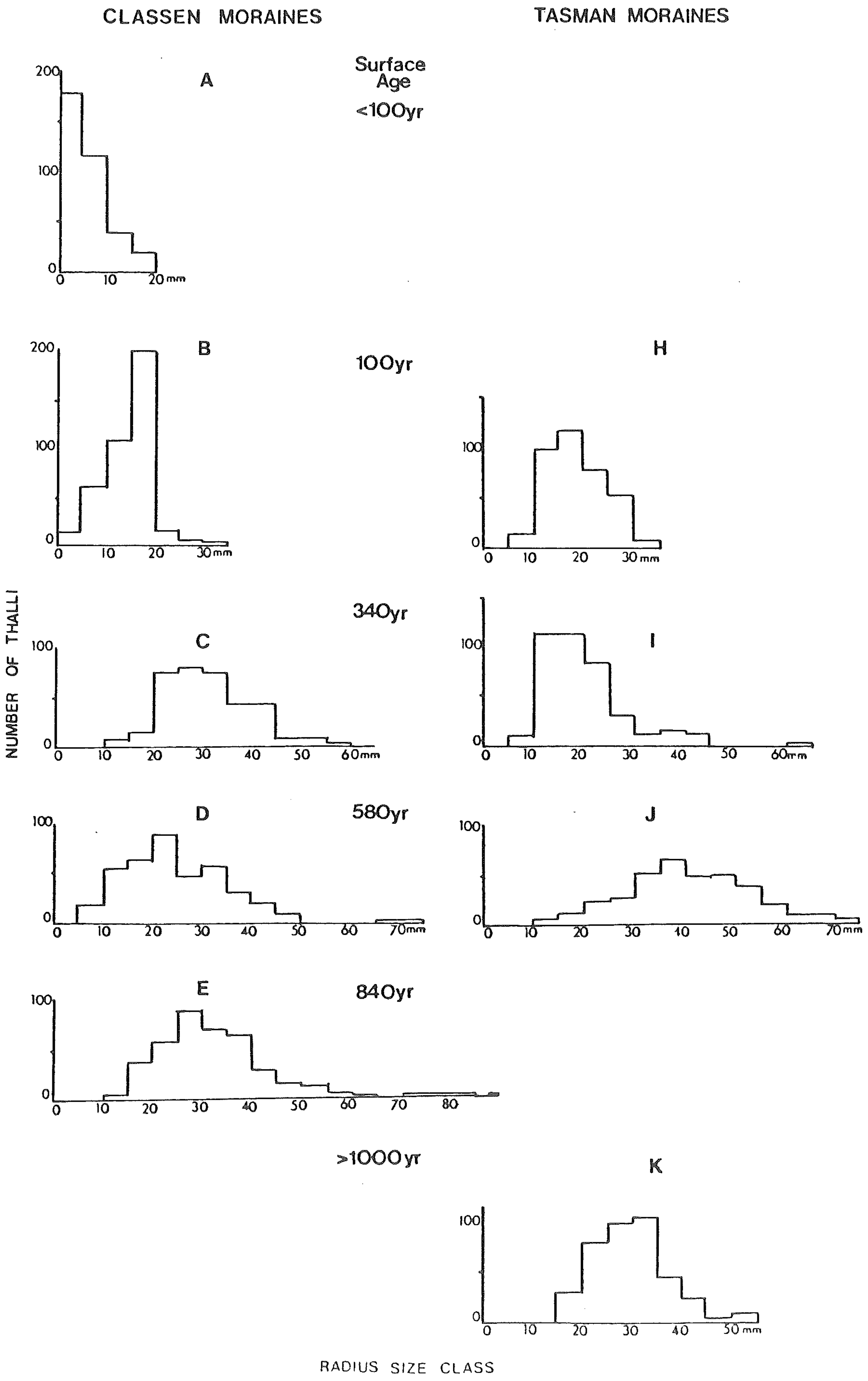
Site A <100 years The site is located by the lake edge and is probably <60 years old (Table 8.1). Lichens are still in the process of colonising. A steady increase in undisturbed surface area during the last 25 years accounts for the high modal value of lichens in the smallest size class, 0-5mm.

Site B 100 years The site is on the youngest latero-terminal moraine. Colonisation is still proceeding but not as rapidly as during the most intensive period of establishment, ie.<60 years ago.

Site C 340 years: The site is located on the long main latero-terminal moraine to the outside of 'B' (Fig.8.1). The modal size class extends from 20-35mm and reflects a steady turnover of thalli towards the end of the last century followed by a sharp drop in the rate of colonisation.

Site D 580 years: The site is on the prominent moraine loop upvalley of the older terminal moraines. The site is characterised by a great number of large boulders and extremely poor soil and vegetation cover. The moraine loop originally enclosed a small tarn. Meltwater has damaged the

Figure 8.5 Size-frequency analysis of the lichen (DLC) population.



moraine structure and the periodic disturbance is indicated in the histogram. No lichens are represented for the period around 300 years ago. The apparent 'fall off' in lichen colonisation rates in the present century is probably accentuated by the sampling design.

Site E 840 years : The site is adjacent to the oldest terminal moraine in the Classen Valley. At the points of contact with the older, well established surface the lichens experience increased competition with the scrub of the older moraine. Only a few, small lichens were recorded. The peak size class was 25-30mm, that is half the size of the largest thalli on the boulders of the moraine. The older lichen thalli may have broken up to yield a greater number of smaller thalli.

Mueller Glacier

No size-frequency data was collected from sites F and G (Fig.8.2) in the Mueller Valley.

Tasman Glacier

Site H 100 years : The site is located at the Blue Lakes. The modal size group is 15-20mm diameter. Lichens colonised over a relatively short period of time as shown by the sharp drop in DLC values of less than 10-15mm. However, as noted earlier, such a marked change in the frequency analysis may be a direct consequence of the rigid sampling design whereby only the largest thalli on each boulder were measured.

Site I 340 years : The site is located at the Blue Lakes and the distribution of thalli sizes is similar to the 100 year old surface (site H). The absence of lichen thalli between 62-48mm may reflect a major disturbance for the period 300-135 years ago. A recovery in lichen growth is indicated for the beginning of the present century.

Site J 580years : The site is situated east of the Blue Lakes (Fig.8.3). The size-frequency distribution indicates a steady turn-over in lichen colonisation with no obvious sign of disturbance.

Site K >1000years : The final site is located on the outer slopes of the Blue Lakes complex. The site is characterised by a low maximum DLC value of 52.4mm. The reduced number of thalli in the 45-50mm size class might be associated with the glacial expansion and associated disturbance around 135 years ago but the connection is purely speculative.

8.8 DISCUSSION

The measurement of crustose lichens shows the changes in growth rate of *Rhizocarpon* thalli. The growth rate is non-linear as opposed to the curves with assumed linearity used by Burrows & Lucas (1967), Burrows & Orwin (1971) and Burrows (1973a). The lichen factor is 33-34mm and not 67mm as was originally suggested, Burrows & Orwin(*loc.cit.*) and Burrows (*loc.cit.*). Values of lichen size on equivalent aged surfaces in different valleys are similar, (Table 8.1,Fig. 8.4).

Whilst, in as much as lichen measurements yielded a growth rate curve broadly consistent with rock weathering rind thickness-based age determinations, the study was successful , it is important to be aware of the many possible sources of error that still surround the technique. There are questions of lichen identification, thallus measurement, site selection, sample number and most importantly the accurate calibration of the lichen growth curve.

Gellatly (1982) described how all three lichen control points used by Burrows & Orwin (1971) were incorrectly dated. The present study shows that the earlier dating of the moraines by rock weathering rind thickness is at least consistent. The lichen thalli measurements presented in Burrows (*op.cit.*) are recalibrated with the corrected surface dates for the moraines from which the original data was collected, Table 8.2. The results show that the use of maximum DLC yields lower values of lichen size on the older section of the curves (Fig.8.4) than those described by Burrows (*op.cit.*). This difference may be explained by Burrows & Orwin's use of the maximum diameter on oval thalli as well as circular specimens.

The results presented here are consistent with conclusions reached by Birkeland (1981,1982). Birkeland visited the area in 1978-79 and questioned the validity of the lichen growth curve described by Burrows & Orwin(*op.cit.*) and its application by Burrows (*op.cit.*). His own results were insufficient to produce a recalibration lichen curve,(cf.Table 5.3, p.79).

The lichen growth curve is not extrapolated beyond 1000 years although several of the older surfaces were sampled. This was done for two reasons:

i - The lichens respond to factors other than time. With increasing age of the moraine surface the lichen population faces increased competition from other plants. Soil development and weathering alter the surface environment and eventually weaken the structure of the lichen population. Individual thalli may fragment in response to this stress; others become senescent and die.

ii - The importance of lichenometry as a dating tool in the concept of this study is its ability to decipher the closely spaced depositional events too old to be determined by historical means. Beyond c.1000 years the radiocarbon record is more reliable (Chapter 9).

The lichen population on a rock surface can also indicate something of the colonising history of that surface as was shown in section 8.7.2 and Fig.8.5 . Accepting the limitations and restrictions of the approach used it is possible to infer two periods of particular disturbance in the lichen record. A decrease in thalli measuring 60-48mm was recorded at four sites. According to the lichen growth curves (Fig.8.4) this interval corresponds with the period c.300-135 years ago. Further work will be required, however, to determine if lichen measurements used in this way can be used to confirm the local history of the site. It should be noted that there is no apparent difference between the Classen and Tasman lichen size-frequency histograms despite the latter area being extensively burnt on a number of occasions.

CHAPTER 9

RADIOCARBON DATING

9.1 INTRODUCTION

Palaeosoils exposed as a 'vertical chronosequence' (Vreeken 1975) in the eroding lateral moraine walls indicate former moraine surfaces, and, when radiocarbon dated, enable the reconstruction of glacier movements during the last 7000 years. Sites have been examined in detail, extending the earlier work by Burrows (1973a,1980) who first described the presence of palaeosoils in the superposed moraine walls in the Mt Cook region. Over thirty new radiocarbon measurements are presented here, including 24 dates from sites with no previous record.

The soils are buried as the glacier increases in height (and volume) and overtops the existing lateral moraine, (cf. 2.4.2, p.15-18). The increase in ice volume may,or may not,be recorded as a distinct till deposit amongst the terminal moraine sequence downvalley. The problems and possible correlations of dates from sites located upvalley from the present day snout with the terminal moraine sequence will be discussed in Section III.

9.2 MATERIAL

Radiocarbon dates are obtained from material both resting on or present within the palaeosoil. The significance of the material sampled and the interpretation of the resulting radiocarbon date varies with the type of organic material present, its position and state of development.

9.2.1 Buried soil

Palaeosoils are studied by the same methods as those used for present day soils. The field recognition of more than one distinct pedogenic feature forms the basis for the recognition of a palaeosoil. Pedological nomenclature and horizon connotations are used in describing all observed features and horizons. These can be supplemented by specific connotations to indicate the palaeosolic nature of the feature (Working group on the origin and nature of palaeosoils 1971), for example, the use of fAh to describe the buried humus A horizon (Rothlisberger *et al.* 1980).

The radiocarbon measurements of palaeosoils in the lateral moraines indicate the 'mean residence time' of the soil carbon at the time of burial plus the time that has elapsed since that event. This is neither the 'true age' nor the age since the buried horizon was covered. The obtained age approximates the true age in situations where the mean residence time of the organic carbon before burial was low, and when a short time span before burial combines with a long one after burial (Sharpenseel 1975). Where the time span prior to burial is too small, however, the buried surface will persist in the sequence as a discoloured weathered horizon, and the required organic material may be absent. The addition of loess to the soil profile prior to burial may, as was demonstrated in Fig.6.1,(p.84), cause the soil surface to 'move upwards' and for this reason the top of the buried soil is often difficult to determine. The A horizon may be stripped off during the process of burial leaving a truncated soil profile.

9.2.2 Buried wood and plant litter

Surfaces which have been left undisturbed and allowed to stabilise are soon colonised by plant species, and a thin soil cover develops. Vegetation studies in Mt Cook National Park (Chapter 7) indicate that herbfield and a few,low woody shrubs are associated with the 200-1000 year old surfaces. Tall shrubs and woody scrub are characteristic of the older surfaces at the present day. Wood from species such as *Phyllocladus alpinus* and *Podocarpus nivalis* are indicative of surfaces which were stable for a period of at least 500 years prior to burial. The wood is rarely more than 100 years old as indicated by the growth rings. Wood and,more particularly, small twigs of short lived species contain a low mean residence time relative to that in the soil, and are therefore more accurate as an estimate of the date of burial.

The presence of wood, in particular whole tree trunks protruding from the lateral moraine walls, was noted by Röthlisberger & Schneebeli (1976) and Röthlisberger *et al.* (1980) from areas in the Swiss Alps and Peru. Röthlisberger discovered further tracts of buried wood and forest in the moraines of Westland National Park, New Zealand (Dr F. Röthlisberger pers.comm. 1980). Only relatively small amounts of wood have been discovered in the eastern ranges of the Southern Alps.

9.2.3 Contamination

Material for radiocarbon dating must satisfy the criteria validating the conceptual model. These are described in full by Geyh, Benzler & Roeschmann (1971). The material to be dated must be derived from organisms assimilating atmospheric carbon dioxide. The material should be free of contamination, such as modern roots, which would otherwise falsify the radiocarbon measurement. The material, in particular the wood and twigs, should be *in situ*. Soils which have been entirely displaced through slumping are still able to be used, but the repositioning of the entire relic surface requires careful interpretation. The problems of radiocarbon dating are further outlined by Sharpenseel (1971), Olsson (1974), Matthews (1974), Röthlisberger *et al.* (1980) and Baillie (1982) and are summarised in Appendix B .

9.3 SITE SELECTION AND SAMPLING

There are more than fifty kilometres of bare, steep-sided lateral moraine walls bordering the glaciers of Mt Cook National Park. These have become exposed during the latter half of the twentieth century by the continued downwasting of the glacier ice. Potential sites for buried soils were investigated by searching the exposed, eroding lateral moraine walls. Investigations were extended to the terminal moraine sequences, but, as will be explained, the chances of a discovery where excavations are required is far less likely than where careful exhaustive searches of the exposed moraine walls are involved.

Initially, present day surface deposits were examined, with emphasis on their post-depositional modification.

Soil and plant cover is rarely continuous in space, except in areas of considerable uniformity and stability. Patterns of surface cover are influenced by the positioning of large boulders and surface streams. The discontinuity of the surface cover is reflected also in the palaeosurface exposure.

The surface topography of the terminal moraines provides some indication of the pattern of glacial events, especially where partially overlapping ridges persist (accretion type moraines). Excavation in certain sites would carry a greater expectancy of success, with the discovery of a palaeosoil, than elsewhere. Such investigations involve a large amount of trial and error, and a great deal of effort. Probing or coring is virtually impossible due to the coarse, bouldery texture of the parent material present in the soil matrix. Röthlisberger,when working in the Swiss Alps, was able to resort to blasting if digging failed (Röthlisberger 1979). Such an approach was not possible in Mt Cook National Park,and an attempt to excavate sections of the moraine was abandoned.

The investigation of sites down the lateral moraines has been described by Röthlisberger as:

> "...less laborious, but more severely exposed to the danger of falling rocks" (Röthlisberger 1979,p.400).

Sampling is carried out on the steep slopes above the glacier (Fig.9.1A, 9.1C). Occasionally a palaeosoil is observed from the top or bottom of the moraine wall but just as often it is necessary to traverse a likely site, carefully checking the till for evidence of a buried surface. Locating the fossil soil horizons often presents difficulties. Whilst the soil is brown in colour, it is usually coated with fine glacial silt. Projecting wood or plant litter if present, may draw attention to the site, Fig.9.1D. Material is sampled by first cleaning off the surface layer of silt and removing any slope wash or slumped debris from positions upslope, Fig.9.1E. Sample size varies according to the nature of the substance being collected. To contain enough carbon for dating a sample consisting of soil alone would weigh approximately 1kg. A sample comprised of wood and roots would weigh just one-fifth this amount, and is therefore

Figure 9.1 Radiocarbon dating of palaeosurfaces in the lateral moraines of Mt Cook National Park.

A - Dr F.Röthlisberger inspecting a moraine slope for evidence of soil burial.

B - Slumping near the Ball Hut shelter, Tasman Valley. Whole sections of the moraine wall have been displaced by up to 3-4m. Elsewhere the downwasting of ice has reduced the stability of the lateral moraines causing collapse of till down the exposed proximal moraine face. Recent examination of the slump scars has revealed palaeosoils buried by the most recent glacier advances.

C - Steep, eroding lateral moraine face opposite the Ball Hut site. Note the upward projecting boulders in the till indicating that this is a distal moraine slope.

D - Buried soil with small wood fragment (arrowed) projecting from the till.

E - Cleaned surface of a buried soil ready for sampling.

F - Northern moraine of the Mueller Glacier showing (white arrow) the sampling site area used in this study.

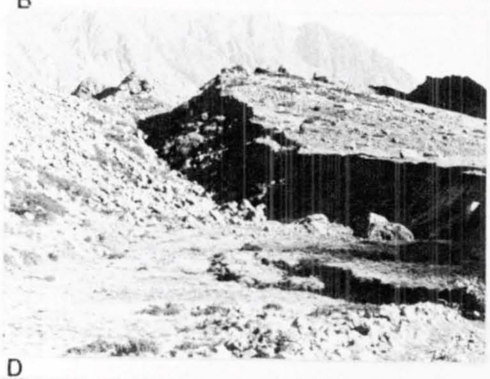
G - Hooker lateral moraines near the glacier terminus with an arrow indicating the approximate site of buried soils sampled in this study.

H - Ball Hut moraines at the junction of the Ball and Tasman Glaciers. Ice overtopped these moraines at the end of the last century, but the level has dropped over 100m in the last 100 years. The steep lateral moraines are eroding.

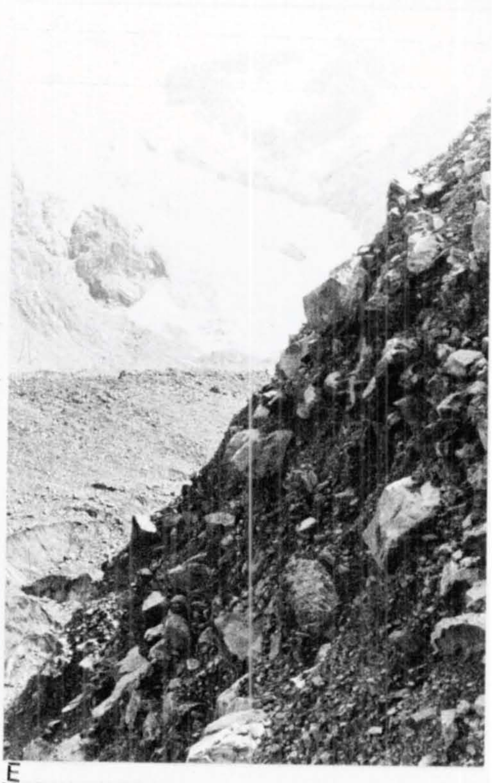
I The distinctive trim line in the Godley Valley with the site of some buried palaeosoils indicated by the white arrow. The site is over 150m above the floodplain. The Classen Glacier moraines can be seen to the left of the photograph in the middle foreground.

A

B

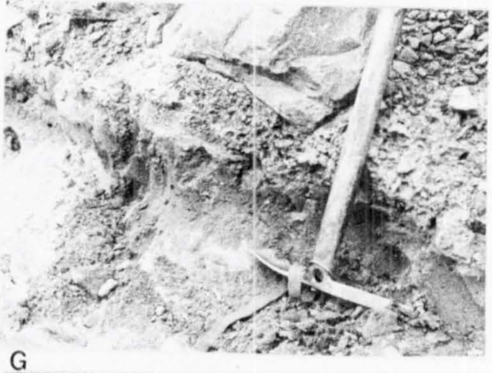


C→



D

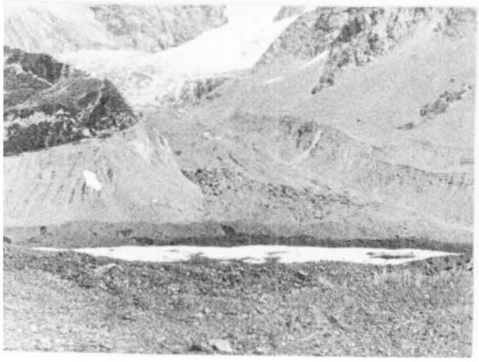
E



F

G

H



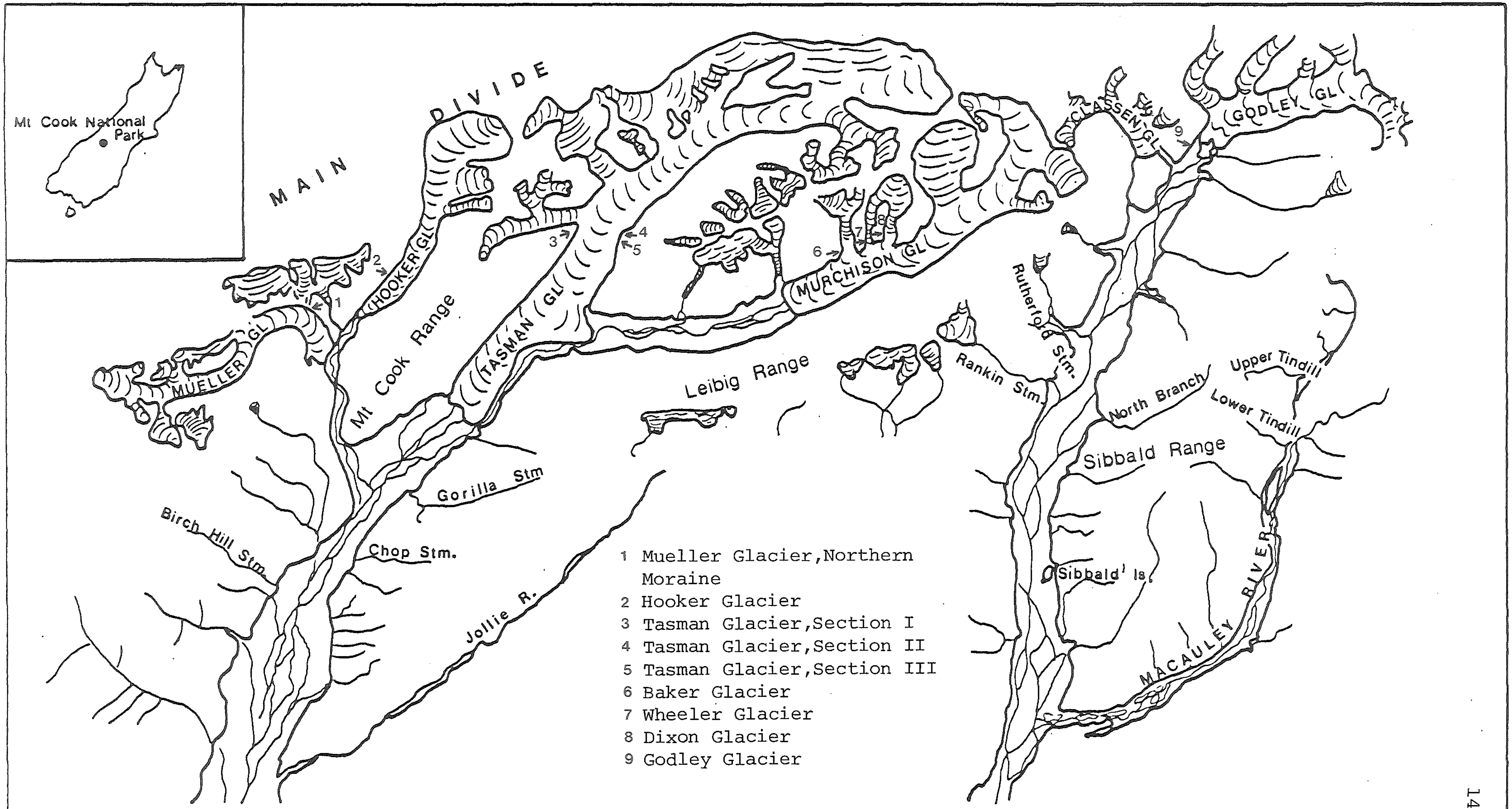
I

preferable. There is, however, a rationale for collecting both wood and soil to date the different attributes of the site history. In all situations, only *in situ* wood is collected for dating. The sample is described in the field. Its stratigraphic position is important for reconstruction of the moraine formation and depositional history. The distance below the moraine crest and the nature of the organic content/soil development are recorded for identification purposes, although the identical exposure is often difficult to find on subsequent visits to the same site.

9.4 RESULTS

Fig.9.2 shows the location of the sampling sites in this study. Table 9.1 presents the radiocarbon dates obtained from these sites. The material was collected with the assistance of Dr F.Röthlisberger (February 1980) and Dr C.J.Burrows (December 1980 and November 1981). Material was dated at one of two laboratories. Samples collected with Dr F.Röthlisberger were analysed at the ^{14}C and ^{3}H Laboratorium, Hannover, Germany as part of an extensive programme by Dr M.A.Geyh. The other material was submitted to the New Zealand radiocarbon dating laboratory, Lower Hutt, New Zealand.

The palaeosoils collected from the nine different sites are described below. Following each description of the buried surfaces exposed at these sites, a short interpretation of the significance of the dated material is presented. This will enable a full discussion in the following section of the significance of the whole list of dates as they relate to earlier work in Mt Cook National Park and to results from radiocarbon sampling elsewhere in New Zealand, and in the Southern Hemisphere.



1 Mueller Glacier,Northern Moraine
2 Hooker Glacier
3 Tasman Glacier,Section I
4 Tasman Glacier,Section II
5 Tasman Glacier,Section III
6 Baker Glacier
7 Wheeler Glacier
8 Dixon Glacier
9 Godley Glacier

Figure 9.2 Location of radiocarbon sampling site, Mt Cook region.

Table 9.1

Radiocarbon dates associated with glacial deposits.

Date yr B.P.	Lab.No.	Location	Moraine/Section	Description of Deposits	Significance	Collector/Reference
343±56	NZ-5330	Tasman Glacier 43°36'40" S. 170°13'09" E.	Tasman Section III Novara Spur,1070m	Wood from slightly organic sand between layers of till,9m below crest.	Minimal age for moraine, dates burial of soil by the expanding glacier.	Gellatly (unpubl.)
685±57	NZ-5253	Hooker Glacier 43°39'43" S. 170°05'35" E.	Lateral moraine near Hooker Hut, 980m.	0.5-1cm fibrous,organic material,resting between sand and till,buried by colluvium.	Minimal age for date of moraine formation.Dates formation of the collovium above.	Gellatly & Burrows (unpubl.)
765±50	HV-10500	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	10-20cm A-horizon with wood buried between till.15m below crest.	Highest of 5 palaeosoils. Dates recent glacier advance.	Gellatly & Röthlisberger (unpubl.)
864±58	NZ-5331	Tasman Glacier 43°36'40" S. 170°13'09" E.	Tasman Section III Novara Spur,1070m	A-horizon in 40cm grey silt band resting in till, 22m below crest.	Minimal age for moraine Dates glacier expansion.	Burrows & Gellatly (1982)
933±58	NZ-5254	Tasman Glacier 43°32'40" S. 170°13'09" E.	Tasman Section III Novara Spur,1070m	1-2cm A-horizon band in grey silt band,resting in till,17m below crest.	As above.	Gellatly (unpubl.)
1075±40	HV-10490	Tasman Glacier 43°37'00" S. 170°11'45" E.	Tasman Section I Ball Hut,1110m	Buried soil between bouldery till.40m below crest.	Highest of 4 palaeosoils. Minimal age for crest formation.	Gellatly & Röthlisberger (unpubl.)
1130±45	NZ-5329	Mueller Glacier 43°41'51" S. 170°04'45" E.	Northern moraine 980m	0.5-3cm organic silt-sand between bouldery till,14m below crest.	Minimal age for moraine. Dates glacier expansion.	Gellatly (unpubl.)
1515±275	HV-10503	Tasman Glacier 43°36'40" S. 170°13'09" E.	Tasman Section III Novara Spur,1070m	2-5cm A-horizon with wood,resting in bouldery till, 15m below crest.	Highest of 3 palaeosoils. Dates glacier expansion.	Gellatly & Röthlisberger (unpubl.)

Table 9.1 cont...

Date yr B.P.	Lab.No.	Location	Moraine/Section	Description of Deposits	Significance	Collector/Reference
1535±55	HV-10508	Dixon Glacier 43°34'07" S. 170°21'03" E.	Right-hand side moraine,1340m	5-10cm A-horizon,10-20cm B-horizon.Wood present. Soil exposed parallel to slope angle.	Good formation with soil providing minimal date of moraine formation.	Gellatly & Röthlisberger (unpubl.)
1620±65	NZ-5332	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section III Novara Spur,1080m	5cm A-horizon with wood. B-horizon resting on till, 29m below crest.	Minimal age for moraine. Dates glacier expansion.	Burrows & Gellatly (1982)
1680±55	HV-10506	Baker Glacier 43°35'10" S. 170°20'07" E.	Right-hand side moraine,1250m	Wood in A-horizon,50m below crest and 30m under HV-10505.	Possibly the same formation as HV-10505.Dates glacier expansion.	Gellatly & Röthlisberger (unpubl.)
1905±75	HV-10510	Mueller Glacier 43°41'50" S. 170°04"45' E.	Northern moraine 980m	Palaeosoil with organic material,10m below crest.	Highest of 2 palaeosoils. Dates glacier expansion.	Gellatly & Röthlisberger (unpubl.)
1955±40	HV-10505	Baker Glacier 43°35'10" S. 170°11'45" E.	Right-hand side moraine,1250m	5-20cm A-horizon,20-40cm B-horizon with wood.20m below crest.	Minimal age for moraine, dates glacier expansion. ? related to HV-10506.	Gellatly & Röthlisberger (unpubl.)
2060±50	HV-10502	Tasman Glacier 43°36'40" S. 170°13'09" E.	Tasman Section III Novara Spur,1070m	5-15cm A-horizon resting in bouldery till. 20m below crest.	Minimal age for moraine surface, dates glacier expansion.	Gellatly & Röthlisberger (unpubl.)
2090±95	HV-10509	Dixon Glacier 43°34'07" S. 170°21'03" E.	Right-hand side moraine,1340m	Buried A-horizon 10m below crest and 40m above HV-10508	Above HV-10508 yet older than the soil below.Indicates slumping.	Gellatly & Röthlisberger (unpubl.)
2110±45	HV-10493	Tasman Glacier 43°37'00" S. 170°11'45" E.	Tasman Section I Ball Hut,1110m	2-5cm A-horizon with wood 60m below crest.Wood is dated separately,HV-10492	Minimal date for surface buried during glacier expansion.	Gellatly & Röthlisberger (unpubl.)
2225±310	HV-10512	Hooker Glacier 43°39'43" S. 170°05'35" E.	Lateral moraine near Hooker Hut, 980m	Silt-sand band with plant 4-20m below erosion surface.	As above.	Gellatly & Röthlisberger (unpubl.)

Table 9.1 cont...

Date yr B.P.	Lab.No.	Location	Moraine/Section	Description of Deposits	Significance	Collector/Reference
2280±50	NZ-5335	Tasman Glacier 43°37'00" S. 170°11'45" E.	Tasman Section I Ball Hut,1065m	Wood from soil buried between layers of till.	Minimal age for moraine formation.Dates glacier expansion.	Gellatly (unpubl.)
2500±55	HV-10494	Tasman Glacier 43°37'00" S 170°11'45" E.	Tasman Section I Ball Hut,1065m	2-5cm A-horizon with wood,80m below crest.	Minimal age for a buried surface.	Gellatly & Röthlisberger (unpubl.)
2690±275	HV-10501	Tasman Glacier 43°36'40" S. 170°13'09" E.	Tasman Section III Novara Spur,1070m	5-15cm A-horizon.25m below crest.	Lowest of 3 palaeosoils. Minimal age for surface buried by glacier expansion.	Gellatly & Röthlisberger (unpubl.)
2765±140	HV-10492	Tasman Glacier 43°37'00" S. 170°11'45" E.	Tasman Section I Ball Hut,1065m	Wood in A-horizon,60m below crest.	Date of glacier advance. Compare with HV-10493.	Gellatly & Röthlisberger (unpubl.)
2815±145	HV-10507	Wheeler Glacier 43°34'40" S. 170°30'40" E.	Right-hand side moraine,1340m	B-horizon 10-20cm deep, A-horizon absent,Soil 30m below crest.	Minimal age for moraine surface,buried during glacier expansion.	Gellatly & Röthlisberger (unpubl.)
2830±90	HV-10513	Hooker Glacier 43°39'30" S. 170°05'42" E.	Lateral moraine near Hooker Hut, 1010m	2-5cm A-horizon,5-10cm B-horizon with wood.40m below crest.	As above.	Gellatly & Röthlisberger (unpubl.)
3180±110	HV-10491	Tasman Glacier 43°37'00" S. 170°11'45" E.	Tasman Section I Ball Hut,1065m	1cm A-horizon,5-10cm B-horizon,50m below crest.	As above.	Gellatly & Röthlisberger (unpubl.)
3360±110	NZ-5333	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	A-horizon poorly preserved,resting on sandy B-horizon 30-60cm deep.	Minimal age for surface. Soil buried by slope wash material.	Gellatly (unpubl.)
3450±80	NZ-5334	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	0-5cm A-horizon,5-10cm B-horizon with wood.55m below crest	Minimal age for moraine surface,buried during glacier expansion.	Burrows & Gellatly (1982)

Table 9.1 cont...

Date yr B.P.	Lab.No.	Location	Moraine/Section	Description/Deposits	Significance	Collector/Reference
4050±80	HV-10495	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	Buried A-horizon,100m below crest.	Minimal age for moraine surface, buried during glacier expansion.	Gellatly & Röthlisberger (unpubl.)
4125±130	HV-10499	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	Thin A-horizon with 5-10cm B-horizon,20m below crest.	Approximate date of burial of the surface during glacial expansion.	Gellatly & Röthlisberger (unpubl.)
4605±365	HV-10496	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	B-horizon only.Stratigraphically similar to HV-10497 & 10498. 50m below crest.	Related to HV-10498 & HV-10497.All three part of same surface.	Gellatly & Röthlisberger (unpubl.)
4780±205	HV-10497	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	B-horizon only present. 50m below crest.	Same soil horizon as HV-10496 above.	Gellatly & Röthlisberger (unpubl.)
5690±140	HV-10498	Tasman Glacier 43°36'37" S. 170°13'09" E.	Tasman Section II Novara Spur,1080m	B-horizon only 5-8cm deep.	From same soil complex as HV-10496 & 10497.Buried by glacial expansion.	Gellatly & Röthlisberger (unpubl.)
6750±135	HV-10511	Mueller Glacier 43°41'45" S. 170°04'45" E.	Northern moraine 980m	Weakly developed palaeosoil between bouldery till.35m below crest.	Lower of two soils.An additional surface did not contain enough organic for dating.	Gellatly & Röthlisberger (unpubl.)
8040±80	HV-10504	Black Birch St. 43°44'32" S. 170°05'57" E.	Right-hand side of stream,under Mt Sebastopol.	Wood embedded in bouldery matrix.	According to Burrows (1980) dates glacial advance in side valley.	Gellatly & Röthlisberger (unpubl.)

9.4.1 Mueller Valley

Three palaeosoils have been dated from the exposed section of the Northern lateral moraine in the Mueller Valley. In February 1980 three palaeosurfaces were observed. However, only the two highest exposures contained sufficient organic material for a radiocarbon measurement. The soils were positioned 10, 35 and 45m below the main moraine crest. The highest soil, HV-10510, contained some wood fragments. It is dated 1905±75 yr B.P. . The second highest soil was, in contrast,poorly preserved and contained no large organic fragments. The soil is dated 6750±135 yr B.P. (HV-10511). The Northern lateral moraine was revisited in December 1980. A palaeosoil was found exposed in a gully approximately 300m downvalley from the original site. The soil (NZ-5329) was 14m below the moraine crest. It contained no plant material and the A-horizon was dated 1130±45 yr B.P.

Discussion The three dates relate to separate depositional events in the Mueller Valley. The burial of wood in surface HV-10510 records a glacial expansion. The youngest date is from a recent soil buried shortly after its formation. It is expected that the mean residence time would be low, and the date for NZ-5329 is considered to be closely associated with a glacier advance dating from c.1100 yr B.P. The third date,from HV-10511, is tentatively correlated with the same glacial expansion which resulted in the deposition of Foliage Hill which is 3km downvalley.

9.4.2 Hooker Valley

In February 1980 two buried surfaces were sampled 4-20m and 40m respectively below the moraine crest near Hooker Hut. The lower surface contained an abundance of plant debris,wood and roots. The higher surface contained plant roots. Organic material was collected from both soil surfaces and dated as follows:

Higher surface-	HV-10512	2225±310 yr B.P.
Lower surface -	HV-10513	2830±90 yr B.P.

In December 1980 a third palaeosoil was located and sampled. The soil comprised a fibrous,organic material and contained sedge leaves. It had been buried by colluvium. The soil rests on till material and was dated 685±57 yr B.P.

Discussion All three dates provide minimal age values for the date of formation of the surfaces on which the soils were found. HV-10512 and HV-10513 are both indicative of periods of glacial expansion, Table 9.1

9.4.3 Tasman Valley, Section I

Section I is the first of three sites examined in the Tasman Valley. It is located near the junction of the Ball Glacier and the Tasman Glacier. The eroded gullies within which the palaeosurfaces are exposed are located near the Ball Hut shelter. In February 1980 four palaeosoils were discovered and the exposure is described in Fig.9.3 . The surfaces were exposed at 40, 50, 60 & 80m below the main crest. The highest soil contained no plant material. Sample HV-10490 comprised organic A-horizon material and was dated 1075±40 yr B.P. The second highest palaeosoil (HV-10491) also lacked 'macrofossils' and the soil date was 3180±110 yr B.P. The third highest palaeosoil contained both woody plant material and a deep A-horizon. The soil and plant material were dated separately. The soil sample (HV-10492) was aged 2765±140 yr B.P. and the wood (HV-10493) dated 2110±45 yr B.P. The wood was from *Phyllocladus alpinus*. The lowest exposed soil (HV-10494), a thin A-horizon containing small woody fragments, was dated 2500±55 yr B.P.

The site was revisited in December 1980 when a buried surface about 40m below the crest was exposed. The buried material included some wood, dated 2280±50 yr B.P. (NZ-5335).

In November 1981 a further four palaseosoils were sampled from positions near the top of the moraine wall, just below the crest. In one place an entire buried slope surface was revealed. The slope, which was an original proximal slope of a lateral moraine ridge, was littered with branches and plant remains. The material was principally from *P.alpinus*. Only the secular corrections are known for these samples at the time of writing.

Discussion An attempt has been made to reconstruct the events which gave rise to the burial and later exposure of the palaeosoils at Section I. Fig.9.3 presents details of some of the soils examined, and a small interpretative

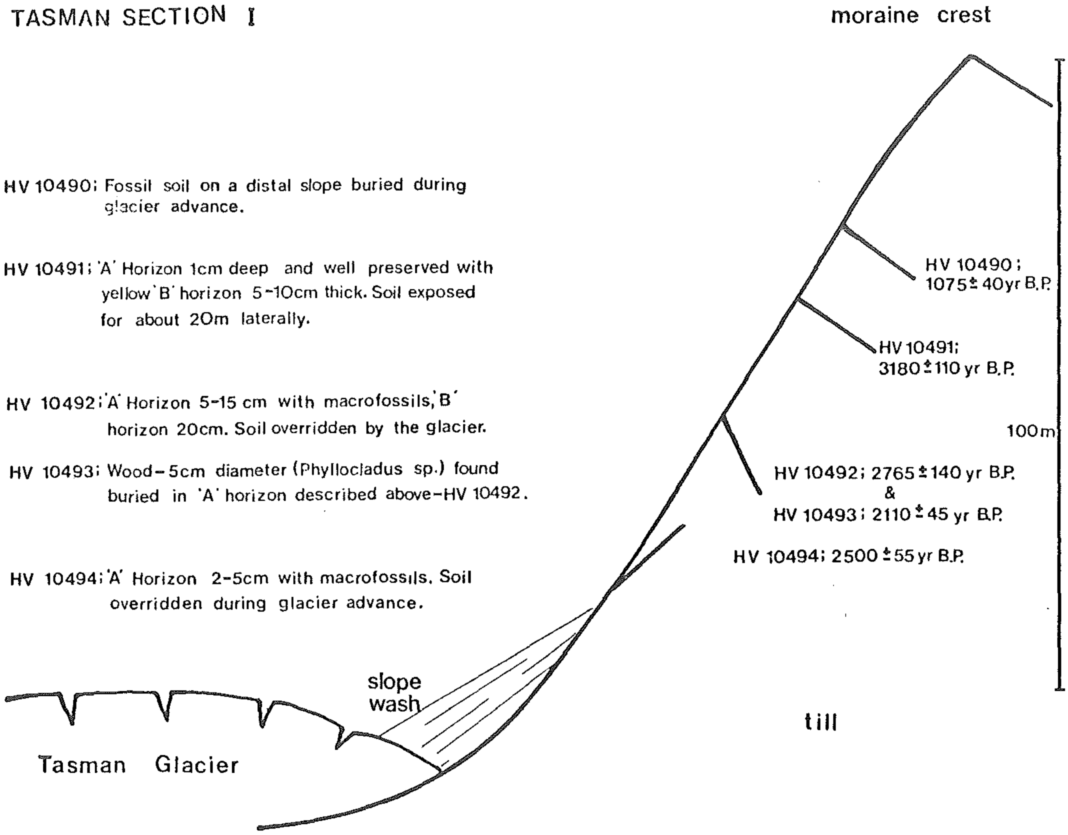
Figure 9.3 Details of Section I, Tasman Valley showing:

a) Stratigraphy of palaeosoils collected in February 1980,

b) Interpretive diagram to show site history and formation of moraine sequence based on observations of the palaeosoil stratigraphy.

BALL HUT SITE

a)



HV 10490; Fossil soil on a distal slope buried during glacier advance.

HV 10491; 'A' Horizon 1cm deep and well preserved with yellow 'B' horizon 5-10cm thick. Soil exposed for about 20m laterally.

HV 10492; 'A' Horizon 5-15 cm with macrofossils, 'B' horizon 20cm. Soil overridden by the glacier.

HV 10493; Wood-5cm diameter (Phyllocladus sp.) found buried in 'A' horizon described above-HV 10492.

HV 10494; 'A' Horizon 2-5cm with macrofossils. Soil overridden during glacier advance.

b)

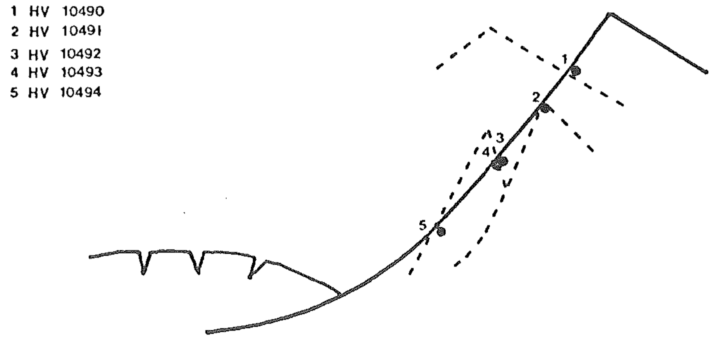


diagram is included. The interpretation is based on field observations coupled with the radiocarbon dated sequence. The highest surface (HV-10490) is a superposed surface and the material examined formed part of the distal moraine slope prior to burial. Likewise, the second highest surface (HV-10491) was also a distal moraine slope which superposed the existing surface. Samples HV-10492 and 10493 are from a buried, distal moraine surface as indicated by their stratigraphic position and the inclination of boulders in the surrounding till. The difference in age between the two dates demonstrates the variations in 'mean residence time' of soil and wood material. *P.alpinus* colonises surfaces aged at least 500 years old (Chapter 7). It is assumed that the minimal age of the soil prior to burial would have been about 500 years. HV-10494 is a buried proximal moraine slope. It described an earlier glacier advance which took place about 2500 yr B.P. in the Tasman Valley. NZ-5335 is from the second lowest exposed palaeosoil and is grouped with samples HV-10492 and 10493.

9.4.4 Tasman Valley, Section II

In February 1980 the high lateral moraines below Novara Spur, Tasman Valley, were examined. The site is directly opposite Section I (Fig.2.2 pocket). Two sections are described from this side of the valley. The sections are about 200m apart. Details of Section II are shown in Figs. 9.4, 9.5 & 9.6.

Within 15m of the moraine crest a well preserved fAh horizon was found. Wood fragments contained within the soil yielded a date of 764±50 yr B.P.(HV-10500). Further downslope, 20m below the crest, a second buried surface was exposed. No wood was associated with this surface and the sample was collected from a shallow A-horizon resting on a thin B-horizon. The material (HV-10499) was dated 4125±130 yr B.P. In another gully, 50m below the crest, two buried soils were found. When traced laterally the two soils (HV-10497 & 10498) merged to give one single soil surface (HV-10496). Radiocarbon dates were obtained from all three exposures, Fig.9.5. The material dated in each sample was from the soil B-horizon. One final soil exposure was

Figures 9.4 - 9.6 p157-159.

Figure 9.4 Left lateral moraine of the Tasman Glacier below Novara Spur showing the positions of palaeosurfaces examined from Sections II and III. Height of moraine wall is about 100m.

Figure 9.5 (overleaf) Details of Section II, Tasman Valley to show:

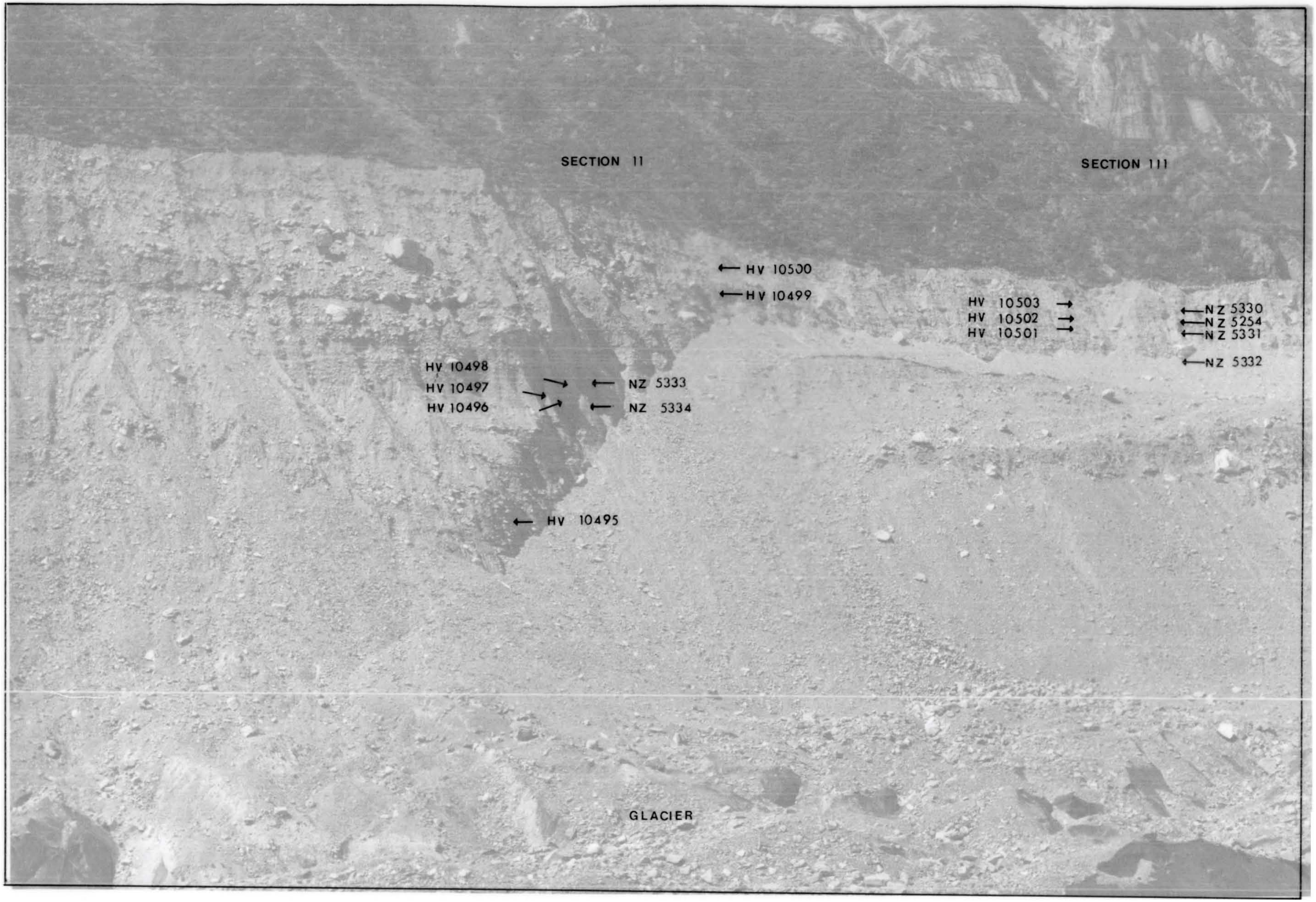
a) Stratigraphy of palaeosoils collected in February 1980,

b) Interpretative diagram to show site history of moraine sequence.

Figure 9.6 (p.159) Details of Section II and II, Tasman Valley to show:

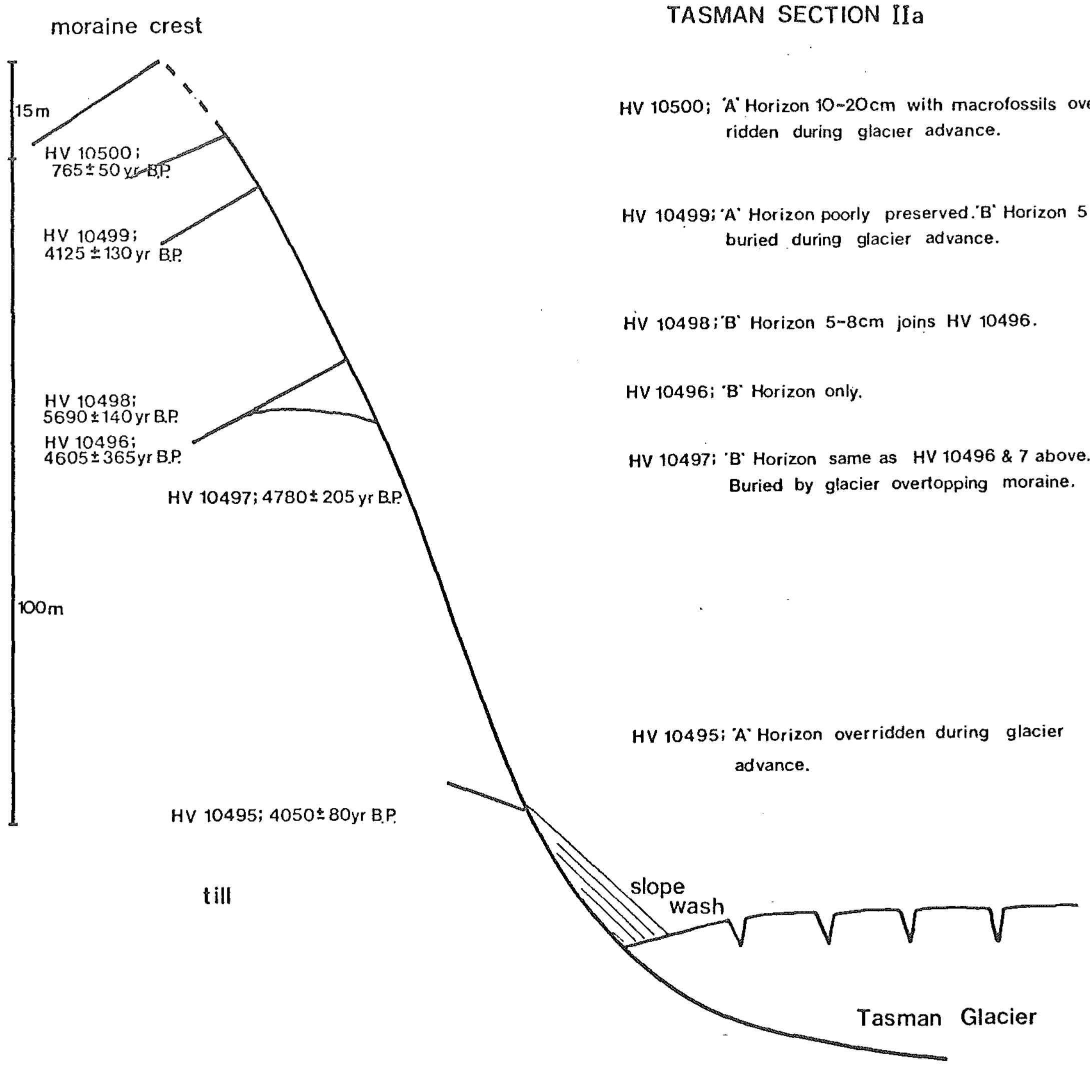
a) Stratigraphy of palaeosoils collected in December 1980,

b) Interpretative diagram to show site history of moraine sequences.


SECTION II
SECTION III
HV 10500
HV 10499
HV 10503
HV 10502
HV 10501
NZ 5330
NZ 5254
NZ 5331
NZ 5332
HV 10498
HV 10497
HV 10496
NZ 5333
NZ 5334
HV 10495
GLACIER

NOVARA SPUR SITE

a)



TASMAN SECTION IIa

HV 10500; 'A' Horizon 10-20cm with macrofossils overridden during glacier advance.

HV 10499; 'A' Horizon poorly preserved. 'B' Horizon 5-10cm buried during glacier advance.

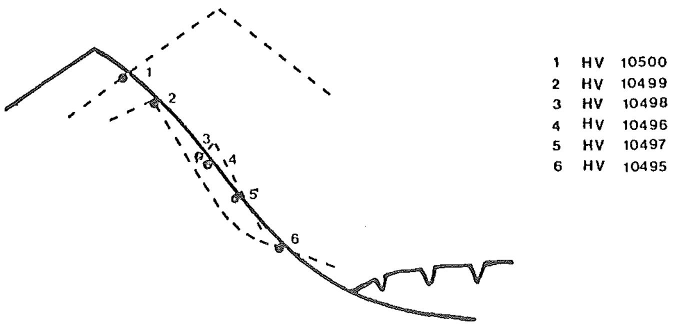
HV 10498; 'B' Horizon 5-8cm joins HV 10496.

HV 10496; 'B' Horizon only.

HV 10497; 'B' Horizon same as HV 10496 & 7 above. Buried by glacier overtopping moraine.

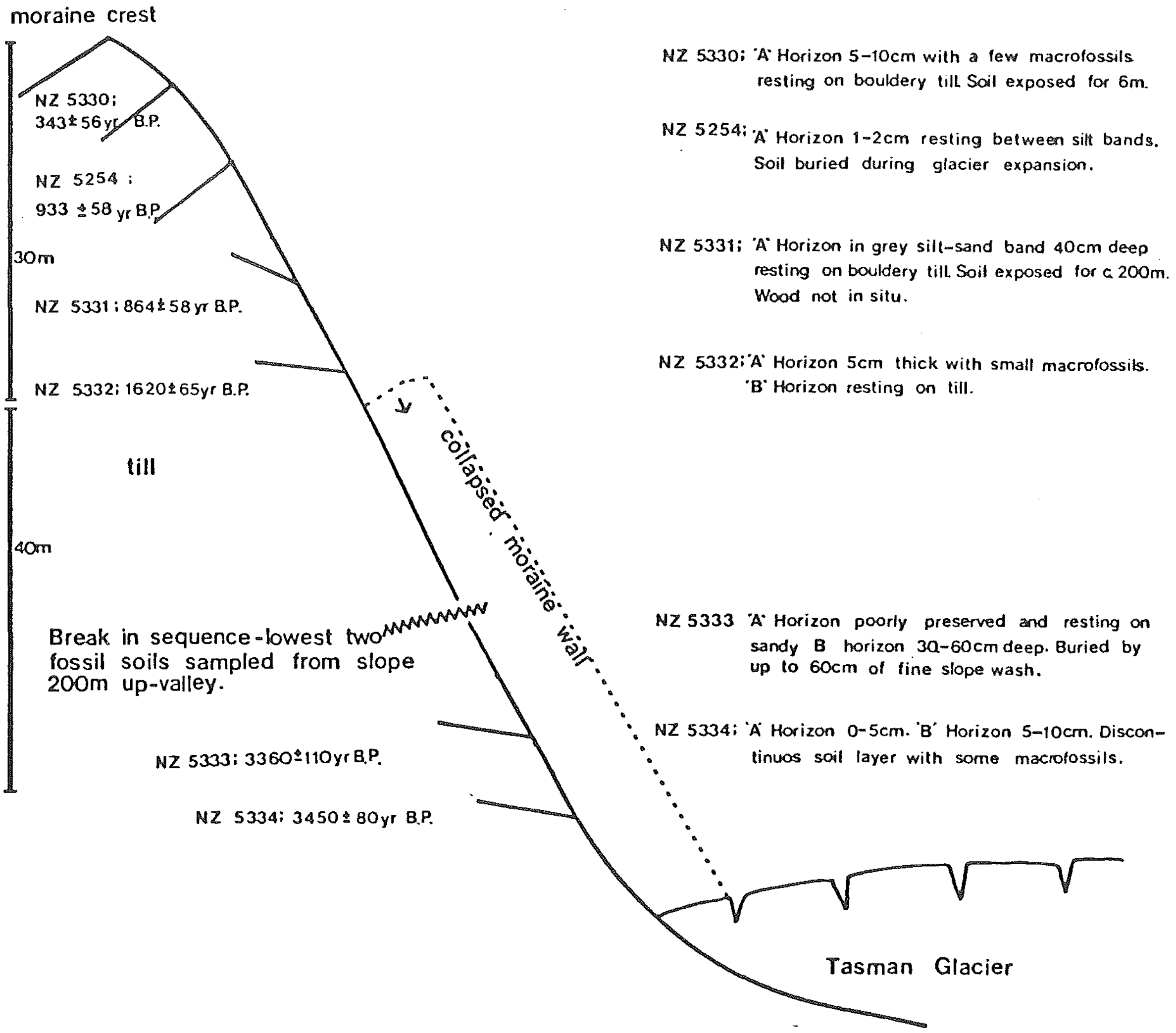
HV 10495; 'A' Horizon overridden during glacier advance.

b)



NOVARA SPUR SITE

a)



TASMAN SECTIONS IIb & IIIb

NZ 5330; 'A' Horizon 5–10cm with a few macrofossils resting on bouldery till. Soil exposed for 6m.

NZ 5254; 'A' Horizon 1–2cm resting between silt bands. Soil buried during glacier expansion.

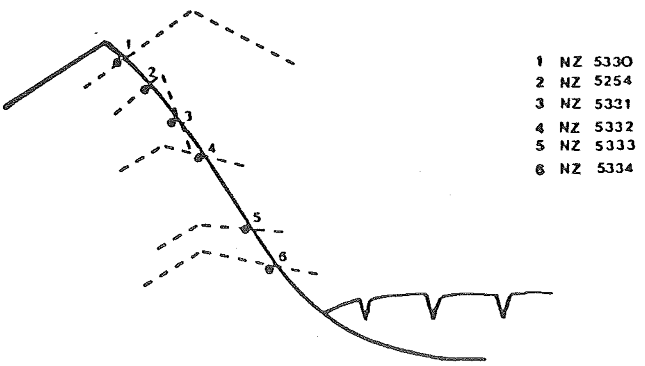
NZ 5331; 'A' Horizon in grey silt–sand band 40cm deep resting on bouldery till. Soil exposed for c. 200m. Wood not in situ.

NZ 5332; 'A' Horizon 5cm thick with small macrofossils. 'B' Horizon resting on till.

NZ 5333 'A' Horizon poorly preserved and resting on sandy B horizon 30–60cm deep. Buried by up to 60cm of fine slope wash.

NZ 5334; 'A' Horizon 0–5cm. 'B' Horizon 5–10cm. Discontinuos soil layer with some macrofossils.

b)



located 100m below the crest (HV-10495) and was dated 4050±80 yr B.P.

Nine months later the site was revisited and the results of this survey are presented in Fig.9.6. In the intervening months the gullies had been further eroded destroying some of the previous exposures but also revealing some new material. Two samples (NZ-5333 & 3334) were believed to be from equivalent positions as HV10496-10498, however the radiocarbon measurements are markedly younger in the later samples; 3360±100 yr B.P. and 3450±80 yr B.P. repectively. It will be recalled (Fig.9.4, 9.5) that the original material was dated 4605±365 yr B.P. and older. If the two sets of samples were from the same exposure, the difference in ages must have arisen from a variety of causes;

- the laboratories have produced different results,
- the material sampled differs in quality, NZ-5334 was on wood, the remainder were all from soil.
- one or both sets of samples were contaminated.

Alternatively, as is suggested here, the two sample sets are derived from separate events

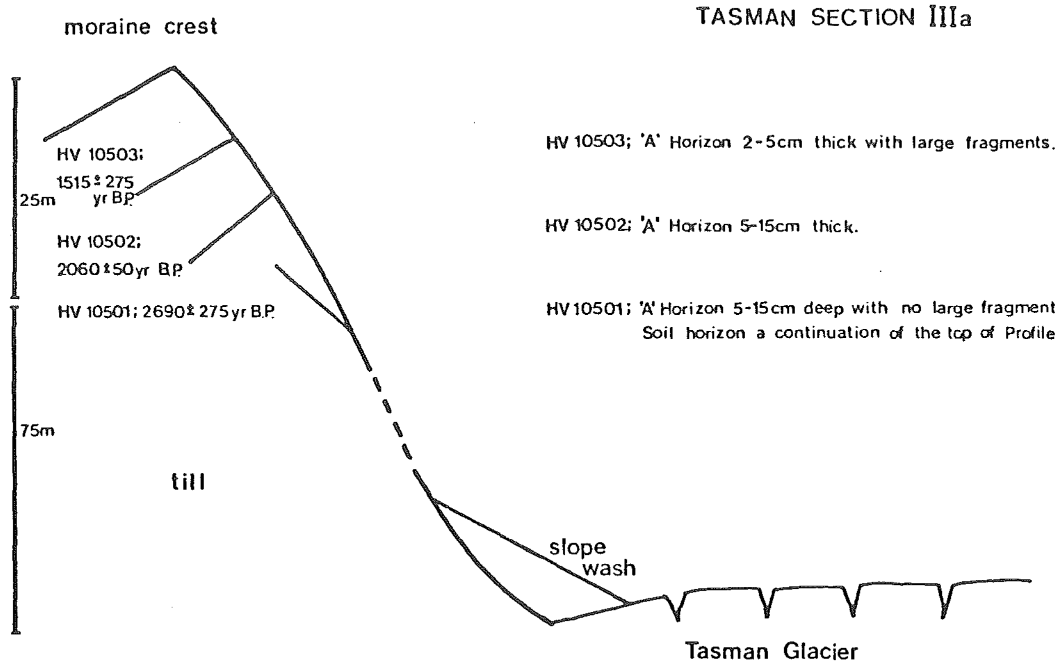
Discussion The highest buried palaeosoil (HV-10500) is from a distal slope of a superposed moraine which was in turn superposed. The second highest soil (HV-10499) is currently being re-dated. It may be related, in the manner suggested in Fig.9.5b, to the lowest dated surface (HV-10495). The exact date of the event which buried samples HV-10496-10498 has been questioned earlier. All three samples are from B-horizon material and are presumed to have had relatively high 'mean residence time' at the point of burial. Whether this value could have been as great as 1500-2500 years it is not possible to say, and in the present analysis the c.3400 year event (NZ-5333-5334) is considered to be unrelated to the older episode.

9.4.5 Tasman Valley, Section III

The details of Section III are shown in Figs.9.4,9.6 & 9.7 . In February 1980 three palaeosoils were found exposed in the upper moraine wall about 200m downvalley from Section a)

NOVARA SPUR SITE

TASMAN SECTION IIIa

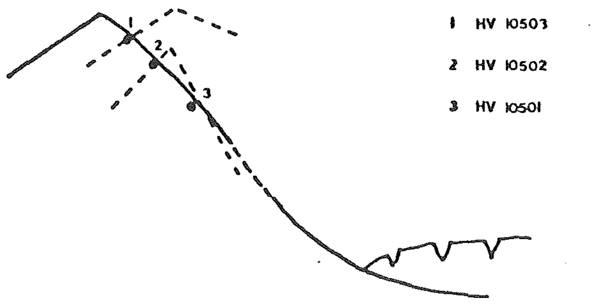


HV 10503; 'A' Horizon 2-5cm thick with large fragments.

HV 10502; 'A' Horizon 5-15cm thick.

HV 10501; 'A' Horizon 5-15cm deep with no large fragments. Soil horizon a continuation of the top of Profile 2.

b)



II. Exposures (HV-10501-10503) were positioned 25, 20 and 15m below the moraine crest. The highest surface (HV-10503) comprised a deep fAh horizon with large wood fragments. The material was dated 1515±275 yr B.P. The second highest soil (HV-10502) comprised organic A-horizon material and was dated 2060±50 yr B.P. The lowest soil (10501) was similarly a fAh horizon aged 2690±275 yr B.P.

When the site was revisited in December 1980 four palaeosoils were sampled, Fig.9.6. The surfaces outcropped at 29,22,17 & 9m below the crest. The youngest surface(wood) (NZ-5330) was dated 343± 56 yr B.P. Downslope two samples were collected from soil (NZ-5254) at 17m and wood (NZ-5331) at 22m. The two were dated 933±58 yr B.P. and 864±58 yr B.P. respectively. The fourth buried surface, 29m below the moraine crest was dated by a large peice of wood (NZ-5332) and was aged 1620±65 yr B.P. The exposure appeared to be related to a distinct yellow boulder line which could be traced for about 150m upvalley, Fig.9.4 .

In November 1981, Dr C.J.Burrows sampled a palaeosoil positioned between NZ-5332 & 5331. The sample is at present undated.

Discussion Figs.9.6b & 9.7b show the sequence of moraine construction at Section III. In Fig.9.7b the highest surface represents the distal slope of a superposed moraine which was buried by superposition of a more recent event c.1500 years B.P. The two lower samples are shown in Fig.9.7b to be related, however there is insufficient evidence to support this interpretation and for the purposes of establishing a radiocarbon chronology of glacial events (cf.9.5) the two dates are used to describe separate phases of glacial expansion around 2500 and 2100 years ago. The chronology at this site was enlarged with evidence for two more recent events c.340 and 900 years B.P. following later visits to the area.

9.4.6 Murchison Valley

Dr F.Röthlisberger has given permission for quotation of results from five palaeosoils found by him in February 1980 in the tributary valleys of the Murchison Valley.

a) Baker Glacier Two palaeosoils were found exposed in the right-hand side moraine of the Baker Glacier. The higher exposure, 20m below the crest, (HV-10505) is dated 1955±75 yr B.P. The sample contained fragments of wood. The lower exposure (HV-10506) is 50m below the crest and wood present in the soil was dated 1680±55yr B.P.

Discussion Dr F.Röthlisberger noted that the two soils were related. The lower surface was the proximal moraine slope corresponding to the higher, distal slope. The original surface was probably overtopped about 1700 yr B.P.

b) Wheeler Glacier One palaeosoil was discovered in the right-hand side moraine of the Wheeler Glacier. The soil, with only a B-horizon, was exposed 30m below the crest. HV-10507 was dated 2815±145 yr B.P.

c) Dixon Glacier Two palaeosoils were sampled from the right-hand side moraine. The higher soil (HV-10509) is 10m below the crest and comprised a fAh horizon which was dated 2090±95 yr B.P. The lower soil(HV-10508)is 50m below the crest and was dated 1535±55 yr B.P.

Discussion The younger surface slumped downslope to a position 40m below the higher surface. The wood sampled from the former surface appeared to have remained intact. The sequence describes two glacier events; c.2150-2000 and 1580-1500 yr B.P.

9.4.7 Godley Valley Buried soil material and wood were sampled from the high lateral moraine beneath Panorama Peak (Fig.9.1I) in November 1981. The material was exposed 2, 8 & 9.5m below the crest . No dates are available for this material at present.

9.5 DISCUSSION

The significance of each date within the vertical chronosequences has been discussed in the above section. The interpretation is based on the dates themselves and information about the site and the position of the material sampled. Some assumptions were made and before proceeding further these will be clarified.

The nature of the organic material is of primary importance when discerning the significance of the result to the overall sequence. A sample containing wood and other relatively short lived plant material is assumed to be more precise than one from a soil which may contain carbon from a long period of accumulation. The 'mean residence time' is less in wood than the underlying soil, and the radiocarbon date minus the approximate age of the wood should give a closer estimate of the actual time of burial (provided the wood has not been contaminated by older or younger carbon). From studies of the surface vegetation development (cf.Table 7.1, p118) it was found that woody species such as *Phyllocladus alpinus* and *Podocarpus nivalis*, for which wood fragments have been found, colonise maturing surfaces aged at least 500 years old. Consequently wood from such plants may be an imprecise age-indicator and the soils on which they are sampled even less so. The variation in radiocarbon dates between wood and soil from the same exposure was clearly demonstrated by HV-10492 & 10493 in Tasman Section I.

Differences in soil development are emphasised when the sample is derived from the B-horizon only (eg. HV-10496-10497 in Tasman Section II) Matthews (1981) has noted the variations in radiocarbon age in a soil with depth down the profile. The measured increase with depth suggests that a considerable amount of caution is required when interpreting material from buried 'B' horizons. The dates obtained from such soil development in Section II (Tasman Valley) are undoubted overestimates of the date of burial during a phase of glacial expansion. It may be desirable, in future, to date both wood and soil from the same exposure.

The height of the buried surface below the crest and/or above the glacier surface is noted to be of little significance. The widespread slumping in all the valleys has lead to the reversal of some sequences and the absence of palaeosurfaces in others.

A useful aid in the interpretation of the sequences is the distinction between proximal and distal slopes. The distinction was made in section 2.4.2 (p.15-18). Soils exposed in the till may show a marked orientation similar to that of the boulders in the till matrix. Where the soil appears to be angled upwards and outwards in the till it often indicates that the soil is from the original distal moraine slope, and vice versa. Inner and outer slopes on present day surfaces frequently showed differences in post-depositional modification and these differences may be detected in some palaeosoil chronosequences (eg. Baker Valley).

Uncertainty and difficulties persist with the accurate calibration of radiocarbon dates and more particularly the correction of radiocarbon dates to solar years, (Süess 1973, Stuiver 1978, Röthlisberger *et al*.1980 and Baillie 1982). Stuiver (1978) showed that because of the fluctuations of the radiocarbon content, a sample with a measured radiocarbon age of 220±50 yr B.P. can be associated with three different periods of calendar years separated by a total of 270 years, (Stuiver 1978, Fig.1 p.272). None of the present results were calibrated with the high precision necessary to reduce this effect. The interpretation of all recent radiocarbon dates (<500 years) are likely to be imprecise for this reason.

The full chronology of radiocarbon dates from the Mt Cook region includes the present results and the work of Burrows (1973a,1980), Burrows & Greenland (1979) and Burrows & Gellatly (1982). Table 9.2 shows the complete distribution of radiocarbon dates from within Mt Cook National Park. The chronosequences from the various sites are compared and a number of distinct pulses of glacial activity can be detected. The radiocarbon chronology for the Mt Cook region is compared with dated sequences in the Rangitata and Rakaia River catchments, and with glacial sequences in Westland National Park, Table 9.2. Finally the Mt Cook data are compared with general Holocene trends in the Southern Hemisphere.

Distinct events are distinguished from the radiocarbon dates of glacial expansion during the last 5000 years. The events occurred approximately 250, 340, 700-800, 1000-1100, 1600-1800, 2100-2200, 2500, 2800, 3400 and 4000-42000 yr B.P. Pre-5000 year events are identified by three dates; a date of 6750±135 for HV-10511 in the Mueller Valley and 7940±70 & 8040±80 yr B.P. for a glacial advance past Mt Sebastopol, (NZ-4508 and HV-10504 respectively).

<u>250 year event</u> The 250 year event is based on a date from the Godley Valley (NZ-5404) 250±55 yr B.P. (Chinn unpubl.) Wood buried in till dates the last major late-Holocene ice advance in the Godley Valley.

340 year event The 340 year event is based on one date from Section III, Tasman Valley; NZ-5330 343±56 yr B.P.

700-800 year event The 700-800 year event is based on three dates; NZ-711 684±48 yr B.P. (a minimal age for a moraine, the surface being buried by an avalanche - Dr.C.J. Burrows pers.comm. 1982), NZ-5253 685±57 yr B.P. Hooker Valley and HV-10500 765±50 yr B.P. Section II,Tasman Valley. Samples NZ-5331 864±58 yr B.P. (Burrows & Gellatly 1982) and NZ-5254 933±58 yr B.P., Section III may be related to this or an earlier period of glacial expansion.

1000-1100 year event The 1000-1100 year event is confirmed by a number of radiocarbon dates; HV-10490 1075±40 yr B.P. Section I, NZ-5329 1130±45 yr B.P. Mueller Valley,and NZ-4403-4405, 4407, 4409 (Burrows 1980).

1600-1800 year event The 1600-1800 year event is based on eight dates; NZ-4406 and NZ-4402 (Burrows 1980), HV-10508 1535±55 yr B.P. Dixon Valley, HV-10506 1680±55 yr B.P. Baker Valley, HV-10510 1905±75 yr B.P. Mueller Valley, HV-10505 1955±40 yr B.P. Baker Valley and NZ-5332 1620±55 yr B.P. (Burrows & Gellatly 1982).

2100-2200 year event The 2100-2200 year event is based on five dates; HV-10502 2106±50 yr B.P. Section III, HV-10509 2090±95 yr B.P. Dixon Valley, HV-10493 2110±45 yr B.P. Section I, HV-10512 2225±310 yr B.P. Hooker Valley and NZ-5335 2280±50 yr B.P. Section I (Burrows & Gellatly 1982).

2500 year event The 2500 year event is based on two dates; HV-10494 2500±55 Section I and HV-10501 2690±275 Section III.

2800 year event The 2800 year event is based on four dates; HV-10492 2765±140 yr B.P. Section I, HV-10507 2815±145 yr B.P. Wheeler Valley, HV-10513 2830±90 yr B.P. Hooker Valley and HV-10491 3180±110 yr B.P. Section I. Samples HV-10513 and 10492 both contained large amounts of wood and are considered the best indicators of the timing of this event.

<u>3400 year event</u> The 3400 year event is based on two dates, both from Section II; NZ-5333 3360±110 yr B.P. and NZ-5334 3450±80 yr B.P.

<u>4000-4200 year event</u> The 4000-4200 year event is based on five dates all from the lower slopes of Section II; HV-10495 4050±80 yr B.P., HV-10499 4125±130 yr B.P. both from fAh horizons, and, HV-10496 4605±365 yr B.P., HV-10497 4780±205 yr B.P. and HV-10498 5690±140 yr B.P. all from fB horizons.

<u>7000 year event</u> The 7000 year event is based on one date from the Mueller Valley; HV-10511 6750±135 yr B.P.

<u>8000 year event</u> The 8000 year event is based on two dates of wood buried in bouldery till at the base of Mt Sebastopol; NZ-4508 7940±70 yr B.P. (Burrows 1980) and HV-10504 8040±70 yr B.P.

Table 9.2 shows the radiocarbon dated glacial record from Mt Cook and valleys elsewhere in the eastern ranges and on the West Coast. The Table documents events during the last 5000 years. The 700-800 year event and the 1700-1800 year event are both represented in the Rangitata and Rakaia Valleys (Burrows 1977, Burrows & Greenland 1979). Burrows & Russell (1975) described a glacial advance to Meins Knob, Rakaia Valley dated 4540±105 yr B.P. (NZ-1287). This event may be related to the glacial expansion around 4000-4200 yr B.P. in the Mt Cook region. Alternatively it may be correlated with an advance of the Franz Josef Glacier in Westland National Park around 4700 yr B.P., (Wardle 1973).

In Westland National Park the Franz Josef, Fox and La Perouse Glaciers all advanced around 100 years B.P. The Horace Walker and Balfour Glaciers were expanded around 1000 yr B.P. and the Franz Josef, La Perouse, Horace Walker and Strauchon Glaciers were all advancing at some point between 1500-1700 yr B.P. There is strong evidence for a glacier advance in the Horace Walker Valley about 2200-2300 yr B.P. and the Franz Josef, Horace Walker and La Perouse Glaciers were expanded around 2500 yr B.P. Further advances from around 2800 yr B.P. are recorded in the Horace

Walker and La Perouse Valleys. Finally there are dates for glacial episodes from around 4000 yr B.P. in the Fox, La Perouse and Horace Walker Valleys. The correlation of glacial activity on both sides of the Main Divide of the Southern Alps is greatly enhanced by an extensive list of unpublished data from recent investigations by Dr F. Röthlisberger, Table 9.2. The general synchroneity of events is very evident.

Early-Holocene radiocarbon evidence of glacial activity in Westland and the eastern ranges is not shown in Table 9.2 . Burrows (1979, 1980) and Burrows & Gellatly (1982) describe those events which occurred between c.12000-5000 yr B.P. which are associated with glacial activity in New Zealand. The most significant date is NZ-4234 11450±200 yr B.P. (Wardle 1978) which dates an advance of the Franz Josef Glacier. The Birch Hill and Sibbalds Island moraines in the Mt Cook region are correlated with this event.

Burrows (1979) described a radiocarbon dated chronology of events related to cool climate phases in the Southern Hemisphere for the period 12 000-1000 yr B,P. There is evidence from a number of localities for colder temperatures and associated events occurring about 115000-9500, 8000, 5400, 4800-4500, 3600, 2700-2200, 1800-1500 and 1100-900 yr B.P. Burrows & Gellatly (1982) describe a series of events for Holocene glacier activity in New Zealand which occurred about 14000-9000, 8000, 4500, 3500, 2300, 1800, 1600, 1000, 860, 660, 530, 340 yr B.P. This sequence differs slightly from observations at Mt Cook where pulses of glacier expansion dated by radiocarbon measurements were as follows; ? 11500, 8000, 7000, 4200-4000, 3400, 2800, 2500, 2200-2100, 1800-1600, 1100-1000, 800-700, 340 and 250 yr B.P.

Burrows (1979) presented evidence from Costin (1972) for unequivocally cool episodes in Australia and Tasmania during the Holocene period. There is a good correlation with the 11500, 3400, 2800, 2200-2100 and 1800-1600 year events at Mt Cook. Bowler *et al.*(1976) presented evidence of a climatic amelioration for Australia and New Guinea between 8000-5000 yr B.P. There is evidence of extensive deglaciation in New Guinea around 11500 yr B.P. (Hope & Peterson 1975, 1976, Bowler *et al.*1976). Burrows (1979) presented the results of work in South America where Mercer

& Palacios (1977) described a glacier advance around 11500 yr B.P. and evidence of glacier recession about 2800 yr B.P. In the Southern Andes, Mercer (1968,1970) provided evidence for glacier recession c.11100 yr B.P. but no evidence of an advance shortly before. Mercer (1968) described major glacial expansion around 4500 yr B.P. and Mercer (1970) noted the presence of additional glacial activity c.3400, 2800, 2300, 1600 and 1400 yr B.P.

Burrows (1979) remarked that there is no evidence, as yet, for cooling around 4500 yr B.P. in the Australian mountains. In East Africa, Coetzee (1967) identified a decline in humid forest growth on the lower slopes of Mt Kenya (interpreted as a cooling) c.4600 yr B.P. A later decline in vegetation was recorded about 3300 yr B.P.

Ancillary evidence of climatic events from Antarctica indicated three periods of cooling around 11500-9500, 6000-3000 and 1800-200 yr B.P. (Burrows 1979). Burrows (*loc.cit.*) noted that the 1000 year event, otherwise recorded for New Zealand alone, features in the Antarctic chronology. Clapperton *et al.*(1978) examined glacial activity in South Georgia and concluded that if glacier advances had occurred during the period 5000-1000 yr B.P. then they must have been less extensive than advances in the 17th and 19th centuries (300 and 100 yr B.P.).

The radiocarbon chronology of glacial events in the Mt Cook region is generally well supported with other chronologies from elsewhere in New Zealand and in the Southern Hemisphere. There is a marked synchroneity of events and this reinforces the results presented here. In the following section the radiocarbon chronology is compared with the glacial moraine chronology based on weathering rind analysis, historical dating , lichenometry, vegetation and soil development in the Mt Cook region.

SECTION III

The need to be right all the time is the biggest bar there is to new ideas. It is better to have enough ideas for some of them to be wrong than to be always right by having no ideas at all.

Edward de Bono

CHAPTER 10

SYNTHESIS

> *Pity me, Be like a painter, Stand back, see me in perspective, see me whole.* *Euripedes* (Hecuba)

The evidence presented in Section II for variations in surface age within the moraine sequence in Mt Cook National Park is now subdivided into 'primary' and 'secondary' source information. Rock weathering rind analysis is considered with radiocarbon measurements and historical dating as the 'primary' dating methods. Together the three approaches provide a complete framework of dates. Rock weathering rinds strictly speaking are a secondary source, being age-dependent. However, following the work of Chinn (1981), the calibrated rind measurements are used for determining the rate of development of other relative-dating criteria and, as such, are elevated to the status of 'primary' dating techniques.

In this chapter information for dating the glacial moraine chronology is combined, Table 10.1, and the various uses and limitations of the techniques used are summarised.

10.1 PRIMARY SOURCES

Events occurring during the last 120 years are described solely by historical sources. The glaciers were furthest advanced by the beginning of this period, in 1862 A.D. The pattern of glacier recession has not been entirely synchronous and the magnitude of glacier retreat and ice downwastage has been extremely variable throughout the Mt Cook region. General glacial recession took place between c.1862-1885 A.D. This was followed by a cooler period during which ice bridges formed over the Hooker River at the Mueller Glacier terminus and the Ball, Baker and Dixon glaciers advanced (cf.4.4, p.52; 4.5, p.57; 4.7, p.59). A widespread and prolonged glacial stillstand occurred during the first forty years of the present century and was followed by an equally ubiquitous recessional phase that continues to the present day.

The rock weathering rind measurements (chapter 5) define a series of depositional events around the glacier termini. The measurements are derived from a continuous series. Each estimate is based on modal rind width values. The moraine surfaces are dated about <100, 135, 340, 580, 840, 1150, 1490, 1830, 2160, 2540, 2940, 3350, 3790, 4200 and 7250 years. The complete sequence is described from the Mueller Valley.

Radiocarbon dates describe a series of glacial expansions within the Mt Cook region which took place about 250, 340, 700-800, 1000-1100, 1600-1800, 2100-2200, 2500, 2800, 3400, 4000-4200, 6750 and 8000 yr B.P.

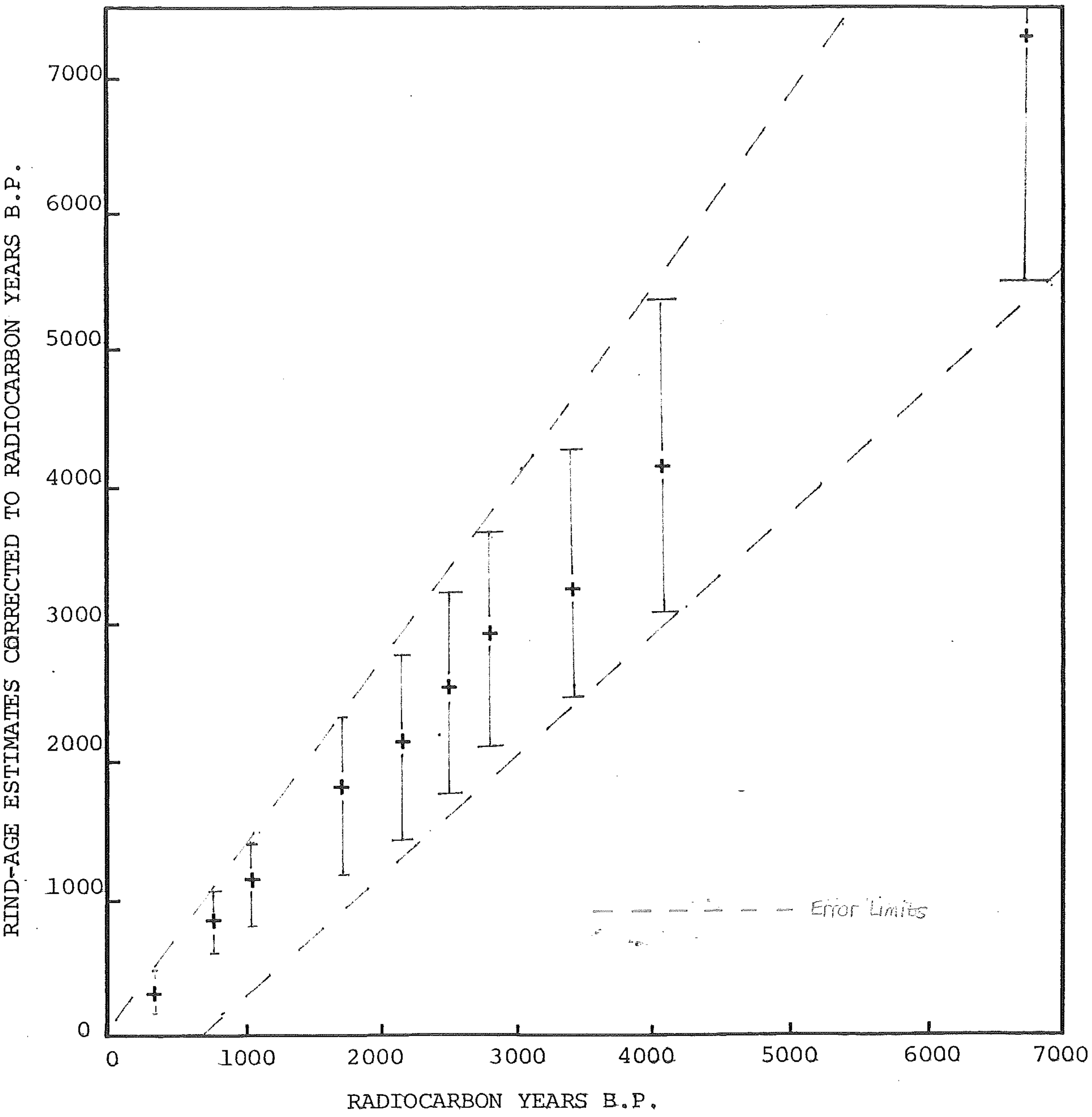
The weathering rind chronology correlates strongly with the radiocarbon chronology, $r=0.99$ ($p<0.001$) (Fig.10.1) implying good concordance between the two independent chronologies. In both chronologies glacial events are defined for periods around 340, 700-800, 1000-1100, 1800, 2100, 2500, 2800, 3400, 4200 and 7000 years B.P.

10.2 SECONDARY SOURCES

The vegetation data for the Hooker and Classen Valleys are rather variable but nevertheless a number of general conclusions about the trend and rate of plant succession are made. Recently deglaciated surfaces, providing that they are fine-textured, are colonised by small herbs and low, widely spaced shrubs. An incompletely closed plant cover characterises the surfaces over the next 800 years during which time there is an increase in species diversity and a transition from the open herb field to shrubland and grassland. The closed plant cover which is widespread on moraines after about 1000 years of development, leads to species rich shrubland and scrub. Tall scrub develops on the oldest surfaces examined, c.4000 year, (cf.7.6, p.123)

The soil chronosequence is similarly quite complex. The rate of devlopment of various weathering and soil parameters vary over time. Levels of organic matter and soil pH in the surface A-horizon reach a steady state within about 100 years (cf.6.4.2, p.94). The organic horizon continues to increase slowly. The B-horizon properties

Figure 10.1 The relation between radiocarbon-dated chronology and weathering rind thickness chronology, 0-7000 yr. in the Mt Cook region.



form rather more slowly and values of % phosphate retention in the subsurface horizons are taken as an indication of soil development change throughout the Holocene period in the Mt Cook region (cf. Fig.6.2, p.98), Table 10.1. Percentage phosphate retention values from the subsurface horizons were strongly correlated with surface age, $r=0.97$ ($p<0.001$). The addition of loess is a major factor accounting for the variability in soil profile morphology and chemical change over time (cf.Fig.6.1, p.84). Soil cover on the recently deglaciated surfaces show no evidence of pedogenesis apart from surface weathering of the small clasts. The soils are merely disorganised accumulations of moraine debris whose significant properties show no regular variation with depth. Soil development on the most recently deposited surfaces is described by Birkeland (1981) (cf.Table 10.1). Weathering of the soil parent material and the addition of loess both help to build up the B-horizon in high country yellow-brown earths and this is very noticeable on the c.1000 year old surfaces. No soils were examined on the 2000-3000 year old moraines. Loess deposition was very evident on the 3400-4200 year old surfaces in the Classen Valley, whilst in the Mueller Valley equivalent aged soils showed evidence of podzolisation . Podzols had developed on both the 7200 and 8000 year surfaces, Table 10.1 .

The lichen measurements are described for the last 1000 years and show a curvi-linear relationship with time (cf.Fig.8.4, p.135). The lichen, soil and vegetation data indicate the consistency of weathering rind age-estimates at the intra- and inter-valley level.

Table 10.1 A summary of results obtained from the multi-parameter dating methods

Surface age yr.	Historical sources	C14 dating yr B.P.	Weathering rind thickness,yr.& mm	Vegetation development	Soil development	Lichen Dating yr. & mm.
0-120	1862-1885 gl. recession. 1888-1900 gl. advance. 1900-1940 gl. stillstand. 1940→ gl. recession.	-	-	Bare ground with a few early colonising species eg.*Epilobium* spp.*Raoulia* spp.,*Blechnum penna-marina* & *Racomitrium lanuginosum*.	Recent soil. AC-horizon with parent material dominating the textural and structural characteristics.	60 /19.0 90 /26.9 100 /33.2,34.1
120-1500	-	-	135/ 0.25	Incompletely closed plant cover	AC profile.Subsurface P.ret. =4%,Surface pH(H_2O)=5.3	135 /48.0,51.0
		250	-	-	-	-
		340	340/ 0.5	Shrubland on moraine	ACn profile(Birkeland 1981)	340 /68.0,84.0
		-	580/ 0.75	Shrubland on moraine	A,Cox,Cn profile(Birkeland)	580 /71.0
		700-800	840/ 1.0	Closed plant cover & *Poa-Cassinia* grassland	-	840 /94.0
		1000-1100	1150/ 1.25	*Chionochloa flavescens* grassland	Distinct soil horizonation with A,Bg or E,B,BC & Cox. P. ret.=19-21%,surface pH(H_2O)= 5.2	1000 /52.0,104.0 122.0
		-	1490/ 1.5	-	-	-
1500-2000	-	1600-1800	1830/ 1.75	*Chionochloa flavescens* shrubland with degraded *Festuca* short tussock	Friable,poorly aggregated peds A^O,Er.B,BC & Cox horizons.Subsurface P.ret.=47%,surface pH (H_2O)=5.3	-
2000-3000	-	2100-2200	2160/ 2,0	Subalpine short scrub & seral medium-height scrub	-	-
		2500	2540/ 2.25	Shrubland on moraine, *Celmisia walkeri* shrubland & *Chionochloa flavescens* seral shrubland	-	-

continued overleaf...

Table 10.1 cont.

Surface age yr.	Historical sources	C14 dating yr B.P.	Weathering rind thickness, yr. & mm	Vegetation development	Soil development	Lichen dating yr. & mm.
2000-3000	-	2800	2940/ 2.5	Subalpine medium-height scrub	-	-
3000-4500	-	3400	3350/ 2.75	Subalpine scrub with *Olearia* sp., *Hoheria lyallii, Gaultheria crassa* & *Dracophyllum*	Loess A horizon, E or Br subsurface horizon, subsurface P.ret.=50-60% surface pH (H_2O)=5.0	-
		-	3790/ 3.0	-	Well aggregated, A, Br, Box. Subsurface P.ret.=56% surface pH (H_2O)=5.6	-
		4000-4200	4200/ 3.75	Tall scrub dominated by *Cassinia* sp., *Senecio* sp., & *Dracophyllum* spp.	Slightly podsolised sandy loam. Subsurface P.ret.=72 Surface pH (H_2O)=5.1	-
7000	-	6750	7250/ 5.0	Surface extensively burnt, once supported *Podocarpus* sp., *Phyllocladus alpinus*. Now supports *Dacrydium bidwilli, Hoheria lyallii* etc.	Podzol. Subsurface P.ret.= 68-69%, surface pH (H_2O)=4.6.	-
8000	-	8000	-	Surface extensively burnt, once supported Beech forest today dominated by various grassland communities and tall scrub.	Podzol. Subsurface P.ret.= 86-94%, surface pH (H_2O)=5.1 Buried charcoal layer Obh.	-

A dash (-) means that no data were collected, or in the case of historical sources, were not available.

10.3 USES AND LIMITATIONS OF THE DATING METHODS

10.3.1 Primary methods

A-Historical dating The historical records define the glacier oscillations since 1862 A.D. The data presented are considered to be accurate to <±5 yr. The only limitation is the availability of records.

B-Radiocarbon dating Radiocarbon dating is used to define periods of glacial expansion between 250-8000 yr B.P. in the Mt Cook region. The radiocarbon record of glacial events covers the whole of the Holocene period at sites elsewhere in the Southern Alps. The problems associated with dating are discussed in Chapter 3,p.36, Chapter 9,p.144 & 163-165 and in Appendix B. The radiocarbon dates are normally given to within one standard deviation. The amount of error varies with sample amount, sample age, contamination and other variables noted in Appendix B. Reliable dates are usually assumed to be obtained from small twigs and/or wood, or thin, organic-rich A soil horizons. The least reliable dates are obtained from deep, organic-poor buried B soil horizons. The radiocarbon-dated chronology concords extremely closely with the rind thickness chronology from the Mt Cook region. An example is given in 11.2.5 (p.188) of an area in the Southern Alps where the two chronologies are in conflict.

C-Weathering rind analysis Modal rock weathering rind analyses are used to date the terminal and latero-terminal moraine surfaces throughout Mt Cook National Park. Measurements are accurate to ±26% (Chinn 1981). The modal values are less variable than the mean (cf. Table 5.2, p.77). The rind thickness versus time curve is the best approximation of the age information available in rock weathering studies. Chinn (*op.cit.*) presented it as a model to be evaluated, refined or rejected as more information on numerical ages and rates of weathering were obtained. Its use is restricted, with the presently available calibration curve, to surfaces aged c.130-7000 years. Additional investigations of post-depositional surface weathering indicate that the rock weathering rind measurements are consistent over a wide area.

10.3.2 Secondary methods

A- Vegetation development The vegetation development data indicate general trends in plant succession which agree with the other patterns of surface ageing of the moraines. As a surface age indicator it was considered to be too unreliable to function independently. Chance and environmental factors exert too great a control on the resulting patterns of colonisation and diversification.

B-Soil development The soil development patterns are examined as part of a chronosequence. The study indicates that values of surface pH and percent weight of organic matter in the A soil horizon are useful for distinguishing changes in recent, deglaciated surfaces. Percentage phosphate retention is most indicative of change in the soil system during the Holocene period. The general pattern of soil development was the same throughout the region with local variations such as the effect of increased loess input in the Classen Valley. Analysis of the soil samples is incomplete and the inability to collect volume weight samples from all horizons at all sites reduced the interpretation of some parameters.

C-Lichen dating Lichen growth rates are presented from three valleys and calibrated separately. The resulting curves are very similar and confirm the consistency of rock weathering rind age-estimates on surfaces less than 1000 years old. The measurements from older surfaces are restricted due to the fragmentation of the thalli and the increase in senescence of thalli on the older surfaces.

CHAPTER 11

DISCUSSION

The magnitude of surface-age differences within the glacial moraine chronology of the Mt Cook region is far greater than earlier work had suggested (Burrows 1973a, 1979, 1980, Burrows & Orwin 1971). The accuracy of the lichen growth curve, on which the earlier estimates were based, has been questioned (Burrows 1980, Birkeland 1981, 1982). Gellatly (1982) described a revised lichen growth curve for the period 0-1000 years which was calibrated against surface age-estimates derived from studies of rind thickness and historical information. Details of the growth curve are presented in Fig.8.4 (p.135).

Results from the present study have forced the author to the conclusion that lichenometry is a relatively ineffective dating tool. The emphasis is placed in this study instead on weathering rind thicknesses and radiocarbon dating. The former is generally available on all surfaces between the age of 130-c.7000 years. Weathering rind thicknesses are probably at least as good as any other age criterion able to be used to date the Holocene deposits. Thirty unpublished radiocarbon dates are described in relation to the Holocene glacial chronology in the Mt Cook region.

In this discussion the Holocene glacial record for the Mt Cook region is summarised looking at three main points:

i - Firstly, the results are examined for evidence of a major period of glacial renewal during the last 500 years which might be correlated with the "Little Ice Age" events in the Northern Hemisphere.

ii - Secondly, the Mt Cook glacial moraine chronology is compared with other Holocene moraine sequences in the Southern Alps of New Zealand which have been described by similar dating techniques.

iii - Thirdly, those deposits which can be consistently recognised and distinguished from other deposits both in the field and as a result of laboratory analysis will be formally named using where possible existing terminology from the Mt Cook region.

11.1 THE 'LITTLE ICE AGE' CONCEPT IN RELATION TO HOLOCENE GLACIER ACTIVITY IN THE MT COOK REGION

According to Grove (1980) the term 'Little Ice Age' was introduced by Matthes who suggested that:

> "...the glacial oscillations of the last few centuries have been amongst the greatest that have occurred during the last 4000 year period" (Matthes 1939,p.520).

These oscillations mark the culminating of the 'Little Ice Age' (Matthew 1941). As a compromise, conforming to the most common usage, Sugden & John (1977) define the 'Little Ice Age' as covering approximately four centuries between 1500-1920 A.D. There is conflicting evidence in the literature to suggest that the climatic cooling and its associated renewed glacier activity began up to two centuries earlier and perhaps extended beyond 1920 A.D. (Denton & Karlèn 1973b, Miller 1969, Theakstone 1965).[1]

Table 11.1 summarises the depositional events in all six main valleys in Mt Cook National Park relating to glacier activity between 0-7000 years. The inferred surface ages are from weathering rind analysis. The two oldest Holocene glacial events recorded at Mt Sebastopol and Birch Hill are omitted because no weathering rind data was obtained from the sites examined. In Table 11.1 an attempt has been made to describe the deposits as 'major' or minor' events according to their present day extent and relative size. The classification is subjective but takes account of the amplitude of each glacial expansion phase according to:

- i - differences in valley size and the expected variations in the extent and volume of deposits of equivalent age,
- ii - preservation factors and the likelihood of erosion, burial or other factors which may have severely modified the moraine following deposition.

---

[1] Sugden and John noted however that:
"It is now becoming clear that the Little Ice Age was not the culmination of the Holocene climatic cooling at all, but simply one of several major glacial phases which have punctuated the period since the last main glaciation....Collectively, some of these phases are referred to as the Neoglacial (Porter & Denton, Denton & Porter 1970) " (Sugden & John 1977, p.120).

Table 11.1 The glacial deposits of Mt Cook National Park. A classification of the intensity of glacial activity between 0-7200 years.

AGE YR B.P.	M	H	T	MU	G	C
<100	△ □	△ □	△ □	△ □	▲ ■	△ □
135	△ □	△ □	▲ ■	▲ □	▲ □	▲ ■
340	▲ □	△ □	▲ □	▲ □		▲ □
580	△ □	▲ ■	▲ □		▲ ■	▲ ■
840	△ □	△ □	△ □			▲ ■
1150	▲ ■	△ □	▲ ■			
1490	▲ ■	▲ □	▲ □			
1830	▲ □	▲ ■				
2160	△ □	▲ ■	△ □			
2540	▲ ■	▲ ■				
2940	▲ ■	△ □				
3350	▲ ■	▲ ■				▲ ■
3790	△ □	△ □	△ □			
4200	△ ■	△ ■				▲ ■
7200	▲ ■					

▲	Major depositional event within the valley.
△	Minor depositional event within the valley.
■	Major depositional event within the Mt Cook area.
□	Minor depositional event within the Mt Cook area.

M	Mueller Valley
H	Hooker Valley
T	Tasman Valley
MU	Murchison Valley
G	Godley Valley
C	Classen Valley

In this way, a deposit may be considered to be 'relatively minor' (with regard to size and/or extent) compared to other deposits of different age in the valley, but, when considered within the context of all the moraine of that age in the Mt Cook region, it may be rated as of considerable significance and be therefore rated as a 'major'event. For example, the 4200 year event in the Classen Valley is well preserved and is rated a major event both within the valley itself, and in the context of the Holocene glacial chronology overall. The same event in the Mueller and Hooker Valleys is poorly preserved and the two respective moraines are of no major ranking as deposits within each valley. However, the mere fact that they have survived and persist in the glacier moraine record warrants their unusual 'split classification' Table 11.1 . More usually, the deposits are important both on a local scale and regionally and vice versa. It is immediately apparent that not all glacial events were of equal importance in all the valleys and the pattern of glacial deposition is described for each glacier in turn:

11.1.1 Mueller Glacier

Recent glacial deposition (1000-0years) at the Mueller Glacier terminus is considered to be comparatively minor in extent in relation to moraine deposition around 7200, 3350, 2940, 2540, 1830, 1490 and 1150 years ago. These earlier events led to the formation of Foliage Hill, White Horse Hill, Kea Point and the Northern moraine the amplitude of which have no counterpart in the more recent glacial history. The 7200, 4200, 3350, 2940, 2540, 1490 and 1150 year events are all considered to be important 'reference' deposits for glacial expansion at these times. With the exception of the 340 year event there is no compelling evidence for a notable glacial expansion during the last 400 years and it is clear that the last major advance occurred over 1000 years ago.

11.1.2 Hooker Glacier

The more prominent depositional events in the Hooker Valley are dated from around 3350, 2540, 2160, 1830, 1490 and 580 years. The older events are represented by high, continuous lateral moraines whilst the 1830, 1490 and 580 year events are all terminal moraine deposits. The 3350, 2540, 2160, 1830 and 580 year old deposits are all 'reference' deposits for glacial expansion in the Mt Cook

National Park at these times, Table 11.1 . Glacial expansion around 580 years ago did not equal earlier ice limits.

11.1.3 Tasman Glacier Two 'reference' moraine deposits are recorded in the Tasman Valley and these define the 1150 and 135 year events. In addition, depositional events of local importance occurred c.1490, 580 and 340 years ago. The most recent glacier advance resulted in extensive deposition and overlapping of the existing moraine deposits, however the glacier did not extend as far downvalley as the earlier major advance c.1150 year. There is no disputing the evidence for a marked glacial advance in the last 400 years of considerable importance in the Tasman Valley.

11.1.4 Murchison Glacier Few references have been made to the Murchison Valley in this study due to the paucity of the glacial deposition record. Locally, two events were significant (340 & 135 year events) however neither set of moraines arising from these events has survived to any great extent and the events are more marked in other valleys.

11.1.5 Godley Glacier Recent deglaciation is very evident in the Godley Valley. Glacial deposition during the last 100 years is most clearly shown in this area, Table 11.1. A prominent trim line dating from c.580 years ago indicates the ice limits in recent years.

11.1.6 Classen Glacier The moraines of the Classen Glacier are all prominent with the exception of deposits formed this century. There is strong evidence for a glacial advance which culminated c.1862 A.D. On this occasion the glacier extended almost as far downvalley as the earlier advances 4200,3350 and c.840 years ago. A glacier advance c.580 years ago expanded laterally, breaching the existing moraine barrier. The two oldest moraines, 4200 and 3350 yr., formed at the same time as the 'car park' moraine and the lower slopes of White Horse Hill in the Mueller Valley. Glacier fluctuations in the last 3000 years have not exceeded the ice limits around 4000 years ago.

Summary

There is conclusive evidence in only three of the six main valleys,in the Mt Cook region,for major glacial activity in the last 500 years and in only one of those valleys has the glacier exceeded the maximum ice limits established in the mid-Holocene period c.5000-1000 years ago. In the three western valleys (Mueller, Hooker and Tasman) the major Holocene glacial events took place c.7200, 4200, 3400, 2940, 2540, 2160, 1830 and 1500-1100 years ago. Both the 4200 and 3400 year events were prominent in the Classen Valley further east.

The supposed 'Little Ice Age' glacier oscillations are marked more by the spectacular glacier retreat in recent decades than by major glacier advances during the last 400 years. The glaciers were further forward between 1500-1100 years ago and the results from this study do not support the assertion that:

> "...the glacial oscillations of the last few centuries have been amongst the greatest that have occurred during the last 4000 year period" (Matthes 1939,p.520).

11.2 NEW ZEALAND HOLOCENE GLACIER RECORD

The Holocene glacier record for the South Island of New Zealand is summarised by Chinn (1975), Burrows (1979), Burrows & Gellatly (1982) and Birkeland (1982). Early attempts to describe the glacial history in areas other than Mt Cook include the Ben Ohau Range (McGregor 1967), the Cameron Valley (Burrows 1975), the Rakaia Valley (Burrows & Maunder 1975, Burrows & Russell 1975), the Rangitata Valley (Burrows 1877, Burrows & Greenland 1979) the Waimakariri Valley (Chinn 1975, 1981) and Westland National Park (Wardle 1973, 1978).

A complex series of glacial deposits have been described by each worker in the different catchments and ranges. McGregor (1967) recognised four glacier advances in the Ben Ohau Range which he named Dun Fiunary (youngest),Jacks Stream, Ferintosh and Birch Hill (oldest). The relative ages of these advances were assessed using imprecise dating methods. Burrows (1975) recognised four moraine sets in the Cameron Valley. These he named the Arrowsmith (c.240-600 yr B.P.), Marquee (2000-4200 yr B.P.), Lochaber (older than Marquee) and Wildman (Birch Hill equivalent). Burrows & Maunder (1975) and Burrows & Russell (1975) described seven glacier advances in the Rakaia Valley using radiocarbon dating for the oldest deposits and lichenometric dating for the youngest. The advances were as follows: Whitcombe (0-400 yr B.P.), Lyell (<1000 yr, later correlated with the c.1700 yr event in the Rangitata, Burrows 1977), Meins Knob[1] (NZ-1287 4540±105 yr B.P.), Reischek (equivalent to Lochaber), Jagged Stream and Lake Stream (10 000-12 000 yr B.P.) and Acheron (equivalent to Lake Heron advance c.11 900 yr B.P.). Burrows (1977) described two radiocarbon dates for glacial advances in the Rangitata Valley from around 1700 yr B.P. and Burrows & Greenland (1979) reported two radiocarbon dates describing glacial activity approx. 650yr B.P., also in the Rangitata Valley. Chinn (1975,1981) recognised four Holocene glacier advances in the Waimakariri catchment using weathering rind analysis; Barker (0-430 yr B.P.), O'Malley (1000-2500 yr B.P.), Arthur's Pass (c.4000 yr B.P.) and McGrath (8000-10 000 yr B.P.). The Westland glaciers are described by Wardle (1973, 1978). Recent additions to the radiocarbon dated chronology on the West Coast have been made by Röthlisberger (unpubl.)

More recent work by Birkeland (1982), Burrows & Gellatly (1982), Gellatly (this study) and Röthlisberger (unpubl.) suggests possible additions and corrections to these glacial chronologies. The results of these investigations are shown in Table 11.2. and are summarised below.

11.2.1 Ben Ohau Range

Birkeland (1982) recognised a fifth glacier advance in the Ben Ohau Range which he named Whale Stream. Birkeland (*op.cit.*) dated the Ben Ohau deposits using weathering rind analysis and other RD methods and his results are as follows; Dun Fiunary c.100 year, Whale Stream c.250 year,Jacks Stream c.3000 year, Ferintosh c.4000 year and Birch Hill c.9000 year.

11.2.2 Rakaia Valley

Birkeland (1982) re-examined the glacier deposits described by Burrows & Maunder (1975) and Burrows & Russell (1975) in the Rakaia Valley and noted some discrepancy between the lichenometric dating and weathering rind measurements. Some of the error he attributed to his measuring technique. The youngest Whitcombe moraines he correlated with the two youngest advances in the Ben Ohau Range; Dun Fiunary and Whale Stream. Weathering rind data for the

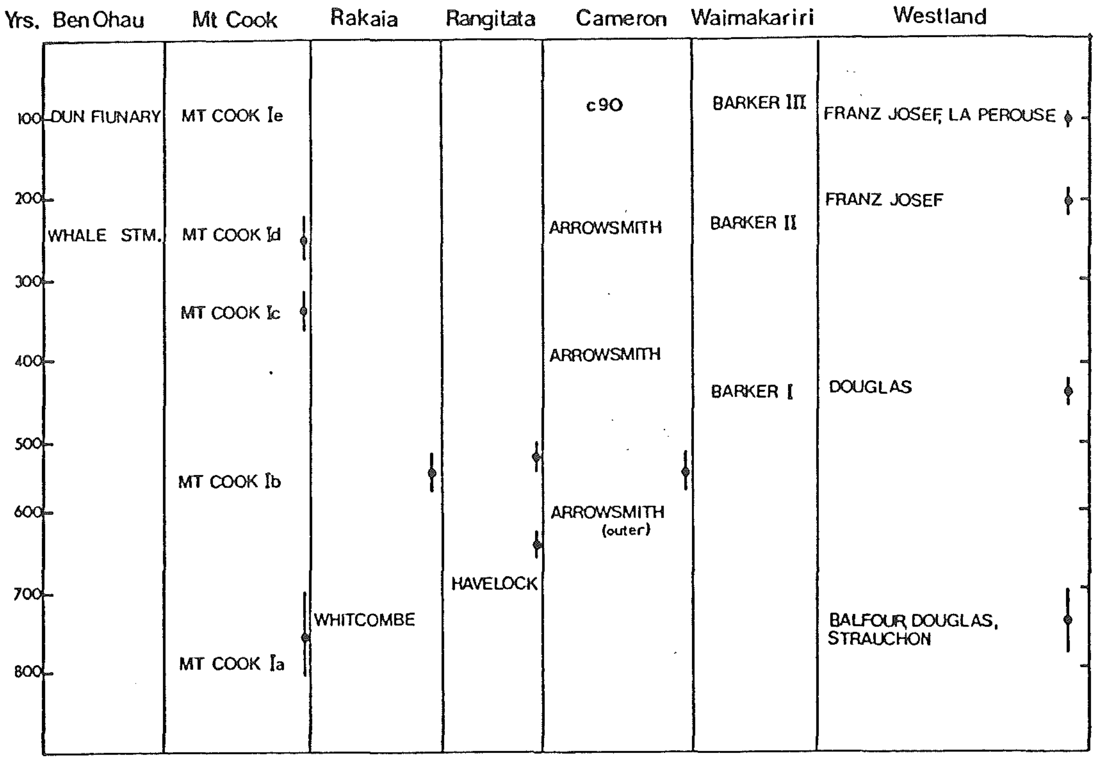
---

[1] This is the 'type' Meins Knob deposit not to be confused with a radiocarbon date from material on the topographic ridge by that name.

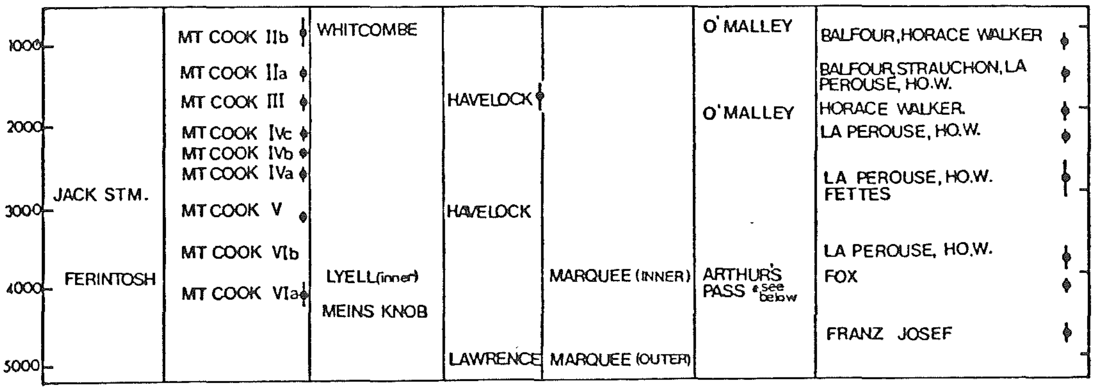
Table 11.2

Holocene glacial chronology for Southern Alps, New Zealand.

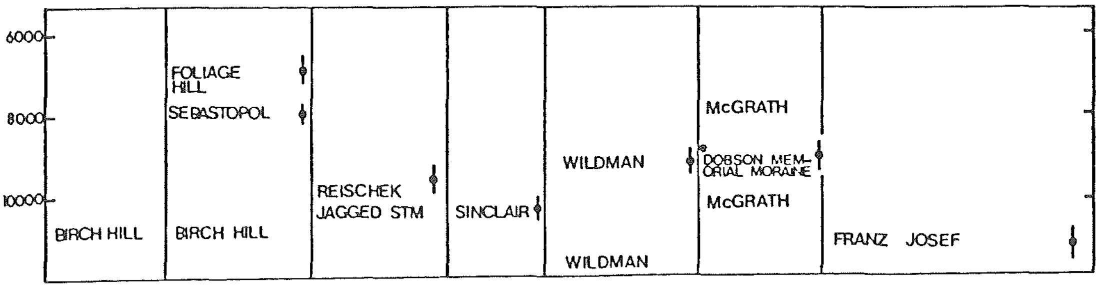
LATE-HOLOCENE



MID-HOLOCENE



EARLY-HOLOCENE



17th century moraine (Burrows & Maunder 1975) yielded an age-estimate of c.1000 years. Birkeland (1982) recorded a weathering rind age of c.4000 years for an inner Lyell moraine. He correlated this deposit with the Ferintosh advance, Ben Ohau Range. Till deposits on top of Meins Knob date from an earlier advance as was demonstrated by Birkeland (1982) and Burrows (1979). Weathering rind measurements could not distinguish between the early-Holocene glacial deposits. Birkeland (1982) suggested grouping the Meins Knob(summit deposits), Reischek, Jagged Stream and Lake Stream advances together and correlated the advances with the Birch Hill II advance in the Mt Cook region (McGregor 1967). Burrows suggests grouping the Meins Knob (summit deposit) and Reischek deposits together and notes that the Jagged Stream deposits are older (Dr C.J.Burrows, pers.comm.1982).

11.2.3 Rangitata Valley

Radiocarbon dated glacial events in the Rangitata Valley are documented for c.550, 680 and 1700 yr B.P. by Burrows (1977) and Burrows & Greenland (1979). Additional advances are reported using weathering rind measurements (Gellatly unpubl.) for approx. 700, 3000 and 5000 years. The 700 and 3000 year old deposits are from the Havelock Valley and St Winifreds Stream respectively and the 5000 year deposit from Hell's Gates, Lawrence Valley.

11.2.4 Cameron Valley

Birkeland (1982) re-examined the moraines in the Cameron Valley. He obtained surface dates younger than those described by Burrows (1975) for the Arrowsmith moraines but older than those described by Burrows (*loc.cit.*) for the Marquee deposits. The Marquee set were redated 4000-5200 years old indicating that the event was shorter than had previously been suggested (Burrows *loc.cit.*). Birkeland (*loc.cit.*) found insufficient evidence to support the existence of a separate Lochaber advance. He obtained results for weathering rind analysis on the Wildman moraines similar to those described by Chinn (1975) and suggested that the Wildman advance is equivalent to the Birch Hill II advance in the Ben Ohau and Mt Cook region. He concluded that most of the Cameron valley deposits had correlatives in the Ben Ohau Range.

11.2.5 Waimakariri Valley

Birkeland (1982) correlates the four glacier advances described by Chinn (1975,1981) with similar events elsewhere in the Southern Alps. The Barker III advance is considered to be equivalent to Dun Fiunary,Ben Ohau Range and to glacier advances in Westland National Park, the Cameron Valley and the Mt Cook region. The Barker II advance correlates with Whale Stream and events in Westland and Mt Cook. Barker I is approximately equivalent to the Arrowsmith advance in the Cameron Valley and correlates with an advance in Westland, Table 11.2.The O'Malley advance is equivalent to glacier advances in Westland, Mt Cook, the Rakaia and Rangitata Valleys.

The Arthur's Pass advance (c.4000 years) (Chinn 1975, 1981) is enigmatic (Burrows *et al*.1976, Burrows & Gellatly 1982, Birkeland 1982). A radiocarbon date (Birm-523) 8960±140 yr B.P. has been reported (Burrows *et al*.1976) from a bog to the inside of the Arthur's Pass moraine. However, Chinn(1975) has used rind data to argue that the till is younger than the radiocarbon date. Birkeland (1982) accepts Chinn's explanation of the apparent difference in the dating of the advance (Chinn 1975). Burrows (pers.comm., 1981) argued that the radiocarbon evidence for a greater than 9000 year age for the Arthur's Pass moraine is very strong. However Chinn (pers.comm. 1982) suggests that incomplete interpretation of the stratigraphic relationship between the radiocarbon date and the till has produced unnecessary conflict over the accuracy of the rind data and radiocarbon age. Rind data at the site is consistent and as yet there is only one radiocarbon date from the site. The status of this type area for the Arthur's Pass advance remains unresolved, Table 11.2. Recent work based on radiocarbon and weathering rind chronologies has demonstrated the widespread nature of glacial activity around 4000 years ago in the Southern Alps,Table 11.2.

The oldest Holocene glacial advance in the Waimakariri Valley is the McGrath event, c.8300-10 000 yr B.P. (NB. The dating of this event is affected if the Arthur's Pass advance is shown to be c.9000 years old). The McGrath advance is correlated with the Wildman advance (Cameron Valley) and Birch Hill II (Ben Ohau and Mt Cook).

11.2.6 Westland National Park

A series of glacier advances are recorded by radiocarbon dating in Westland National Park (Wardle 1973,1978, Rőthlisberger unpubl.) and these are indicated in Table 11.2. The relation of the radiocarbon dated chronology with glacial events east of the Main Divide was discussed in section 9.5 (p.168-169).

11.2.7 Mt Cook National Park

The Mt Cook glacier record is the most detailed in any region in the Southern Alps of New Zealand, Table 11.2. The moraines are dated according to the methods described in this study and the glacial events are grouped according to geomorphic criteria and radiocarbon dating (section 9.5, p.163-168). During the late-Holocene period six separate phases of glacial expansion took place in one or all of the valleys in the Mt Cook region. The two most recent events, c.<100 & 135 year correlate with glacier advances in the Ben Ohau Range (Dun Fiunary), in the Cameron, Waimakariri and Westland Valleys. The 'reference' deposits for these two advances are in the Godley, Tasman and Classen Valleys, (cf. Table 11.1). The 250 year event is recorded by a radiocarbon date and has equivalents in the Cameron, Waimakariri, Ben Ohau and Westland regions. The 340 yr event is recorded in five of the valleys in the Mt Cook region yet has no known equivalents elsewhere in the Southern Alps. The 580 year advance is matched by glacial expansion in the Rakaia, Rangitata and Cameron Valleys. The earliest, late-Holocene, event occurred about 800 years ago and is loosely correlated with advances in Westland and the Rakaia Valley, Table 11.2.

The glacial record for the mid-Holocene period at Mt Cook is closely paralleled by glacier activity in Westland National Park. Glacial expansion around 1500-1100 years ago is correlated with glacial activity in the Rakaia, Waimakariri and Westland regions. The'reference' deposits for this period of glacial activity include the main crest of White Horse Hill(Mueller Valley) and outer moraines at the Blue Lakes (Tasman Valley). The 1830 year advance is matched by glacier advances in the Rangitata and Waimakariri Valleys and in Westland. The three events recorded between 3000-2000 are correlated with glacial activity elsewhere in the Southern Alps, Table 11.2 as are the 3400 and 4200-

4000 year events. The latter event has correlatives in the Ben Ohau Range, the Rakaia, Cameron and Waimakariri Valleys and in Westland National Park.

The early-Holocene advances at Mt Cook are specified by three sets of deposits; Foliage Hill (c.7000 yr), Sebastopol (c.8000 yr) and Birch Hill (c.11 000-9000 yr). The 8000 year Sebastopol advance is correlated with McGrath I (Waimakariri Valley). The Birch Hill deposits are correlated with Canavans Knob, Waiho Loop, Westland NZ-4234 11450±200 Wardle (1978).

11.3 STRATIGRAPHIC NOMENCLATURE OF HOLOCENE GLACIAL DEPOSITS

Birkeland *et al.* (1979) discussed the problems of classification, naming and correlation of glacier deposits. They noted that the:

> "...correlations are inferences, and sound inferences need to be founded on objective observations" (Birkeland *et al.* 1979, p.532).

Because of the general paucity of numerical age-determinations such as radiocarbon and historical dating, surface dating of glacial deposits is achieved through the use of relative dating methods. In New Zealand, in the areas of Torlesse sandstone rocks, the most widespread method of relative dating developed recently is rock weathering rind analysis. Deposits have been examined in all the major catchments east of the Main Divide between Mt Cook and Arthur's Pass using weathering rind thickness measurements. Supporting the weathering rind chronologies to some extent are studies of soil development, lichen growth and plant succession although widespread burning has restricted the usage of plant development for ageing surfaces in the eastern ranges. In Westland the glacier record is dated by radiocarbon measurements (Wardle 1973,1978, Röthlisberger unpubl.). The post-depositional surface modifications vary substantially in Westland from rates and patterns recorded further east across the Main Divide and this restricts comparisons of the glacial chronologies, to details of the numerical-age estimates.

According to Birkeland *et al.*(1979), in order for alpine deposits to be subdivided and formally named, sufficient field data for consistent recognition and mapping need to be collected. Furthermore, the subdivision and naming of the glacial deposits should be no more detailed than the resolution of the relative dating methods, which generally decreases with time. The use of multi-parameter dating reduces the impact of local variations, disturbance factors and operator bias which may cause several correlations problems. According to Birkeland *et al*. (1979):-

- i - measurements of some parameters from different sites on the same deposit may vary, *eg. soil and vegetation development.*
- ii - deposits of the same age in adjacent areas may have different values for some parameters, *eg. soil development patterns in the Mueller and Classen Valleys on the 3000-4000 year old surfaces, this study.*
- iii - deposits of different ages in adjacent areas may have similar values for some parameters, *eg. lichen growth measurements in the Ben Ohau Range (Birkeland 1982). and in the Mt Cook region, this study.*

Within New Zealand, stratigraphic nomenclature of the Holocene glacial deposits has been restricted to intra-valley classification. This has resulted in several different sets of formal names for deposits in adjacent catchments, Table 11.2 It is possible that with further intensive study, a generally applicable single series of rock stratigraphic unit names may replace the complicated nomenclature.

Inconsistencies in inter-valley correlations may be reduced if all the deposits in question are examined by the same worker(s) using reliable, objective dating methods. Birkeland (1982) made a significant contribution to this objective when in 1978 he visited two of the main catchments in the eastern ranges and made comparisons with his detailed examination of the glacial chronology in the Ben Ohau Range.

The present study describes the Holocene glacial record for the Mt Cook region. A series of glacial advances are dated and 'reference' deposits described from within the region. The events are numbered rather than named (except where names were already in common usage) to avoid further confusion with the accumulating nomenclature that already

Table 11.3

The Mt Cook Holocene glacial moraine chronology

Event	Date yrs.[1]	Location of reference deposits[2]
If	<100	Godley Valley
Ie	135	Tasman & Classen Valleys
Id	250	-
Ic	340	Mueller, Hooker, Tasman, Classen & Murchison Valleys
Ib	580	Hooker,Godley & Classen Valleys
Ia	c. 800	Classen Valley
IIb	c.1100	Mueller & Tasman Valleys
IIa	c.1500	Mueller Valley
III	c.1700-1800	Hooker Valley
IVc	c.2100	Hooker Valley
IVb	c.2500	Mueller & Hooker Valley
IVa	c.2800-2900	Mueller Valley
V	c.3400	Mueller,Hooker & Classen Valleys
VIb	c.3800	Mueller,Hooker & Tasman Valleys
VIa	c.4000-4200	Mueller,Hooker & Classen Valleys
Foliage Hill	c.7000	Mueller Valley
Sebastopol	c.8000	Black Birch Stream,Mueller Valley
Birch Hill	c.9000-11500	Tasman and Godley Valleys

---

[1] Dates derived from radiocarbon, weathering rind and historical chronologies of the glacial moraine sequence.

[2] Classification of reference deposits shown in Table 11.1, p.181

characterises the New Zealand Holocene glacial record. Moraines deposited during an advance and its subsequent recession are grouped together and then appropriately subdivided (Table 11.2). The Mt Cook glacial record for the Holocene period is defined in Table 11.3 .

CHAPTER 12

CONCLUSIONS

The substantive findings of this work have been presented and discussed in the previous chapters. The purpose of this chapter is to examine the results in the broader context of the field and to derive from these the implications of the work. Suggestions for future research arise from a number of unanswered questions and as a consequence of the results.

The Holocene glacial chronology for the Mt Cook region has been substantially revised using three precise chronologies. Glacial activity recorded over the last 130 years is the most accurate. The pattern of events during the 'historical period' support suggestions of recent climatic warming in New Zealand. The rapid recession of the glaciers in the present century has had a profound effect on the landscape. There are indications to suggest that the recession is continuing. In view of the impact recession has on the environment, it is interesting to speculate on whether events of a similar magnitude have occurred in the past. An early account from the Murchison Valley (Ross 1892) gave some indication that the glacier had once been "much diminished". It is likely that previous glacier recession would have been accompanied by collapse of the lateral moraine walls similar to events near Ball Hut shelter at the present day. The marked absence of lateral moraines dating from the Holocene period in the Murchison and Godley Valleys may indicate extensive deglaciation in both these valleys at some time in the past.

The frequent oscillations by the glaciers during the last 8000 years are recorded by two independent chronologies which are strongly correlated. Radiocarbon dated events recorded from sites often some distance upvalley of the glacier termini are linked to the depositional events downvalley. Radiocarbon measurements noted by earlier workers are re-interpreted in the light of present research.

The three age-dependent dating methods used in this study are less reliable. They are grouped together as 'secondary dating methods'. The descriptions of soil and vegetation change on ageing surfaces are useful in areas within Mt Cook National Park for which there is little or no primary dating control. The general pattern of soil and vegetation development is of use in equivalent areas along the eastern ranges of the Southern Alps.

Lichen growth rates are defined for the Mt Cook region alone. It is not recommended that the revised lichen growth rate curve be used in other areas without first of all calibrating independently some lichen control points.

A number of questions have arisen from the use of the relative dating techniques selected in this study. The effect that loess might have on a developing soil chronosequence remains largely unsolved. Vegetation patterns recorded on the older moraine surfaces were unexplained and the lichen growth rates on surfaces greater than one thousand years old were inconsistent.

Problems remain such as the necessary differences in data to justify different age assignments and how relative dating features are preserved and used for age indication in spite of erosional alteration of the landscape. A model of the glacial events in the Mt Cook region is presented which attempts to subdivide glacier deposits into major and minor events reflecting on the past glacial activity. The model indicates that the amplitude of glacier advances in the different valleys may vary quite considerably, although, on the whole, glacier behaviour is synchronous.

No attempt was made to designate further subdivision of the New Zealand Holocene glacial chronology at this stage. The need for similar detailed investigations of the glacial record in other catchments and ranges is required before the formal naming of early-, mid- and late-Holocene glacier advances is instigated. Future workers should consider carefully all the available dating techniques and evaluate their applicability before attempting to define a similar surface chronology. Wherever possible, workers should combine primary and secondary dating methods. Finally, the most complete understanding of Holocene glacial activity is made possible only through extensive inter-disciplinary research. The glacial record requires explanations of geological, pedological, botanical, climatological, geomorphological and glaciological phenomena.

ACKNOWLEDGEMENTS

I am grateful to the New Zealand Commonwealth Scholarships Committee who funded this research and to Jean Grove who encouraged me to accept the opportunity to study in New Zealand.

A great many people deserve my thanks and appreciation for their assistance in this study. Colin and Vivian Burrows very kindly made me welcome in New Zealand on my arrival. I am thankful to Colin who supervised this research and who gave assistance in the field. John Lovis was of considerable help with the preparation of this thesis and I wish to acknowledge his assistance.

I am indebted to a great many people who helped with the collection and analysis of the data presented here. Considerable logistic support was given me by the Mt Cook National Park Board whose interest and enthusiasm in this project was much appreciated. I am particularly grateful to Martin Heine and Jane Pearson for their hospitality and to Lisle Irwin and Bert Youngman for arranging field assistance and transport in the more inaccessible areas of the Park.

Peter Jackson, Kirsty McNab and Johann Konlechner were the principal field assistants. Pete was of considerable assistance in identifying the vegetation. Hans was responsible for collecting many of the lichen measurements and Kirsty was an excellent companion in the hills. Additional field assistance was received from Bruce Harrison, David Cook, Ray Bellringer and Lakpah Norbu Sherpah.

I am grateful to Bruce Scott (Godley Peaks Station), Gary Joll and Ian Spannon (Lilybank Station) and D.B. Burnett (Mt Cook Station) for allowing me access to field sites in the Godley Valley and Leibig Range.

Mick Steele (Tekapo), Simon Towles and Graham Ayres (Mt Cook National Park Board) and Ron Small (Whirlwide Helicopters) greatly assisted with transport in the Godley Valley.

Discussions with Colin Burrows, Trevor Chinn, Gavin Daly, Peter Holland, David Norton, Joanna Orwin, Jim Salinger, Phil Tonkins, Friedrich Röthlisberger, Ian Whitehouse and Hugh Wilson were most rewarding.

I am particularly indebted to Phil Tonkins of Soil Science, Lincoln College, who patiently sorted out my confusion with regards to soil chronosequences, and to Friedrich Röthlisberger, Swiss Federal Institute of Forest Research, who showed me how to sample and interpret the palaeosurfaces exposed in the lateral moraine walls at Mt Cook. It is with great respect that I have included unpublished data relating to field work by Friedrich Röthlisberger, Trevor Chinn and Peter Birkeland.

Ray Crawford kindly drew my attention to the mis-usage of the term 'absolute dating'. Hilary Langer helped with the statistical analysis whilst Lindsay Connor and Neil Mitchell explained the use of reciprocal averaging. Frances Fox (Soil Science, Lincoln College) suffered my incompetency in the laboratory and ensured that I understood and carried out properly all of my soils analysis. The late Tom Grant-Taylor (Geological Survey) was responsible for the radiocarbon dates of many of the samples. Derek Stewart helped in the preparation of the photographic plates. In addition to so much specialist help, I have received considerable support from the staff of the Botany, Geography and Geology Departments at the University of Canterbury which I wish to warmly acknowledge.

When not in the field it has been impossible not to be distracted by the presence of some wonderful friends, in particular the research students of the "no talking room" ; Matthew, Mary, Lindsay, Kevin, Paul, Caroline and Peter with whom there was never a dull moment and without whose help I might have finished sooner!

Finally I wish to acknowledge the constant support of my parents who have still to see their first glacial moraine.

REFERENCES

Ahlmann, H.W. (1953) Glacier variations and climatic fluctuations. Bowman Memorial Lecture. New York (American Geographical Society 15p).

Allan, H.H. (1961) Flora of New Zealand, Volume I. Government Printer, Wellington, New Zealand. 1085 p.

Andersen, J.L.; Sollid,J.L. (1971) Glacial chronology and glacial geomorphology in the margin zones of the glaciers of Mitdalsbreen and Nigardsbreen, south Norway. *Norsk Geografisk Tiddsskrift* 25: 1-38

Anderson, L.W.; Anderson, D.S. (1981) Weathering rinds on quartzarenite clasts as a relative-age indicator and the glacial chronology of Mount Timpanogos, Utah. *Arctic and Alpine Research* 13: 25-31.

Andrews, J.T.; Webber,P.J. (1964) A lichenometrical study of the northwestern margin of the Barnes Ice Cap: a geomorphological technique. *Geographical Bulletin* 22: 80-104.

Archer, A.C. (1976) Pedogenesis and vegetation trends in the Elefulvic and Eldefulvic zones of the Ben Ohau Range, New Zealand. Lincoln College, New Zealand. (Thesis: PhD.: Soil Science)

Archer,A.C.; Simpson, M.J.A.; Macmillan, B.H. (1973) Soils and vegetation of the lateral moraine at Malte Brun, Mount Cook Region, New Zealand. *New Zealand Journal of Botany* 11: 23-48.

Baillie, M.G.L. (1982) Tree-Ring dating and archaeology. Croom Helm, London.

Baker, J.H. (1891) On Mount Cook glacier motion. *Report of Australasian Association for Advancement of Science.* 3: 153-161.

Benedict, J.B. (1967) Recent glacial history of an alpine area in the Colorado Front Range, USA -1 Establishing a lichen-growth curve. *Journal of Glaciology* 6:817-832.

Beschel, R.E. (1957) A project to use lichens as indicators of climate and time. *Arctic* 10: 60.

____________ (1958) Lichenometrical studies in West Greenland. *Arctic* 11: 254.

____________ (1961) Dating rock surfaces by lichen growth and its application to glaciology and physiography (lichenometry). In Raasch, G.O. *ed.* Geology of the Arctic 2. University of Toronto Press, Toronto.1044-62.

____________ (1973) Lichens as a measure of the age of recent moraines. *Arctic and Alpine Research* 5: 303-309.

Birkeland,P.W. (1973) Use of relative age-dating methods in a stratigraphic study of rock glacier deposits, Mt Sopris, Colorado. *Arctic and Alpine Research* 5:401-416.

____________ (1974) Pedology, Weathering and Geomorphological Research. Oxford University Press, London 285p.

____________ (1981) Soil data and the shape of the lichen growth-rate curve for the Mt Cook area (Note). *New Zealand Journal of Geology and Geophysics* 24:443-445.

____________ (1982) Subdivision of Holocene glacial deposits, Ben Ohau Range, New Zealand, using relative-dating methods. *Geological Society of America Bulletin* 93: 433-449

Birkeland,P.W.; Colman,S.M.; Burke,R.M.; Shroba,R.R.; Meierding,T.C. (1979) Nomenclature of alpine glacial deposits, or,what's in a name? *Geology* 7: 532-536.

Birks,H.J.B. (1980) The present flora and vegetation of the moraines of the Klutlan Glacier, Yukon Territory, Canada: A study in plant succession. *Quaternary Research* 14: 60-86.

Blackwelder,E. (1931) Pleistocene glaciation in the Sierra Nevada and Basin Ranges. *Geological Society of America Bulletin* 42: 865-922.

Bowler,J.M.; Hope,G.S.; Jennings,J.B.; Singh,G.; Walker,D. (1976) Late Quaternary climates of Australia and New Guinea. *Quaternary Research* 6: 359-394.

Burke,R.M.; Birkeland,P.W. (1979) Re-evaluation of multi-parameter relative-dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada.*Quaternary Research* 11: 21-51.

Burrows,C.J. (1973a) Studies of some glacial moraines in New Zealand - 2.Ages of moraines of the Mueller,Hooker and Tasman Glaciers.*New Zealand Journal of Geology and Geophysics* 16: 831-855.

___________ (1973b) Chronology of the moraines of the Tasman,Mueller and Hooker Glaciers. *Guide Book 7, INQUA Congress, Christchurch, New Zealand.*

___________ (1975) Late Pleistocene and Holocene moraines of the Cameron Valley, Arrowsmith Range,New Zealand. *Arctic and Alpine Research* 7: 125-140.

___________ (1976a) Exceptional snowstorms in the South Island high country. *Tussock Grasslands and Mountain Lands Institute Review* 32: 43-47.

___________ (1976b) Icebergs in the Southern Ocean. *New Zealand Geographer* 32: 127-138.

Burrows, C.J. (1977) Late Pleistocene and Holocene glacial episodes in the South Island, New Zealand, and some climatic implications. *New Zealand Geographer* 33:34-39.

____________ (1979) A chronology for cool-climate episodes in the Southern Hemisphere 12000-1000 yr B.P. *Palaeogeography,Palaeoclimatology, Palaeoecology* 27:287-347.

____________ (1980) Radiocarbon dates for post-Otiran glacial activity in the Mount Cook region, New Zealand. *New Zealand Journal of Geology and Geophysics* 23:239-48.

Burrows,C.J.; Chinn,T.J.H.; Kelly,M. (1976) Glacial activity in New Zealand near the Pleistocene-Holocene boundary in the light of new radiocarbon dates. *Boreas* 5: 57-60.

Burrows,C.J.;Gellatly,A.F. (1982) Holocene glacier activity in New Zealand. *Striae* 18: 41-47.

Burrows,C.J.; Greenland,D.E. (1979) An analysis of the evidence for climatic change in New Zealand in the last thousand years. Evidence from diverse natural phenomena and from instrumental records. *Journal of the Royal Society of New Zealand.* 9: 321-373.

Burrows,C.J.; Heine,M. (1979) The older moraines of the Stocking Glacier,Mount Cook region. *Journal of the Royal Society of New Zealand.* 9: 5-12.

Burrows,C.J.; Lucas,J. (1967) Variations in two New Zealand glaciers during the past 800 years. *Nature* 216:467-468.

Burrows,C.J.; Maunder,B.R. (1975) The recent moraines of the Lyell and Ramsay Glaciers, Rakaia Valley, Canterbury. *Journal of the Royal Society of New Zealand* 5: 479-491.

Burrows,C.J.; Orwin,J. (1971) Studies on some glacial moraines in New Zealand-1.The establishment of lichen growth curves in the Mount Cook area. *New Zealand Journal of Science* 14: 327-335.

Calkin,P.E.; Ellis,J.M. (1980) A lichenometric dating curve and its application to Holocene glacier studies in the Central Brooks Range, Alaska. *Arctic and Alpine Research* 12: 245-264.

Campbell,A.C. (1975) Chemical and mineralogical properties of a sequence of terrace soils near Reefton, New Zealand. Lincoln College, New Zealand. (Thesis: PhD.: Soil Science).

Carrara,P.E.; Andrews,J.T. (1975) Holocene glacial/periglacial record, northern San Juan Mts., southwestern Colorado. *Zeitschrift fur Gletscherkunde und Glazialgeologie* 2: 155-174.

Carroll,T. (1974) Relative age-dating techniques and a late-Quaternary chronology,Arikaree Cirque, Colorado. *Geology* 2: 321-325.

Chinn,T.J.H. (1969) Snow survey techniques in the Waitaki Catchment,South Canterbury. *Journal of Hydrology (N.Z.)* 8: 68-76.

__________ (1975) Late Quaternary snowlines and cirque moraines within the Waimakariri Watershed. University of Canterbury, New Zealand. (Thesis: MSc.: Geology).

__________ (1979) Moraine forms and their recognition on steep mountain slopes. In Schluchter,C. *ed.* Moraines and Varves Balkema, Rotterdam. p.51-58.

__________ (1981) Use of rock weathering-rind thickness for Holocene absolute age-dating in New Zealand. *Arctic and Alpine Research* 13: 33-45.

Clapperton,C.M.; Sugden,D.E., Birnie,R.V.; Hanson,J.D.;Thom,G. (1978) Glacier fluctuations in South Georgia and comparison with other island groups in the Scotia Sea. In Bakker,E.M. *ed.* Antarctic Glacial History and World Palaeoenvironments. Balkema, Rotterdam. p.95-104.

Clark,M.M. (1967) Pleistocene glaciation of the drainage of the West Walker River, Sierra Nevada, California. Stanford University, California. (Thesis: PhD,: Microfilm no. 68 6401 Ann Arbor,Michigan).

Coetzee,J.A. (1967) Pollen analytical studies in east and southern Africa. In Bakker,E.M. *ed.*Palaeoecology of Africa, the surrounding Islands and Antarctica. Balkema Cape Town. p.5-140.

Colman,S.M. (1977) The development of weathering rinds on basalts and andesites and their use as a Quaternary dating method, Western United States. University of Colorado, USA. (Thesis: PhD.: Geology).

__________ (1981) Rock-weathering rates as functions of time. *Quaternary Research* 15: 250-264.

Colman,S.M.; Pierce,K.L. (1981) Weathering rinds on andesitic and basaltic boulders as a Quaternary age indicator, Western United States. *Geological Survey Professional Paper* 1210: 56 p.

Cooper,W.S.C. (1923) The recent ecological history of Glacier Bay,Alaska. *Ecology* 4: 93-365.

__________ (1931) A third expedition to Glacier Bay, Alaska. *Ecology* 12: 61-95.

__________ (1939) A fourth expedition to Glacier Bay, Alaska. *Ecology* 20: 130-155.

Costin,A.B. (1972) Carbon-14 dates from Snowy Mountains area, southeastern Australia and their interpretations. *Quaternary Research* 2: 579-590.

Crocker,R.L.; Dickson,B.A. (1957) Soil development on the recessional moraines of the Herbert and Mendenhall Glaciers,southeastern Alaska. *Journal of Ecology* 45: 169-185.

Crocker,R.L.; Major,J. (1955) Soil development in relation to vegetation and surface age at Glacier Bay,Alaska. *Journal of Ecology* 43: 427-448.

Cutler,E.J.B. (1968) Soils. In Cutler,E.J.B. *ed.* General Survey of the Soils of the South Island, New Zealand. Soil Bureau Bulletin 27, p.17-74.

____________ (1980) Soil profile forms. A synoptic approach to soil development. *Soil Science* : 194-199.

Denton,G.H.; Karlèn,W. (1973a) Lichenometry, its application to Holocene moraine studies in southern Alaska and Swedish Lappland. *Arctic and Alpine Research* 5:347-372.

Denton,G.H.; Karlèn,W. (1973b) Holocene climatic variations-their pattern and possible cause. *Quaternary Research* 3: 155-205.

Dobson,A.D. (1930) Reminiscences of Arthur Dudley Dobson, Engineer. Whitcombe and Tombs,Auckland, 224 p.

Dunwiddie,P.W. (1979) Dendrochronological studies of indigenous New Zealand trees. *New Zealand Journal of Botany* 17: 251-266.

Embleton,C.; King,C.A.M. (1969) Glacial and Periglacial Geomorphology. Edward Arnold, London. 608 p.

Farrar,J.F. (1974) A method for investigating lichen growth rates and succession. *Lichenologist* 6: 151-156.

du Faur,F. (1915) The Conquest of Mt Cook. Allen and Unwin, London. 250 p.

Fitzgerald,E.A. (1896) Climbs in the New Zealand Alps. Being an Account of Travel and Discovery. Unwin,London. 363 p.

Fletcher,T.A. (1921) The Godley Peaks. *New Zealand Alpine Journal* 3: 25-38.

Fletcher,T.A. (1922) The Godley Peaks. *New Zealand Alpine Journal* 3: 91-99.

Fletcher,T.A. (1925) The Godley Peaks. *New Zealand Alpine Journal* 3: 240.

Franzmeier,D.P.; Whiteside,E.P. (1963) A chronosequence of podzols in Northern Michigan. 1. Ecology and description of pedons. *Quarterly Bulletin Michigan State University, Agricultural Research Station* 46: 2-20.

Gage,M.; Suggate,R.P. (1958) Glacial chronology of the New Zealand Pleistocene. *Geological Society of America Bulletin* 69: 589-598.

Gair,H.S. (1967) Sheet 20, Mt Cook. Geological map of New Zealand 1:250 000. *New Zealand D.S.I.R. Wellington.*

Garnier,B.J. (1958) The Climate of New Zealand Edward Arnold, London. 191 p.

Gauch,H.G.; Whittacker,R.H.; Wentworth,T.R. (1977) A comparative study of reciprocal averaging and other ordination techniques. *Journal of Ecology* 65: 157-174.

Gauch,H.G.; Whittacker,R.H. (1972) Comparison of ordination techniques. *Ecology* 48: 793-806.

Gellatly,A.F. (1982) The use of lichenometry as a relative-age dating method with specific reference to Mount Cook National Park, New Zealand. *New Zealand Journal of Botany*, 20: (in press).

Geyh,M.A.; Benzler,J.H.; Roeschmann,G. (1971) Problems of dating Pleistocene and Holocene soils by radiometric methods. In Yaalon,D.H. *ed.* Palaeopedology, origin, nature and dating of palaeosoils. Israel Universities Press, Jerusalem. 347 p.

Griffey,N.G.; Matthews,J.A. (1978) Major Neoglacial glacier expansion episodes on Southern Norway: Evidence from moraine ridge stratigraphy with ^{14}C dates on buried palaeosoils and moss layers. *Geografiska Annaler* 60A: 73-90.

Given,D.R.; Soper,J.H. (1975) Pioneer vegetation on moraines near Clachnacudainn Snowfield, British Columbia. *Syesis* 8: 349-354.

Goldthwait,R.P. *et al.* (1966) Soil development and ecological succession in a deglaciated are of Muir Inlet, southeast Alaska. *Institute of Polar Studies, Ohio State University Research Report* 20.

Green,W.S. (1883) The High Alps of New Zealand or a trip to the glaciers of the Antipodes with an ascent of Mt Cook. Macmillan, London. 350 p.

Grinsted,M.J.; Wilson,A.T. (1979) Variations of $^{13}C/^{12}C$ ratio in cellulose of *Agathis australis* (kauri) and climatic change in New Zealand during the last millenium. *New Zealand Journal of Science* 22: 55-61.

Grove,J.M. (1980) The glacial history of the Holocene. *Progress in Physical Geography* 3: 1-54.

Haast,J.von (1879) Geology of the Province of Canterbury and Westland, New Zealand. A report comprising the results of official exploration. Times Office, Christchurch. 486 p.

Harper,A.P. (1934) Glacier retreat.*New Zealand Alpine Journal* 5: 173-175.

__________ (1935) Glacier retreat.*New Zealand Alpine Journal* 5: 322-326.

Harper,A.P. (1946) Memories of Mountains and Men. Simpson and Williams, Christchurch. 208 p.

Harrington,H.J. (1951) Glacier wasting and retreat in the Southern Alps of New Zealand. *Journal of Glaciology* 2: 140-145.

Heine,M.; Burrows,C.J.B. (1980) Who fills the Stocking? *New Zealand Alpine Journal* 33: 69-71.

Hessell,J.W.D. (1980) Apparent trends of mean temperature in New Zealand since 1930. *New Zealand Journal of Science* 23: 1-9.

Hilgendorf,C. (1932) History of Mt Cook District, New Zealand to the year 1895. University of Canterbury, New Zealand. (Thesis: MA.: History).

Hill,M.O. (1973) Reciprocal averaging.An eigenvector method of ordination. *Journal of Ecology* 61: 237-249.

Hill,M.O.; Gauch,H.G. (1980) Detrended Correspondence Analysis: an improved ordination technique. *Vegetatio* 42: 47-58.

Hope,G.S.; Peterson,J.A. (1975) Glaciation and vegetation in the high New Guinea mountains. In Suggate,R.P.: Cresswell,M. *eds*. Quaternary Studies. iX INQUA Congress, Christchurch 1973, 155-162.

Hope,G.S.; Peterson,J.A. (1976) Palaeoenvironments. In Hope, G.S.; Peterson,J.A.; Radok,U.; Allison,I. *eds*. The Equatorial Glaciers of New Guinea. Balkema, Rotterdam. p.173-205.

Hutton,F.W. (1888) Notes on the Mueller Glacier,New Zealand. *Proceedings Linnean Society, N.S.W.* 3: 429-442.

Jacobsen,G.L.; Birks,H.J.B. (1980) Soil development on recent end moraines of the Klutlan Glacier, Yukon Territory, Canada. *Quaternary Research* 14: 87-100.

Jenny,H. (1980) The Soil Resource, Origin and Behaviour. Springer, New York. 377 p.

Jochimsen,M. (1973) Does the size of lichen thalli really constitute a valid measure for dating glacial deposits? *Arctic and Alpine Research* 5: 417-424.

Lamb,H. (1977) Climate Past, Present and Future - Volume 2 Methuen & Co. London. 835 p.

Lawrence,D.B. (1958) Glaciers and vegetation in southeastern Alaska. *American Scientist* 46: 89-122.

Lawrence,D.B.; Lawrence,E.G. (1965) Glacier studies in New Zealand. *Mazama* 47: 17-27.

Lock,W.W.; Andrews,J.T.; Webber,P.J. (1979) A Manual for Lichenometry. *Technical Bulletin 26. I.B.G. Research Group.*

Lüdi,W. (1958) Beobachtungen über die Besiedlung von Gletschervorfeldern in den Schweizeralpen.*Flora* 146:3.

Mahaney,W.C. (1973) Neoglacial chronology in Fourth of July Cirque, central Colorado Front Range. *Geological Society of America Bulletin* 84: 161-170.

Mannering,G.E. (1980) On the Murchison Glacier. *Transactions New Zealand Institute* 23: 355-366.

Mansergh,G.D. (1973) Quaternary of the McKenzie Basin. *Guide Book 7, INQUA Congress,Christchurch,New Zealand.*102-111

Marshall,P. (1907) Notes on Glaciation in New Zealand.*Report of Austalasian Association Advance of Science* 11:283-9

Matthes,F.E. (1939) Report of committees on glaciers. *Transactions of American Geophysical Union* 20: 518-23.

____________ (1941) Rebirth of glaciers of the Sierra Nevada during the late post-Pleistocene time (abstract). *Geological Society of America Bulletin* 52: 2030.

Matthews,J.A. (1973) Lichen growth curve on an active medial moraine,Jotunheim,Norway. *Journal of Glaciology* 12: 305-313.

____________ (1974) Families of lichenometric dating curves from Storbreen gletschervorfeld, Jotunheim, Norway. *Norsk Geografisk Tiddskrift* 28: 215-235.

____________ (1977) A lichenometric test of the 1750 end-moraine hypothesis, Storbreen gletschervorfeld, Jotunheim, Norway. *Norsk Geografisk Tiddskrift* 31: 129-136.

____________ (1979) The vegetation of the Storbreen gletschervorfeld, Jotunheim, Norway. 1-Introduction and approaches involving classification. *Journal of Biogeography* 6: 17-47.

____________ (1980) Some problems and implications of ^{14}C dates from a podzol buried beneath an end moraine at Haugabreen, Southern Norway. *Geografiska Annaler* 62A 185-208.

____________ (1981) Natural ^{14}C age/depth gradient in a buried soil. *Naturwissenschaften* 68: 472-474.

McGlone,M.S.;Moar,T. (1977) The *Ascarina* decline and post-glacial cimate changes in New Zealand. *New Zealand Journal of Botany* 15: 485-489.

McGlone,M.S.; Topping,W.W. (1977) Aranuian (post-glacial) pollen diagrams from Tongariro region,North Island, New Zealand. *New Zealand Journal of Botany* 15: 749-760.

McGregor,V.R. (1963) The geology of parts of Lilybank station,Canterbury, New Zealand. University of Auckland,New Zealand. (Thesis: MSc.: Geology).

____________ (1967) Holocene moraines and rock glaciers in the Central Ben Ohau Range, South Canterbury,New Zealand. *Journal of Glaciology* 6: 737-748.

McKellar,I.C. (1955) Stranded moraines of the Hooker and Mueller Glaciers. *New Zealand Journal of Science and Technology* 37B; 221-223.

Meierding,T.C. (1977) Age differentiation of till and gravel deposits in the Upper Colorado Basin. University of Colorado, U.S.A. (Thesis: PhD.: Geology).

Mercer,J.H. (1968) Variations of some Patagonian glaciers since the late-Glacial. *American Journal of Science* 266: 91-109.

____________ (1970) Variations of some Patagonian glaciers since the late-Glacial II. *American Journal of Science* 269: 1-25.

____________ (1976) Glacier history of southern-most South America. *Quaternary Research* 6: 125-166.

Mercer,J.H.; Palacios,O. (1977) Radiocarbon dating of the last glaciation in Peru. *Geology* 5: 600-604.

Miller,C.D. (1969) Chronology of Neoglacial moraines in the Dome Peak area, North Cascade range, Washington. *Arctic and Alpine Research* 1: 49-66.

Miller,G.H. (1973) Variations in lichen growth from direct measurements: preliminary curves for *Alectoria miniscula* from eastern Baffin Island,N.W.T. Canada. *Arctic and Alpine Research* 5: 333-339.

Miller,R.B. (1968) Soil Chemistry. In Cutler,E.J.B. 1968 (*op.cit.*).

Olson,J.S. (1958) Rates of succession and soil changes on southern Lake Michigan sand dunes. *Botanical Gazette* 119: 125-170.

Olsson,I.U. (1974) Some problems in connection with the evaluation of C^{14} dates. *Geologiska Foreningens i Stockholm Forhandlinger* 96: 311-320.

Orwin,J. (1970) Lichen succession on recently deglaciated rock surfaces. *New Zealand Journal of Botany* 8:452-77.

_______ (1972) The effect of environment on assemblages of lichens growing on rock surfaces. *New Zealand Journal of Botany* 10: 37-47.

Paul,J. (1974) Twelve watercolours of glaciers in the province of Canterbury. Julius Haast and John Gully: Collaborators. *Turnbull Library Record* 7: no.2.

Platt,R.B.; Amsler,F.P. (1955) A basic method for the immediate study of lichen growth rates and succession. *Journal of the Tennessee Academy of Science* 30:177-183.

Porter,S.C. (1975) Equilibrium line altitudes of late Quaternary glaciers in the Southern Alps,New Zealand. *Quaternary Research* 5: 27-47.

Porter,S.C. (1979) Glaciological evidence of Holocene climatic change. *International Conference on Climate and History, University of East Anglia Review Paper*: 148-179.

Porter,S.C.; Denton,G.H. (1967) Chronology of Neoglaciation in the North American cordillera. *American Journal of Science* 267: 177-210.

Rampton,V. (1970) Neoglacial fluctuations of the Natazhat and Klutlan Glaciers, Yukon Territory,Canada. *Canadian Journal of Earth Science* 7: 1236-1263.

Reiners,W.A.; Worley,I.A.; Lawrence,D.B. (1971) Plant diversity in a chronosequence at Glacier Bay, Alaska. *Ecology* 52: 55-69.

Ross,M. (1892) Aorangi; or the Heart of the Southern Alps New Zealand. Government Printers, Wellington. 64 p.

______ (1914) A Climber in New Zealand Edward Arnold,London.

Ross,W.C.;Mew,G.; Searle,P.L. (1977) Soil sequences on two terrace systems in the North Westland area,New Zealand. *New Zealand Journal of Science* 20: 231-244.

Röthlisberger,F. (1976) Gletscher-und Klimaschwankungen im Raum Zermatt, Ferpècle und Arolla. *Die Alpen* 52:59-152.

Röthlisberger,F.; Schneebeli,W. (1979) Genesis of lateral moraine complexes,demonstrated by fossil soils and trunks; indicators of postglacial climatic fluctuations. In Schluchter,C. *ed.*Moraines and Varves Balkema Rotterdam. p.387-420.

Röthlisberger,F.; Haas,P.; Holzhauser,H.; Keller,W.; Bircher,W.; Renner,F. (1980) Holocene climate fluctuations-radiocarbon dating of fossil soils (fAh) and woods from moraines and glaciers in the Alps. *Geographica Helvetica* 35:21-52 (special issue).

Rowley,J.A. (1966) The vegetation of the lateral moraines of the Hooker Glacier, Mount Cook. *Science Record* 16: 74-77.

Ruhe,R.V. (1975) Geomorphology Houghton Mifflin Co. USA 246p.

Runemark,H. (1956) Studies in *Rhizocarpon*. 1-Taxonomy of the yellow species in Europe. *Opera Botanica* 2:5-150.

Salinger,M.J. (1976) New Zealand temperatures since 1300AD. *Nature* 260: 310-311.

Salinger,M.J. (1979) New Zealand climate; the temperature record, historical data and some agricultural implications. *Climatic Change* 2: 109-126.

___________ (1980a) New Zealand climate 1.Precipitation patterns. *Monthly weather review* 108:1892-1904.

___________ (1980b) New Zealand Climate 2.Temperature patterns. *Monthly weather review* 108:1905-1912.

___________ (1981) Some aspects of climatic change in New Zealand. Victoria University of Wellington, New Zealand. (Thesis: PhD.: Geography).

___________ (1982) On the suggestion of post-1950 warming over New Zealand. *New Zealand Journal of Science* 25: 77-86.

Salinger,M.J.; Gunn,J.M. (1975) Recent climatic warming around New Zealand.*Nature* 256: 396-398.

Sara,W.A. (1968) Franz Josef and Fox Glaciers 1951-1967. *New Zealand Journal of Geology and Geophysics* 11:768-80.

________ (1970) Glaciers of Westland National Park. *New Zealand D.S.I.R. Information series* No.75 47 p.

Schneebeli,W. (1976) Untersuchungen von Gletscherwankungen im Val de Bagnes. *Die Alpen* 52: 5-57.

Sharp,R.P. (1969) Semiquantitative differentiation of glacial moraines near Convict Lake, Sierra Nevada, California. *Journal of Geology* 77: 68-91.

Sharpenseel,H.W. (1971) Radiocarbon dating of soils- Problems, Troubles and Hopes. In Yaalon,D.H. *ed.* Palaeopedology Israel Universities Press, Jerusalem.

______________ (1972) Natural radiocarbon measurements of soil and organic matter fractions and on soil profiles of different pedogenesis. *Proceedings of the 8th Int.Conf. on Radiocarbon dating,New Zealand* 2:382

Sigafoos,R.S.; Hendricks,E.L. (1969) The time interval between stabilization of alpine glacial deposits and the establishment of the seedlings. *U.S. Geological Survey, Professional Paper* 650B: 89-93.

Speight,R. (1940) Ice wasting and glacier retreat in New Zealand. *Journal of Geomorphology* 3:131-143.

Speight,J.G. (1961) Pleistocene historical geomorphology of the area around Lake Pukaki. University of Canterbury, New Zealand. (Thesis: MSc.: Geology).

____________ (1963) Late Pleistocene historical geomorphology of the Lake Pukaki area, New Zealand. *New Zealand Journal of Geology and Geophysics* 6:160-188.

Spörli,K.B.; Lillie,A.R. (1974) Geology of the Torlesse Supergroup in the N. Ben Ohau Range,Canterbury. *New Zealand Journal of Geology and Geophysics* 17: 115-141.

Stevens, G.R. (1974) Rugged Landscape. Reed, Wellington 286p.

Stevens,P.R. (1964) A preliminary report on a chronosequence of soils and vegetation near the Franz Josef Glacier. *New Zealand Soil News* 2.

____________ (1968) A chronosequence of soils near the Franz Josef Glacier. Lincoln College, New Zealand. (Thesis: PhD.: Soil Science).

Stevens,P.R.; Walker,T.W. (1970) The chronosequence concept and soil formation. *Quarterly Review of Biology* 45: 333-350.

Stork,A. (1963) Plant immigration in front of retreating glaciers, with examples from the Kebnekajse Area, Northern Sweden. *Geografiska Annaler* 45: 1-21.

Stuiver,M. (1978) Radiocarbon timescale tested against magnetic and other dating methods. *Nature* 273: 271-274.

Süess,H.E. (1973) Der radioaktive Kohlenstoff in der Natur. *Endeavour* 32: 34-38.

Sugden,D.E.; John,B.S. (1976) Glaciers and Landscapes Edward Arnold, London. 376 p.

Theakstone,W.H. (1965) Recent changes in the glaciers of Svartisen. *Journal of Glaciology* 5:411-431.

Thorn,C.E. (1975) Influence of late-lying snow on rock-weathering rinds. *Arctic and Alpine Research* 7:373-8.

Tisdale,E.W.; Fosberg,M.A.; Poulton,C.E. (1966) Vegetation and soil development on a recently glaciated area near Mt Robson, British Columbia. *Ecology* 47: 517-523.

Trenberth,K.E. (1976) Fluctuations and trends in indices in the Southern Hemisphere circulation. *Quarterly Journal of the Royal Meteorological Society* 102:25-35.

__________ (1977) Climate and Climatic Changes,a New Zealand Perspective. N.Z. Meteorological Service, miscellaneous publication 161. Government Printer, Wellington.

Tuck,R.G. (1975) The late Holocene glacial chronology of the Lake Tekapo valley. University of Auckland,New Zealand. (Thesis: MSc.: Geology).

Ugolini,F.C. (1968) Soil development and alder invasion in a recently deglaciated area of Glacier Bay, Alaska. In Trappe,J.M. *et.al. (eds.)* The Biology of Alder, U.S. Forest Service Publication, p.115-140.

Viereck,L.A. (1966) Plant succession and soil development on glacial outwash of the Muldrow Glacier,Alaska. *Ecological Monographs* 36: 181-199.

Vreeken,W.J. (1975) Principal kinds of chronosequence and their significance in soil history. *Journal of Soil Science* 26: 378-394

Wall,A. (1925) The Flora of Mt Cook Lyttleton Times Press, Christchurch. 55 p.

Walker,T.W.; Syers,J.K. (1976) The fate of phosphorus during pedogenesis. *Geoderma* 15:1-19.

Wardle,P. (1973) Variations in glaciers of Westland National Park and the Hooker Range,New Zealand. *New Zealand Journal of Botany* 11: 349-388.

_________ (1978) Further radiocarbon dates from Westland National Park and the Omoeroa River mouth,New Zealand. *New Zealand Journal of Botany* 16: 147-152.

_______ (1980) Primary succession in Westland National Park and its vicinity, New Zealand. *New Zealand Journal of Botany* 18: 221-232.

Webb,T. (1976) Pedological studies of soil of the Tekapo set, in east Lake Pukaki region,South Canterbury, New Zealand. Lincoln College, New Zealand. (Thesis: PhD.: Soil Science).

Williams,E.W. (1967) Expedition in the Godley (1917). *The Press, Christchurch* 23.12.1967, p.5.

Williams,J. (1973) Neoglacial chronology of the Fourth of July Cirque,Central Colorado Front Range: Discussion. *Geological Society of America Bulletin* 84:3761-3765.

Wilson,H.W. (1976) Vegetation of Mt Cook National Park,New Zealand. Government Printers, Wellington. 138 p.

__________ (1978) Field Guide: Wild plants of Mt Cook National Park. Whitcoulls, Christchurch. 294 p.

Working Group on the Origin and Nature of Palaeosoils. (1971) Criteria for recognising and classification of Palaeosoils. In Yaalon,D.H. *ed.* Palaeopedology. Israel Universities Press, Jerusalem. 350 p.

Wright,H.E. (1980) Surge moraines of the Klutlan Glacier, Yukon Territory, Canada: Origin, wastage, vegetation succession, Lake development and application to the Late-Glacial of Minnesota. *Quaternary Research* 14: 2-18.

APPENDICES

APPENDIX A

GLOSSARY OF TERMS USED IN THE TEXT

Geomorphological Terms

ABLATION TILL- Downwasting of the glacier surface causes the surface moraine cover to be dumped, hence the term 'marginal dumping' and 'supra-glacial meltout'. Both processes are associated with the formation of ABLATION TILL.

DISINTEGRATION MORAINE- An area of confused topography which has resulted from the rapid retreat of the glacier. The deposits are characteristically 'chaotic' and show little orientation.

LODGEMENT TILL- The process whereby small pieces of detritus are released and transported by the ice and are lodged or plastered onto the glacier bed and sides as a result of pressure melting beneath the actively moving ice. The debris is deposited from this position in the glacier ice-stream.

MARGINAL DUMPING - see ABLATION TILL above.

MELTOUT TILL - see ABLATION TILL above.

MORAINE - An accumulation of debris from the mountains which is transported down and deposited by the glacier. Moraine may be sub-, en- or supra-glacial. Moraine is deposited principally as lateral and terminal deposits.

Pedological Terms

Texture profile terms, after Cutler (1980).

UNIFORM - mineral soils in which texture remains relatively uniform throughout the profile.

GRADATIONAL POSITIVE - mineral soils in which the texture becomes finer with depth without sharp changes.

GRADATIONAL NEGATIVE - soil texture becomes progressively coarser with depth, as in many soils in the South Island,New Zealand.

DUPLEX POSITIVE - soil texture changes abruptly from coarse to fine within the profile.

DUPLEX NEGATIVE - soil texture changes abruptly within the profile from finer at the top to coarser below; typical of some soils formed on thin loess or alluvium over sandy gravels.

VARIABLE -soils with texture profile which include thin sedimentary layers of contrasting texture.

APPENDIX B

RADIOCARBON DATING- validity, reliability and accuracy of radiocarbon-age determination. A brief explanation is given of the principles and problems of radiocarbon dating based on two accounts; Rothlisberger,F. *et al.*(1980) and Burrows,C.J. (unpubl. schedule). For further information, some references not cited in the main text are included.

The method is based on:

- Formation of radiocarbon in the upper atmosphere by interaction of cosmic rays with nitrogen (N^{14}).
- Oxidation of this radiocarbon to radioactive carbon-dioxide $C^{14}O_2$, which mixes freely with the atmosphere and surface waters and whose molecules are in a proportion with non radioactive carbon dioxide molecules of 1 to 10^{12}.
- Free exchange with the atmosphere of the radiocarbon dioxide being taken in by all living things, while they are alive, but fixation of the radiocarbon contained in their bodies at their death, with subsequent decay of the radiocarbon at a constant rate.
- Measurement of the radioactivity remaining in a sample, with a detecting instrument or counter to give a measure of time elapse since death of the organism. (NB. there is a statistical counting error). Burrows,C.J. (unpubl.)

Four factors are cited in the text as determining the numerical value and deviation of a radiocarbon date:

- the influence of cosmic rays on the upper atmosphere
- the mathematical-physical laws of radioactive decay
- the type of sample materials
- the laboratory equipment

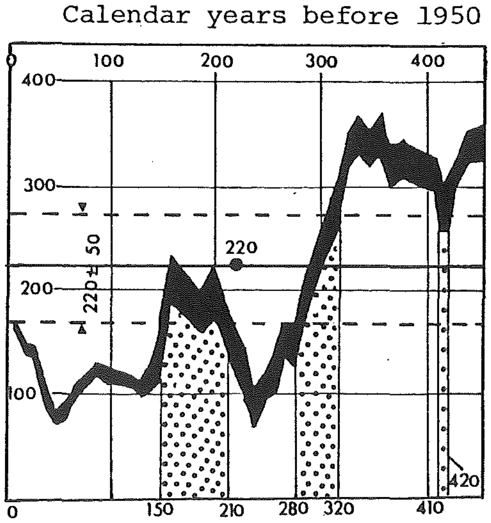
These factors are explained in full by Rothlisberger,F.*et al.* (1980) whose account is included here:

A) Influence of cosmic rays on the upper atmosphere

The C^{14} content of the atmosphere is not constant, i.e. the proportion of the radioactive isotope to C^{12} is variable. This variation is caused by:

- solar activity and extragalactic events influencing the cosmic rays producing the C^{14} (continuous nuclear reactions in the upper atmosphere between neutrons and nitrogen atoms produce C^{14}).
- combustion of fossil fuels and artificial particle emission. According to current geophysical knowledge, long term fluctuations of C^{14} content are attributable to variations in the earth's magnetic field, short term fluctuations to irregularities of solar activity. By means of dendrochronology it was possible to demonstrate (Suess 1973, Stuiver 1978) and confirm (de Jong *et al.* 1979) the fluctuations of C^{14} production rate for the last 8000 years. Stuiver (1978) showed that because of the fluctuations of the C^{14} content, a sample with a measured C^{14} age of 220±50 yr B.P. can be associated with three different periods of calendar years separated by a total of 270 years (Fig.B.1) Such uncertainties and difficulties in correcting C^{14} dates probably arise in other postglacial periods as well.

Fig.B1 Radiocarbon variations of the last 400 years.



Curve showing relationship between conventional C^{14} years and tree-ring calibrated calendar years (Stuiver,1978,Fig.1).Width of curve is twice the standard deviation of the measurements. Any radiocarbon year may be equivalent to more than one calendar year; in the example illustrated a C^{14} age of 220±50 is equivalent to all calendar dates within the ranges of 150-210, 280-320 and 410-420 years (after Porter,1979,162).

(from Rothlisberger *et al.* 1980,p. 25)

B) The mathematical-physical laws of radioactive decay

Each radioactive decay is a random event. Hence the number of decays observed in a given period is random dependent. Repeated measurements made over many similar periods produce differing numbers of decays. Only the averaging of an infinite number of periods would give an exact mean value from which the exact sample age could be calculated. Each time-limited measurement is a random sample giving only an assessed value for the real number of decays and therefore only an assessed age value for the real sample age. Therefore the age calculated from the sample also exhibits a deviation. This deviation (standard deviation) mathematically termed sigma (σ) obeys the laws of statistics. C^{14} dates are normally given with a standard deviation of ±1 σ, i.e. the true radiometric age lies with 68% certainty in this scatter band. The following points define the band width of the standard deviation:

-sample amount
-sample age
-counting time
-contamination

The standard deviation is smaller when the sample amount is increased. A high sample age will increase the standard deviation. The longer a sample is counted the smaller the standard deviation and contamination will falsify the sample age and thereby affect the standard deviation to a similar degree.

C) The type of sample material

The type of sample material can strongly influence the reliability and accuracy of a C^{14} age. Thus the interpretation of the soil data requires knowledge of the basic processes of soil formation. C^{14} may reach the fossil soil from the bedrock or by infiltration of humic acids. At the same time soils contain older organic material from the beginning of the soil formation as well as younger material from the current production. This mixture of older and younger organic matter cannot be separated according to the C^{14} content. The quantity of C^{14} from the beginning and the end of soil formation is in any case unknown. The C^{14} age formally calculated on the basis of the C^{14} concentration is called the *apparent parent age* (Geyh 1970, Schneebeli 1976). The shorter the duration of the soil formation phase, the nearer this apparent age lies to the glacial superposition (cold phase). Long soil formation exhibits an apparent age nearer to the warm phase (Porter 1979). Therefore soil dates must always be judged individually, since their ages can give warm or cold periods of transitions in between. Woods are considerably easier to date. However, the interpretation of published dates is often problematic; the data do not indicate how many growth rings the trunk had and whether the wood sample was taken from the inner or peripheral part of the trunk's cross-section.

D) Laboratory equipment

Various ranges of error in the C^{14} age appear, depending on the method of sample preparation and the counting apparatus. Furthermore, C^{14} technology is still rapidly developing, so that as the method is refined, more and more exact datings become possible. Since the development of C^{14} technology is not at the same stage in all C^{14} laboratories, it is advisable to double, possibly even treble, the significance level ($\pm 1\sigma$) when comparing dates from different laboratories.

Conclusion

In the present study material was dated by two different laboratories in Germany and New Zealand. Only a very few samples were submitted for dating at both laboratories. One such sample from the Mt Cook region was HV-10504 8040±70 which concords with an earlier New Zealand dated sample from the same site; NZ-4508 7940±70. The significance of inter-laboratory inconsistency in radiocarbon dating was recently demonstrated by an International Study Group which looked at twenty C^{14} laboratories and submitted similarly aged material to each. The results showed inexplicable variation and some systematic bias despite general agreement within the sample group. (International Study Group,1982). Notwithstanding the problems of radiocarbon dating, it remains as the best available age parameter where suitable material exists for dating events during the Holocene period older than the historical record for any one area.

Additional references not listed in the main reference list, this study.

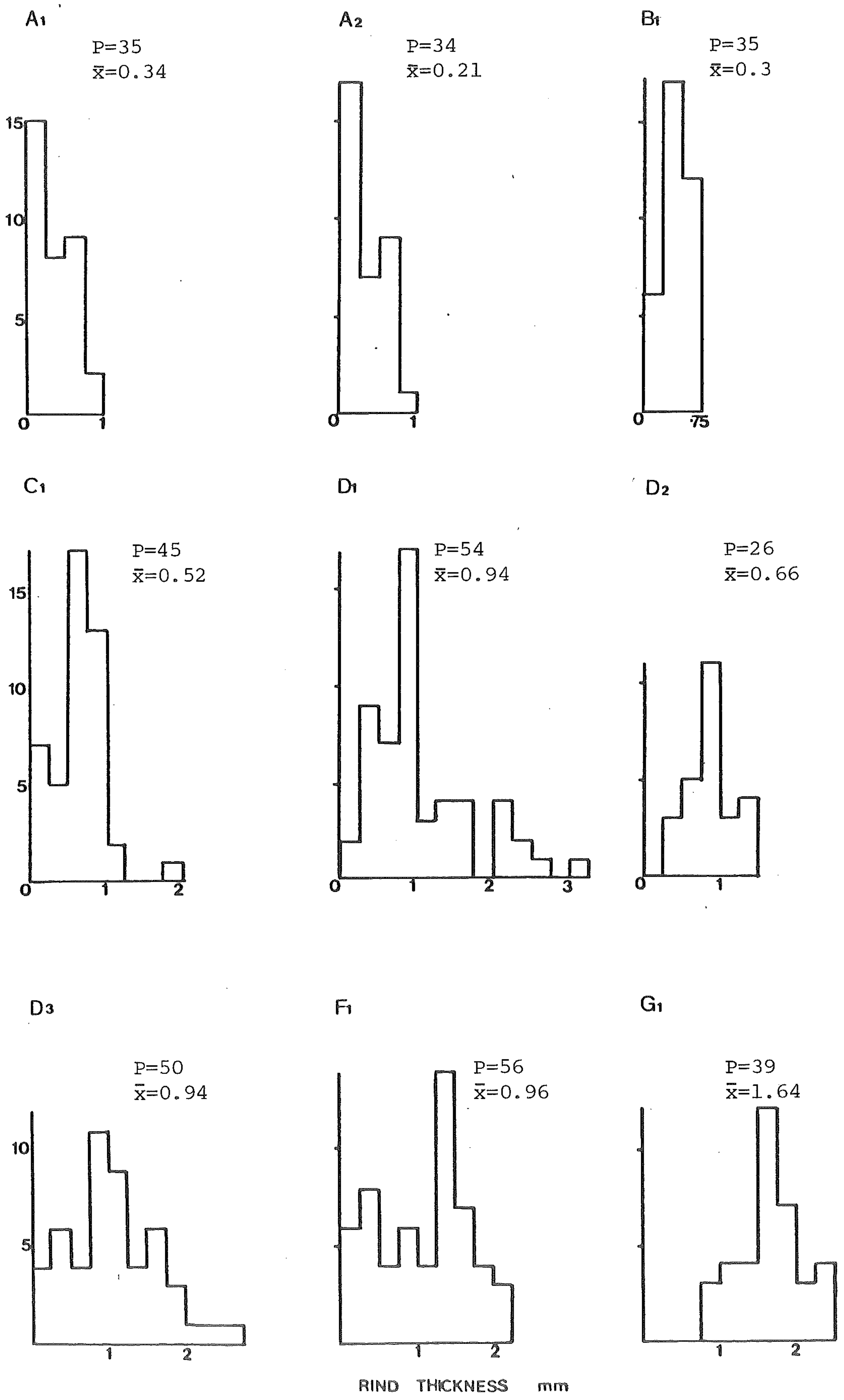
Geyh,M.A. (1970) Moglichkeiten und Grenzen der Radiokohlenstoff-Alter bestimmung von Boden:Methodische Probleme. *Mitt. Dtsch. Bodenkundl Gesellschaft,* 10.

de Jong,A.F.M, *et al.* (1979) Confirmation of the Süess Wiggles: 3200-3700 BC. *Nature* 280: 48-49.

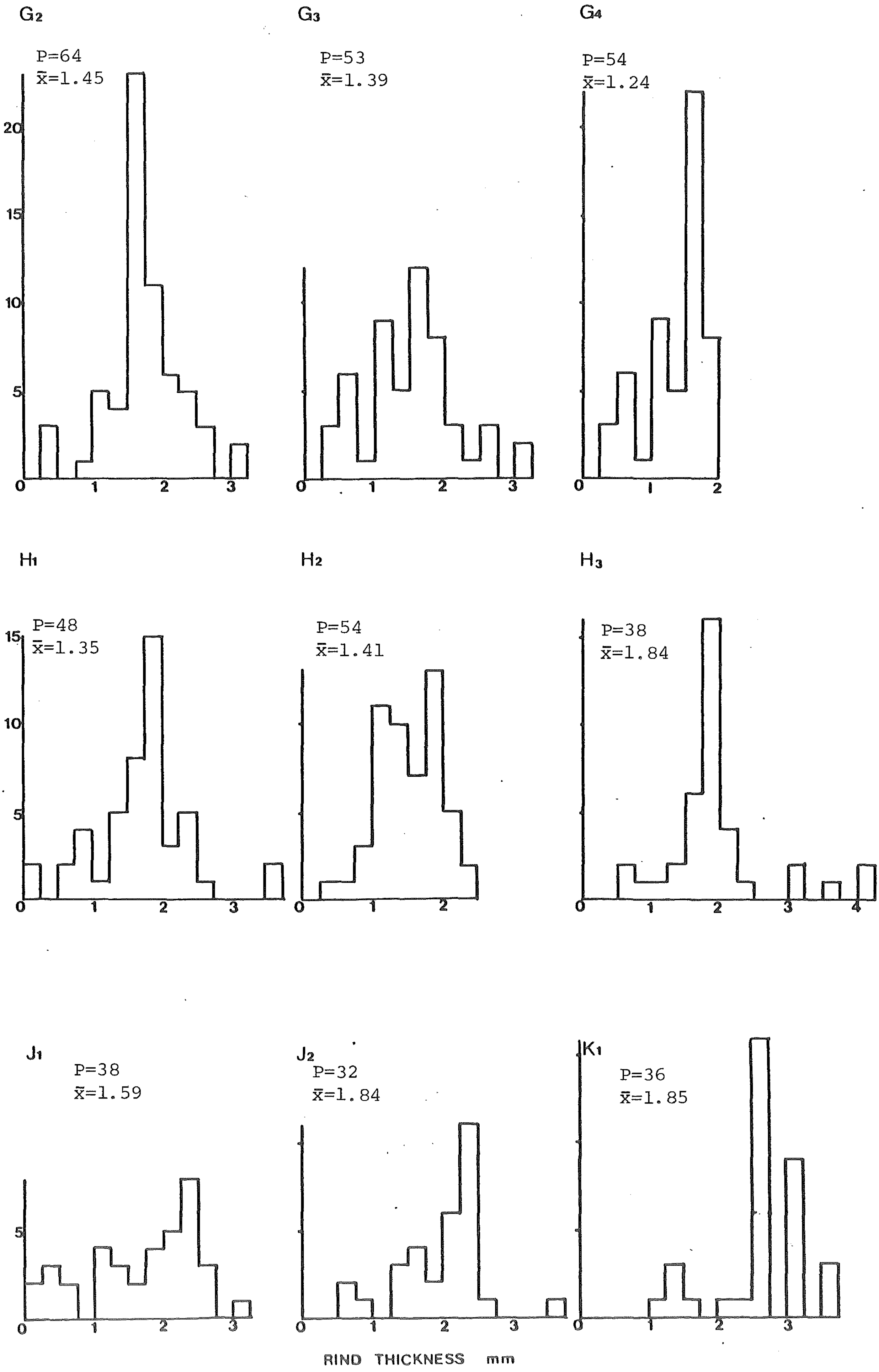
International Study Group (1982) An inter-laboratory comparison of radiocarbon measurement in tree rings. *Nature* 298: 619-623.

MUELLER GLACIER WHITE HORSE HILL

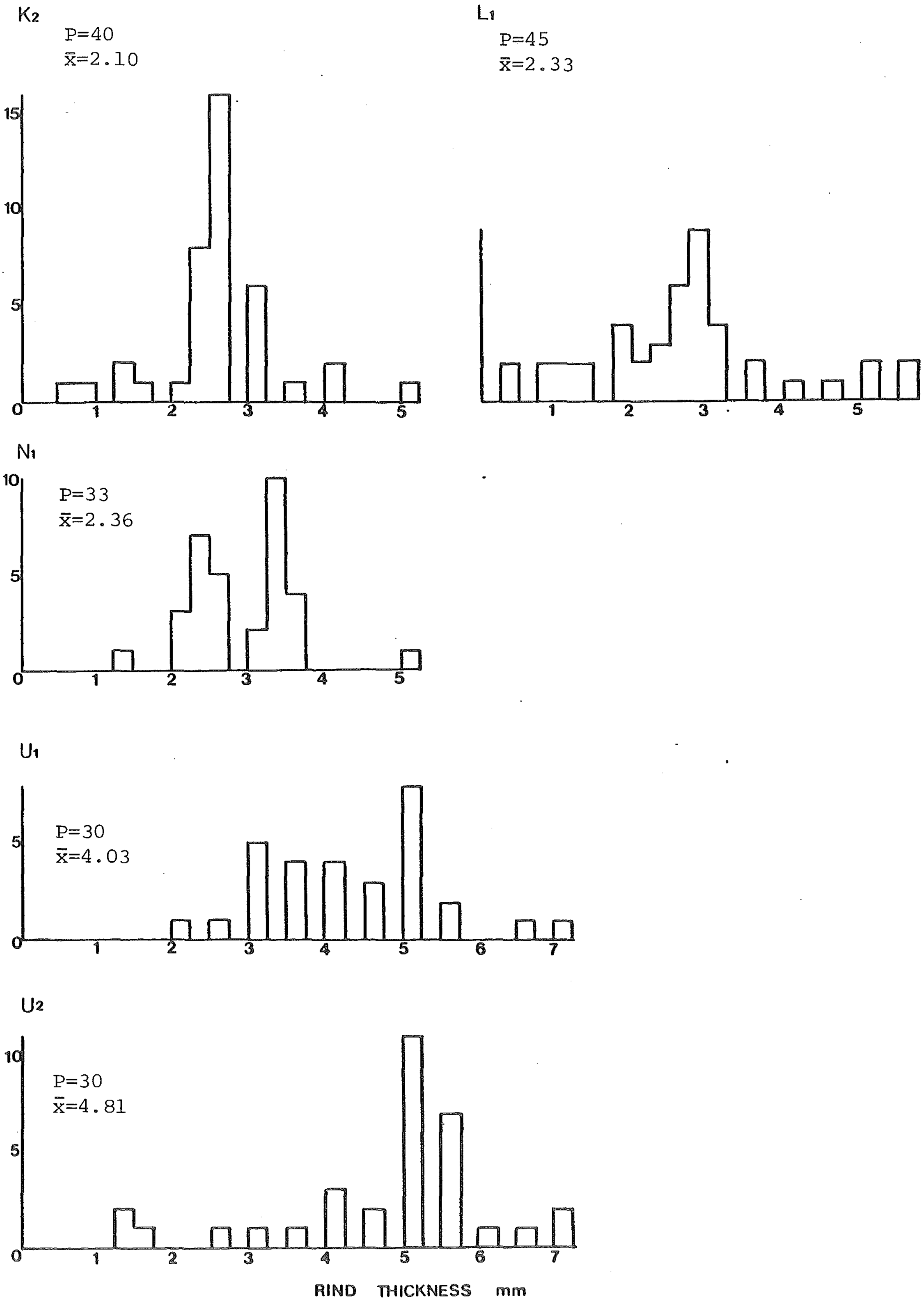
Histograms to show Rock Weathering Rind Distributions for each Site



MUELLER GLACIER WHITE HORSE HILL

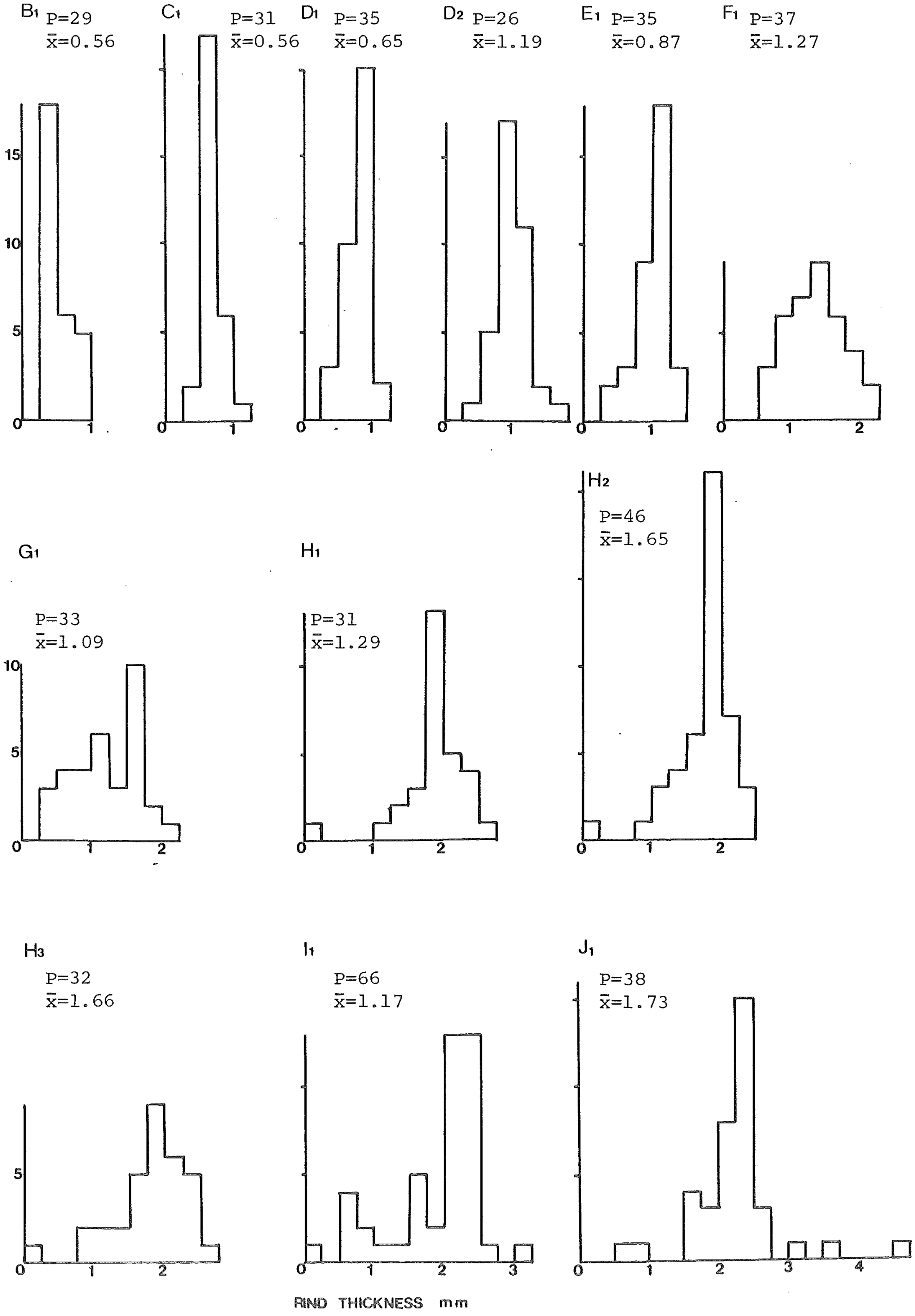


MUELLER GLACIER WHITE HORSE HILL



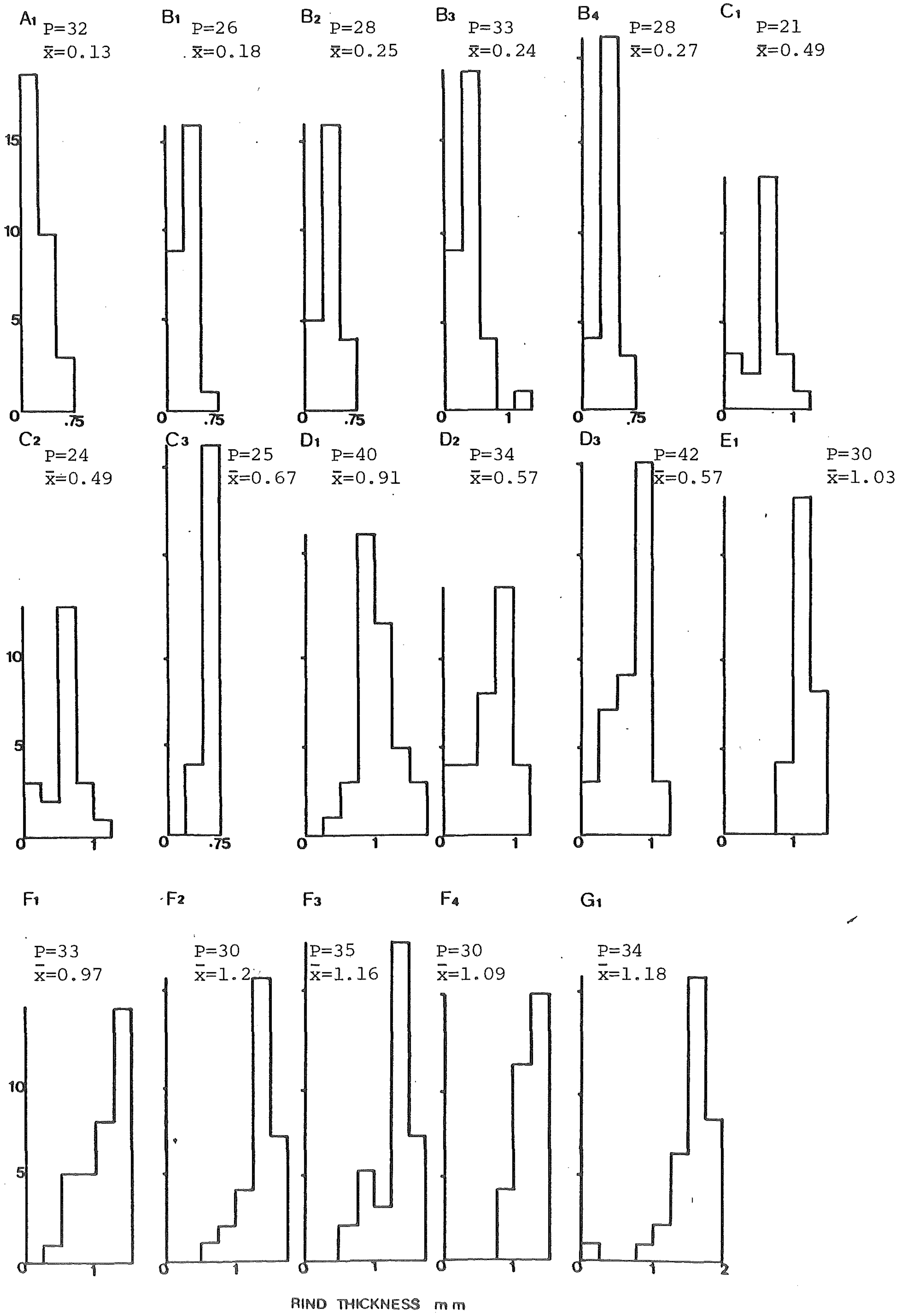
MUELLER GLACIER HOOKER RIVER

Histograms to show Rock Weathering Rind Distributions for each Site

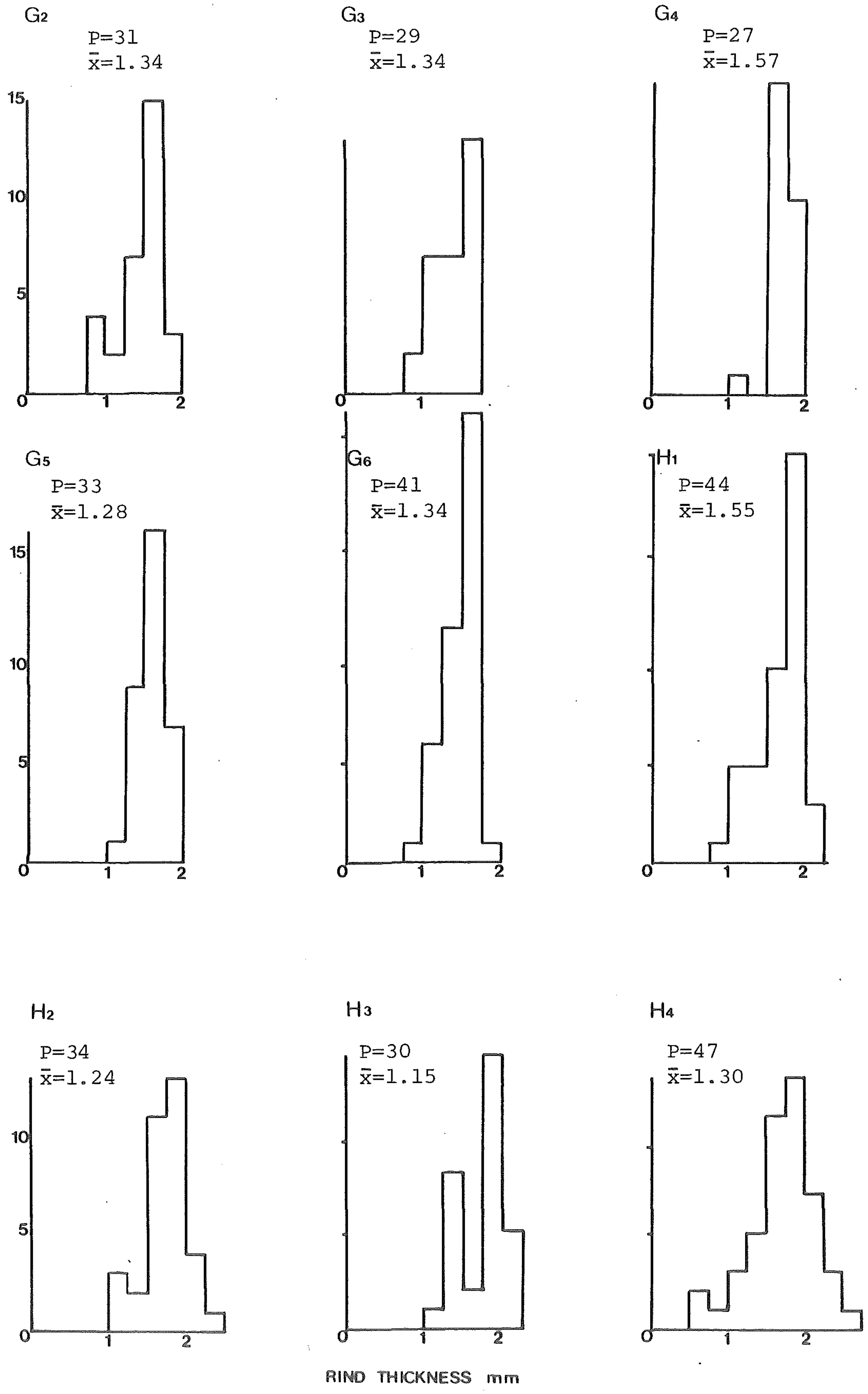


HOOKER GLACIER

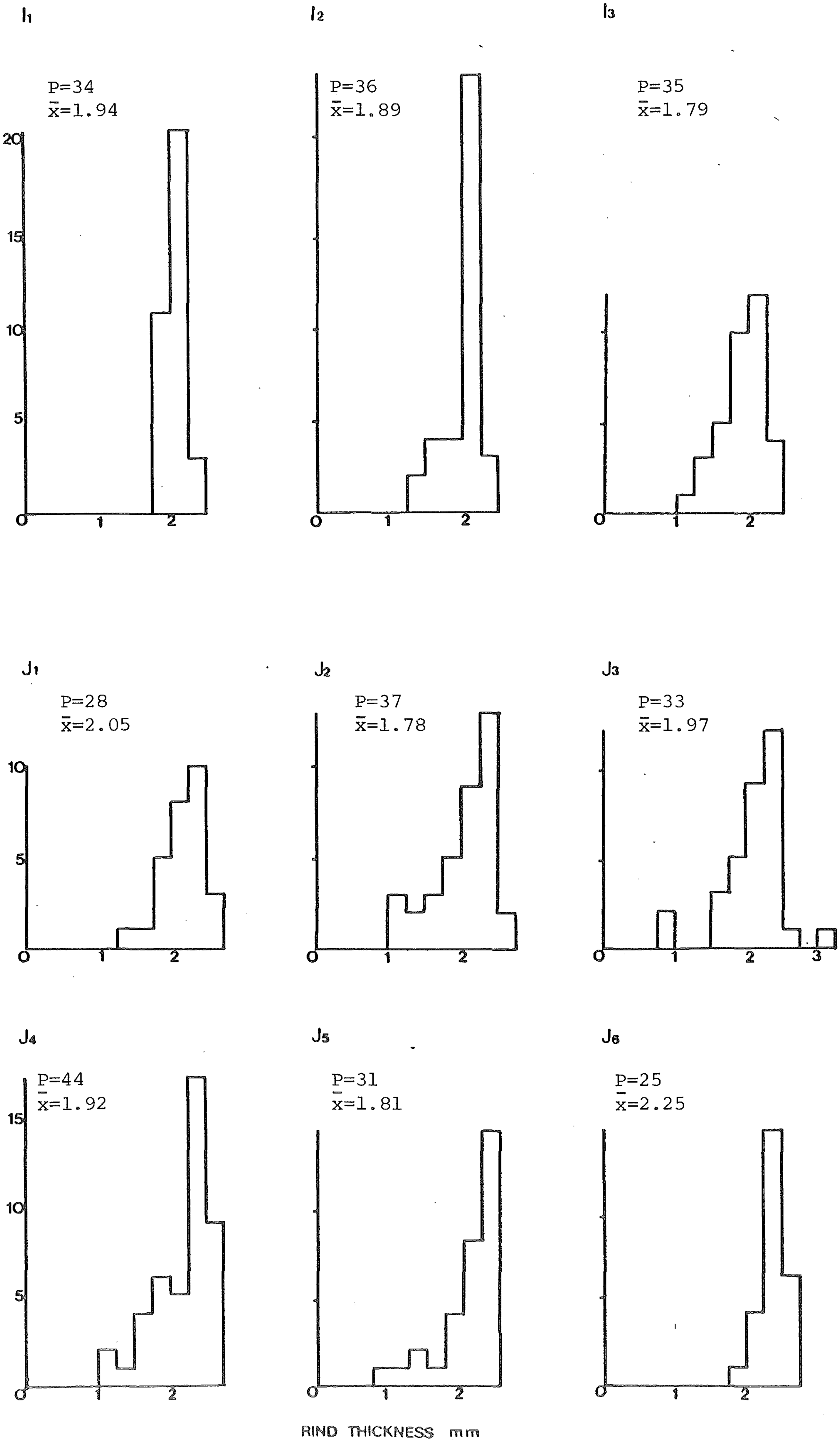
Histograms to show Rock Weathering Rind Distributions for each Site



HOOKER GLACIER

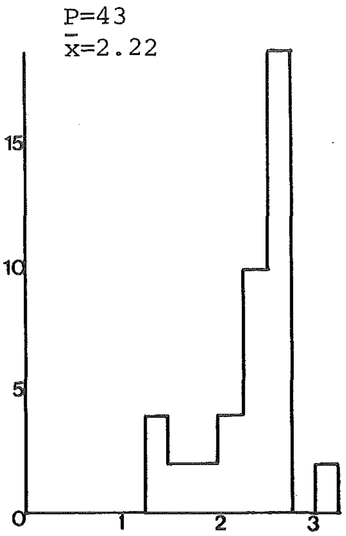


HOOKER GLACIER

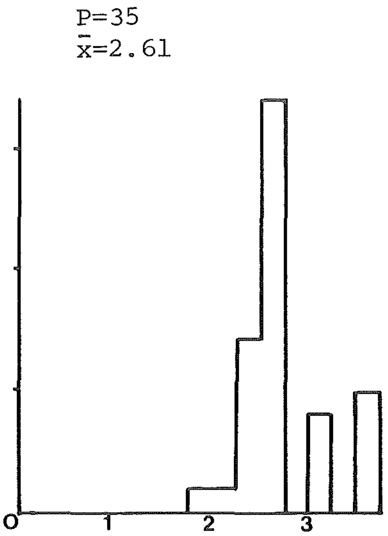


HOOKER GLACIER

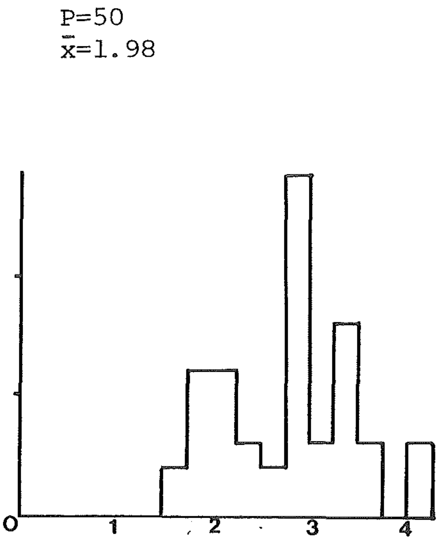
K_1



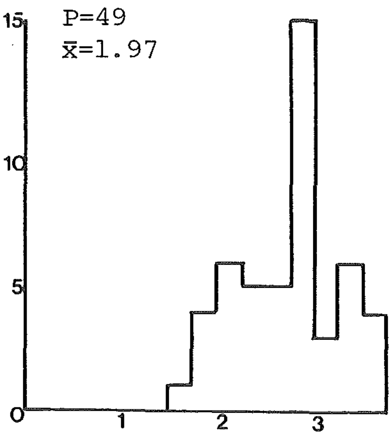
K_2



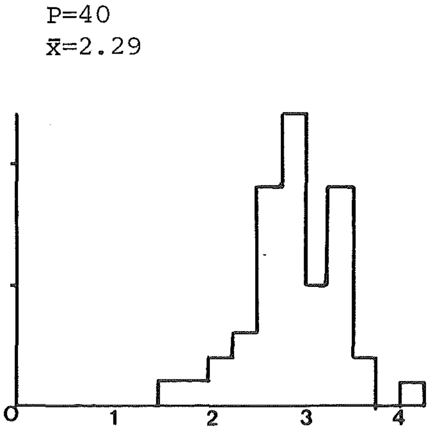
L_1



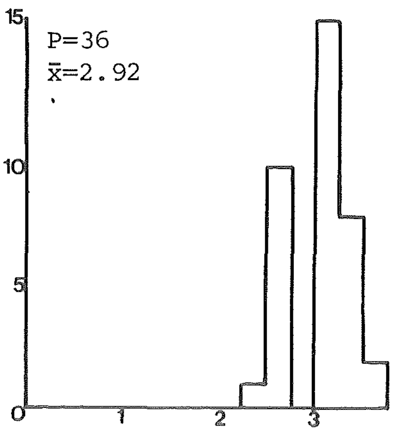
L_2



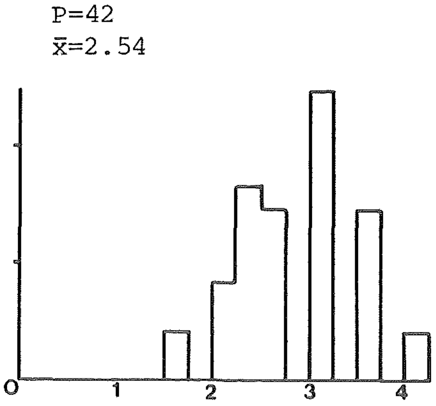
L_3



M_1

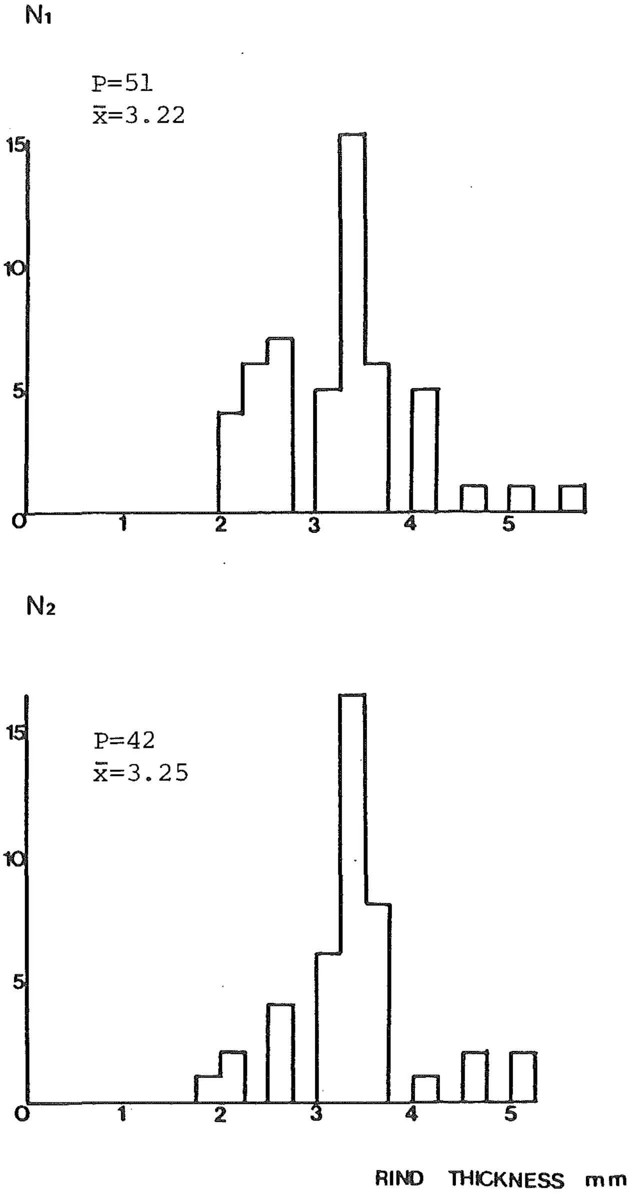


M_2



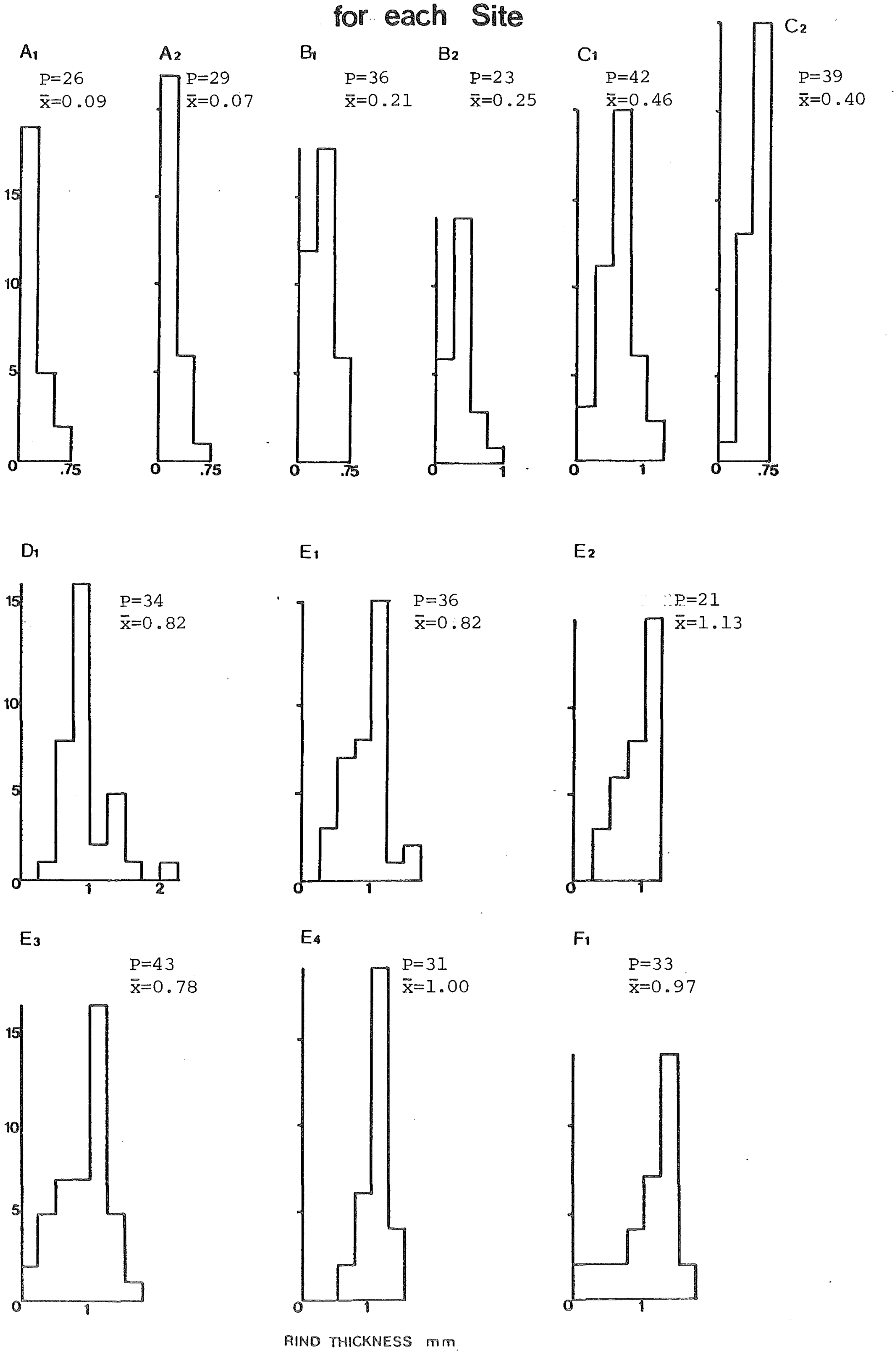
RIND THICKNESS mm

HOOKER GLACIER



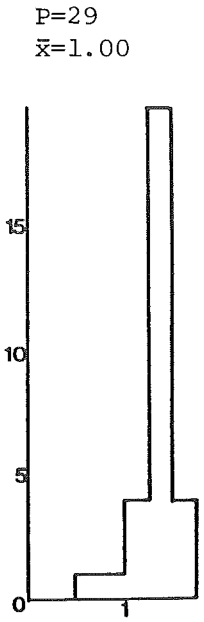
TASMAN GLACIER

Histograms to show Rock Weathering Rind Distributions for each Site

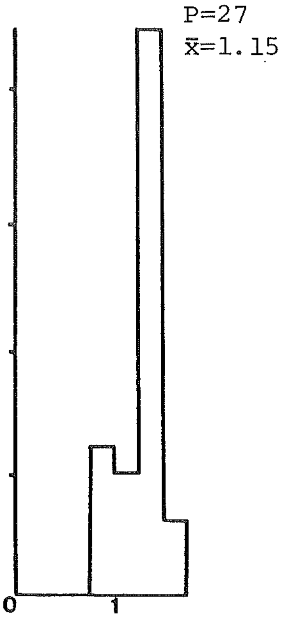


TASMAN GLACIER

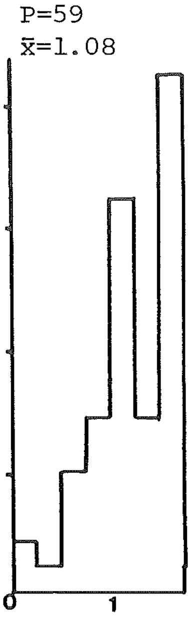
F_2



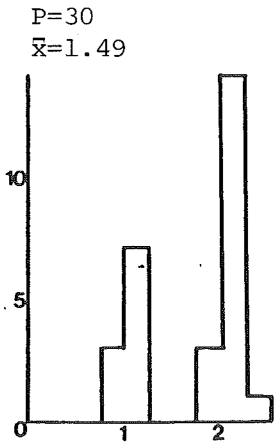
F_3



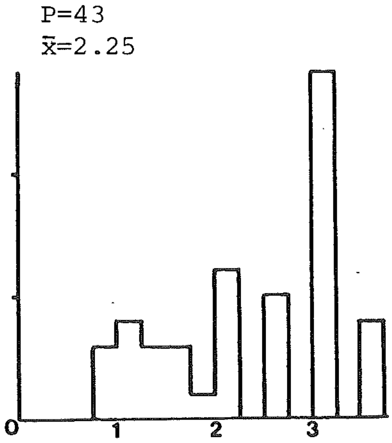
G_1



I_1



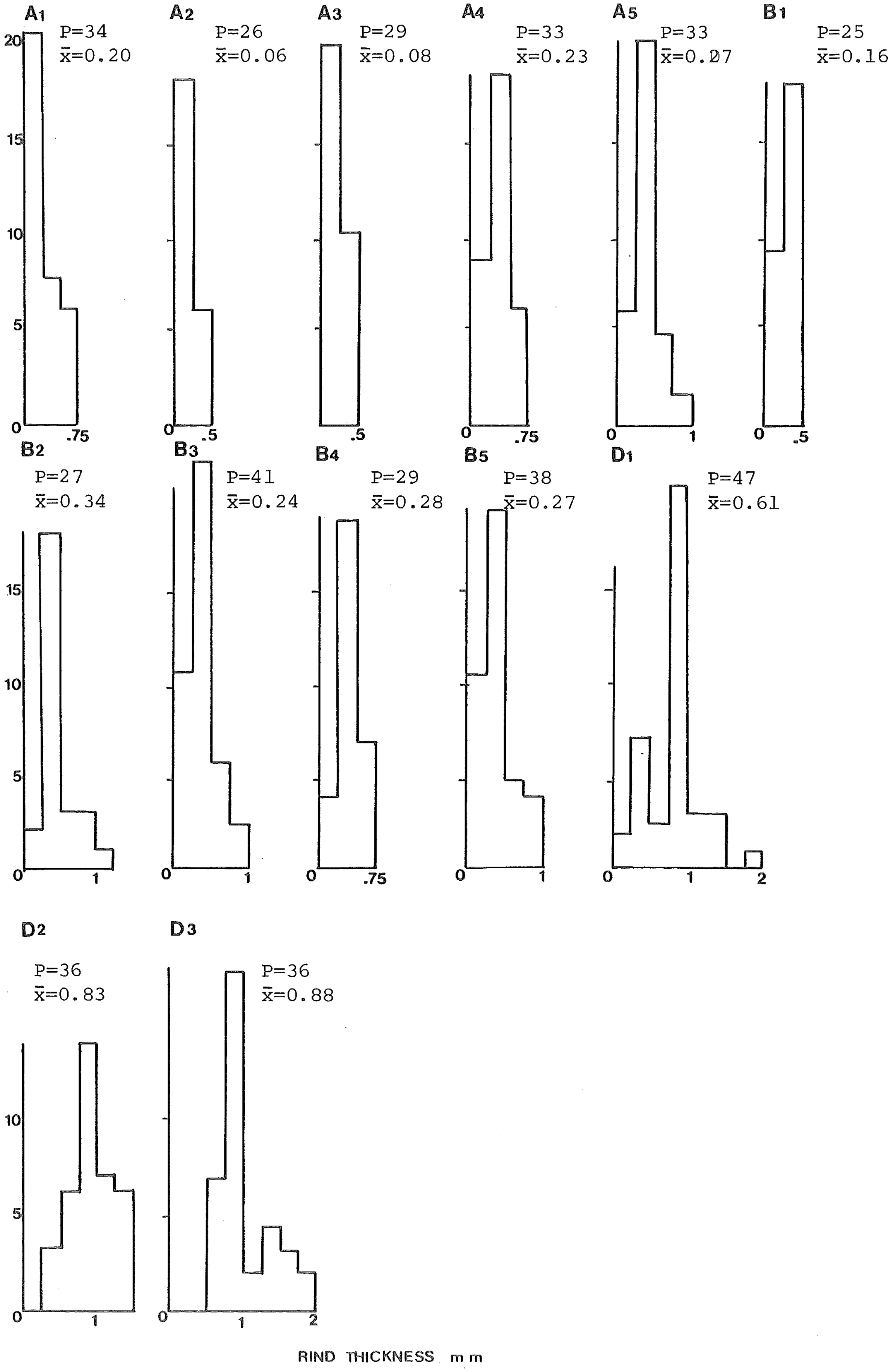
M_1



RIND THICKNESS mm

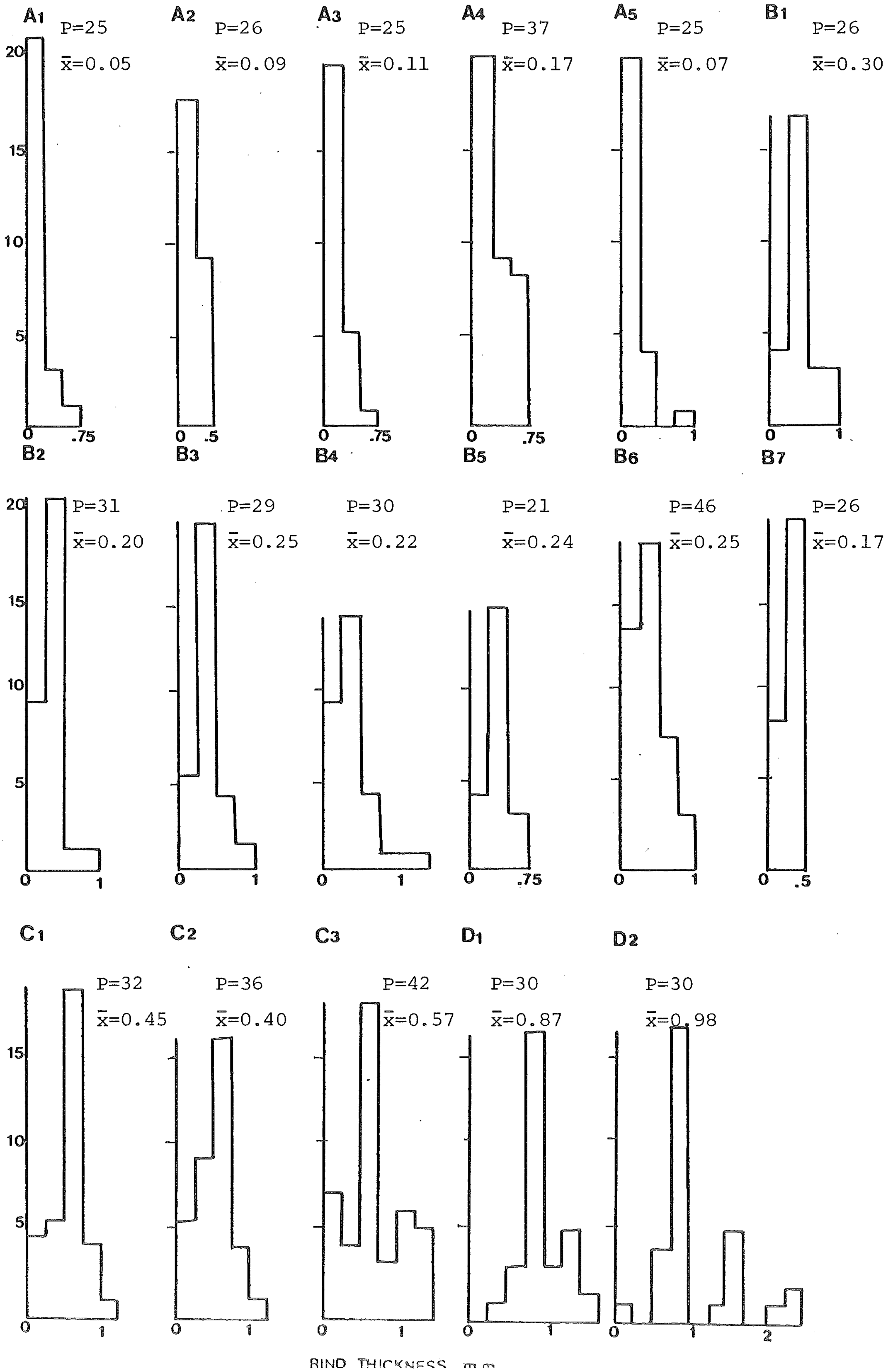
GODLEY GLACIER

Histograms to show Rock Weathering Rind Distributions for each Site

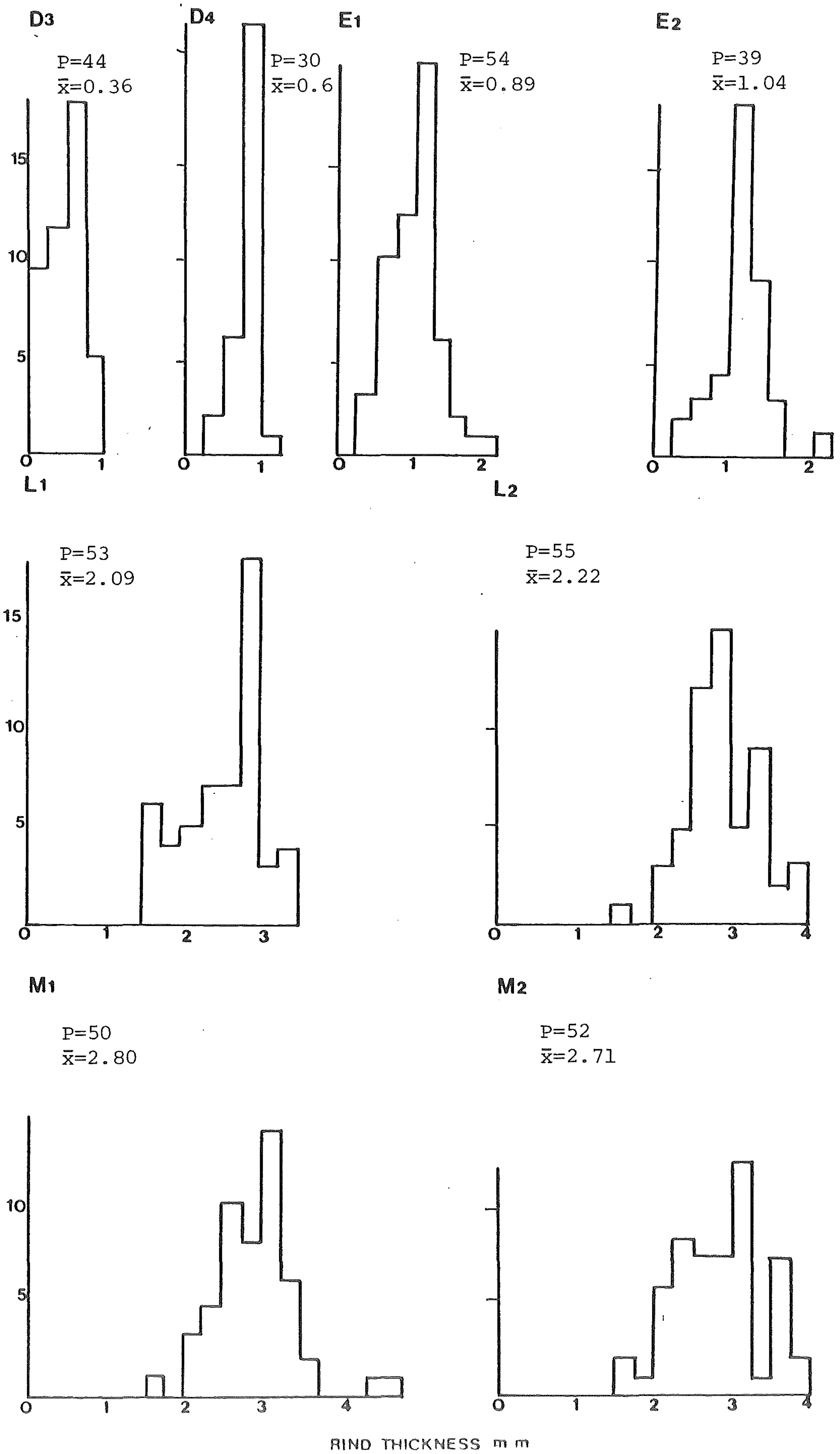


CLASSEN GLACIER

Histograms to show Rock Weathering Rind Distributions for each Site



CLASSEN GLACIER



APPENDIX D

SOIL ANALYSES

NaF Field Test

Poorly-ordered aluminosilicate gels and oxides dissolve in 0.85 molar NaF releasing OH^- ions.

$$Al - OH + F^- \rightarrow Al - F + OH^-$$

In the field the release of OH^- is detected by indicators (phenolphthalein, or a mixture of phenolphthalein and thymolphthalein). The test is carried out using a small sample of soil which is placed on a porcelain plate and to which is added NaF followed by the indicator. Sufficient solution is added as will dampen the soil. The indicator turns red if allophane is present.

after: A.S.Campbell, Department of Soil Science, Lincoln College.

Measurement of Soil pH

see Blakemore,L.C.; Searle,P.L.; Daly,B.K. (1977) Methods for chemical analysis of soils. New Zealand Soil Bureau Scientific Report 10A. D.S.I.R.

Procedure:

Thoroughly mix a portion of the sample as received, but remove any sticks, large roots and stones. Weigh 10g of this material into a 100ml beaker and add 25ml distilled water. Stir vigorously with a high speed stirrer and pour into a suitable vessel for pH measurement. Leave to stand overnight. Repeat procedure and add 10ml 0.1molar KCL solution instead of distilled water. Stir and leave to stand overnight.

Record pH using pH meter buffered using pH4.0 and pH7.0 solutions. Take care to position the electrode in the solution and rinse between each measurement with distilled water.

Repeat experiment with fresh samples.

Phosphate Retention Determination

see Blakemore,L.C. *et al. (op.cit.)*

Procedure:

Preparation of reagent Phosphate retention solution is prepared by dissolving 8.8g potassium dihydrogen phosphate (KH_2PO_4) A.R. and 32.8g anhydrous sodium acetate (CH_3COONa) A.R. in distilled water. Add 23ml glacial acetic acid,A.R. and dilute to 2 litres in a volumetric flask. The pH of this solution should be between 4.55 and 4.65. This is the 'Working Stock Solution' or 'extracting solution'.

Procedure Weigh 5g air dry soil (<2mm) into a stoppered 50ml polypropylene centrifuge bottle or tube and add 25ml P-retention solution. Shake for 24 hours at about 20^{oC}. Centrifuge at 2000 rpm for 15min. Filter into plastic bottles.

Determination

a) Preparation of reagent: Kitson and Mellor reagent was used. Dissolve 8.0g Ammonium molybdate in 160ml distilled water at 60^{oC}. To 244ml H_2O add 60ml conc. $HNCO_3$. Cool, mix together. Add 16ml of 2,5% Ammonium vanadate (in 0.2N NaOH) This makes 480ml altogether. Working reagent prepared by adding 38ml Kitson and Mellor reagent to 82ml H_2O. Add 1ml reagent to 20ml working stock solution, see procedure below.

b) Preparation of standards: Working stock solution; pipette 0,10,20,30, 40, and 50ml aliquots of extracting solution (1mg P/ml) into 50ml flasks and make to volume with distilled water, These solutions contain 0,0.2, 0.4,0.6,0.8 and 1.0mg P/ml and correspond to 100,80,60,40,20 and 0% retention respectively.

Procedure Take 1ml aliquots with an automatic dilutor from the samples in the containers and dispense into labelled 30ml tubes with 20ml of the reagent. Shake well. This is very important. Wipe the delivery tip of the dilutor after each step, and carry out a complete step with distilled water between standards, to avoid possible contamination of working stock solutions. Read absorbance after 15 minutes at 466nm.

Calculation of results Prepare a standard curve and read off unknowns.

APPENDIX E

DETAILS OF THE VEGETATION TRANSECTS DESCRIBED IN CHAPTER 7

Present Vegetation of the Hooker Glacier, Lateral Moraines

Transect I, Quadrats 1-21, 23-25.

QUADRAT NUMBER	1	2	3	4	5	6	7	8	13	9	10	11	12	14	15	16	17	18	19	20	21	23	24	25
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE ^{o}	7	9	6	6	8	10	4	11	16	15	16	15	16	23	17	12	12	14	22	16	16	17	9	19
ASPECT	NE	S	NE	S	N	SE	SE	SE	SE	NW	NW	NW	W	W	E	W	W	W	W	NW	W	W	W	W
AGE yr B.P.	100	100	135	135	135	340	580	580	1830	1150	1150	1490	1490	2160	2160	2540	2540	2540	2540	2540	2540	2540	2540	2540
VEGETATION GROUPS	Bareground		Mid-seral Community on Moraine			*Festuca* Short Tussock				*Chionochloa flavescens* Grassland				Subalpine Short scrub		Shrubland on Moraine								
SPECIES																								
Bareground	5	4	4	3	4	4	3	3																
Epilobium melanocaulon		1	1		1	1	1	1																
Raoulia hastii		1	1	1	1	1	1	1	1															
Parmelia martinii			1				1																	
Raoulia glabra			1	1	1		1																	
Blechnum penna-marina			1	1	1	1	1																	
Parahebe decora			1	1		1									1	1								
Luzula colensoi			1	1	1	1	1	1										1	1					
Racomitrium lanuginosum			1	4	1	1	2	1	2						1	1	1	1	1	1	1	1	2	1
Dracophyllum longifolium			1					1											1	1	1			
Acaena spp.				1	1		1	1		1			1	1	1		1	1			1	4	3	2
Podocarpus nivalis				1					1	5	3	4	3	3	2	3	2	4	2	1				
Hymenanthera alpina				1						1	1	1	1	2		1	1	1	1		1	1	1	1
Aciphylla aurea				1		1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	2	1	
Chionochloa flavescens					1					1	2	1		1	1	1	1	1	1	1	1	1	1	1
Gaultheria crassa					2		1	1	4	1	1	1	1	2	2		2	1	1	1				
Hebe buchananii						1															1	1	1	1
Hebe subalpina						1		1	1	1	2		2					1	1	1				
Festuca novae-zelandiae							1										1							
Anisotome aromatica							1	1																
Blechnum fluviatile								1																
Celmisia walkeri								1	1															
Celmisia hectori								1	1															
Wahlenbergia albomarginata								1	1									1						
Anisotome flexuosa								1	1															
Epilobium brunnescens									1									1	1					1
Pimelea traversii									1						1								1	1
Gentiana corymbifera									1									1						1
Cyathodes fraseri									1															1
Coprosma rigida										1	1	1	1		1			1	1	1	1			
Anisotome haastii										1	1		1	1			1		1		1	1	1	1
Celmisia coriacea										1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Usnea cilifera										1	1	1	1	1	1		1	1						1
Cassinia vauvilliersii											1	1	1	1					1	1	1	1	1	
Coprosma rugosa											1	1	1	2	1	1		1				1	1	1
Pseudopanax colensoi												2							2	1		1	1	
Phyllocladus alpinus													2			1		1						
Ranunculus lyallii													1											
Hebe macrantha															1			1					1	
Myrsine nummularia														1	1									
Coriaria angustissima															1		1	1						
Lycopodium fastigiatum														1	1			1						
Celmisia petiolata														1	1									
Hebe treadwellii														1	1	1	1	1	1					
Olearia nummularifolia														1						1		1	1	
Dracophyllum kirkii																2		1						
Polytrichum juniperinum																			1					
Chionochloa pallens																				1				
Coprosma parviflora																					1			
Hebe sessiliflora																				1	1	1		
Dracophyllum uniflorum																					1			
Olearia moschata																					1	1		

Present Vegetation of the Hooker Glacier, Lateral Moraines,

Transect I, Quadrats 22, 26-48

QUADRAT NUMBER	26	27	28	29	30	31	32	22	33	34	35	36	38	39	40	41	42	43	37	44	45	46	47	48
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE °	23	21	24	7	11	13	23	6	8	22	6	9	17	14	14	13	18	8	16	24	23	7	8	12
ASPECT	W	W	W	NW	W	W	N	W	E	E	E	E	NE	NE	E	E	E	E	E	NW	NW	E	SE	W
AGE yr B.P.	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	3000	3000	3000	3000	3350
VEGETATION GROUPS	Shrubland on Moraine							*Celmisia walkeri* Shrubland	*Chionochloa flavescens* Seral Shrubland										*Chionochloa flavescens* Shrubland	Subalpine Medium-Height Scrub				
SPECIES																								
Bareground											4						2	3		1				
Parahebe decora										1								1						
Luzula colensoi											1		1	1		1			1	1				
Racomitrium lanuginosum						1			1		1	1	1	1		1	1	1	3	1	1	1	1	3
Podocarpus nivalis	1	1	3	1	3	4	3		2	1	1	2	3	1	1	2	3	4						
Hymenanthera alpina					1			1									1		1	1	1			
Aciphylla aurea	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1		2
Chionochloa flavescens			2		2	1	1	3	1	2	1	2		1	2		2	1			2	1		2
Dracophyllum longifolium	1	2	3	1	1						1		2	2	3		1		2	5	1	1	1	1
Gaultheria crassa	1	1	1	1	1	1	2	2	1	1	1	2	1	1	1	3	1	1						
Wahlenbergia albomarginata																		1						
Anisotome flexuosa											1									1				
Epilobium brunnescens																1			1					
Pimelea traversii								1		1									1		1	1	1	
Gentiana corymbifera										1									1					
Cyathodes fraseri								1		1	1					1	1	1		1			1	1
Hebe subalpina								1				1	1	1					1				1	
Cassinia vauvilliersii	1	1	1		1	1	1							1									1	1
Coprosma rigida	3	1		1	1	1							2		2								1	1
Pseudopanax colensoi			1				1		1				1			1		1					1	
Anisotome haastii	1		1	1	1	1	1	1	1	1		1	1	1		1	1	1	1	1	1		1	1
Celmisia coriacea		1	1	1	1	1	1	2	1	1		1				1	1							1
Coprosma rugosa	4	4		5	1		1						3	2	1				1		4	5		3
Phyllocladus alpinus	1									1						1						1		
Ranunculus lyallii	1	1	1	1	1	1	1		1	1			1	1	1	1			1	1			1	1
Usnea cilifera					1								1	1		1								
Hebe macrantha								1							1									
Myrsine nummularia			1		1					1		1	1			1			1				2	
Coriaria angustissima													1						1			1		
Lycopodium fastigiatum								2	1	3	1								1					
Celmisia petiolata	1	2		1		1				1			1	1					1	1				
Hebe treadwellii													1					1	1	1				
Olearia nummularifolia				1								1	1											
Dracophyllum kirkii	1			1															1					
Polytrichum juniperinum												1	1											
Chionochloa pallens		1	1	1						1														
Coprosma parviflora		1	1						2			2					1			1				
Hebe sessiliflora			1			1			1			1			2				1				4	
Dracophyllum uniflorum		1		1		1																2		
Olearia moschata			1					1		1	1	1					1							
Senecio bennettii								1		1	1	1					1					2		
Cardamine debilis								1						1	1				1					
Hieracium praealtum										1						1								
Helichrysum bellidiodes									1	1							1		1					
Hydrocotyle nove-zelandiae																			1					
Muehlenbeckia axillaris																		1	1					
Aristotelia fruticosa								1																
Geum parviflorum								1																
Taraxacum magellanicum								1																
Viola filicaule								1																

Present Vegetation of the Hooker Glacier,Lateral Moraines

Transect I, Quadrats 49-56.

QUADRAT NUMBER	49	50	51	52	53	54	55	56
PLOT AREA m^2	4	4	4	4	4	4	4	4
SLOPE ^{o}	7	15	14	9	10	13	26	16
ASPECT	E	W	W	W	W	W	NW	NW
AGE yr B.P.	3350	3350	3350	3350	3350	3350	3350	3350
VEGETATION GROUPS	Subalpine Medium-Height Scrub		*Hoheria* Scrub					
SPECIES								
Bareground	1							
Luzula colensoi			1					
Racomitrium lanuginosum	3	2		1	2	1	2	1
Podocarpus nivalis				1				
Hymenanthera alpina	1	1	1	1	1	1	1	1
Aciphylla aurea						1	1	1
Chionochloa flavescens	2	2		1	2	1	1	2
Dracophyllum longifolium	1	1	1	1		1		
Anisotome flexuosa			1					
Cyathodes fraseri						1	1	1
Cassinia vauvilliersii	1	1		1	1			
Coprosma rigida	2	2	2	2		1	2	
Pseudopanax colensoi				1		1		
Anisotome haastii	1	1	1	1	1	1	1	1
Celmisia coriacea		1	1	1	1	1		
Coprosma rugosa	2	3	4	2	2	4	3	2
Phyllocladus alpinus	1	1				1		
Ranunculus lyallii	1	1			1	1	1	1
Coriaria angustissima		1						
Lycopodium fastigiatum			l	1				
Celmisia petiolata				1	1			
Hebe sessiliflora				2			1	1
Dracophyllum uniflorum	1	2	1		2			1
Hoheria lyallii			1	2	2	1	2	1

Present Vegetation of the Hooker Glacier, Terminal Moraines, Transect II, Quadrats 1-18.

QUADRAT NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE^o	5	7	11	3	8	13	14	17	9	24	26	12	19	22	27	21	15	18
ASPECT	N	S	N	S	N	N	N	N	S	N	N	SE	SE	SE	SE	S	S	S
AGE yr B.P.	100	135	135	135	340	340	580	1490	1490	1830	1830	2160	2160	2160	2160	2160	2160	2160
VEGETATION GROUPS	New Moraine				Shrubland on Moraine					*Chionochloa flavescens* Shrubland		Seral Medium Height Scrub						
SPECIES																		
Ourisia sessiliflora	1																	
Polytrichum junipernum	1	1																
Raoulia haastii	1	1	1	1	1	1												
Epilobium melanocaulon	1	1																
Blechnum penna-marina	1	1	1		1		1					1						
Bareground	5	4	2	1	1	3						1	1				1	
Hieracium praealtum	1		1	1	1	1	1	1	1	1								
Racomitrium lanuginosum	1	1	4	2	4	2	4	1	1	1	1		1		1		1	
Wahlenbergia albomarginata	1	1	1	1	1	1	1											
Luzula colensoi		1																
Parmelia martinii		1	1			1												
Hymenanthera alpina		1						1	1									
Gaultheria crassa		2	1	2	1	2	1	2	2				1			1		
Luzula rufa			1		1	1				1	1	1	1	1	2	2	1	1
Trifolium repens			1												1			
Epilobium brunnescens			1	1		1	1											
Geum parviflorum			1												1			
Plantago novae-zelandiae			1								1	1				1		
Lycopodium fastigiatum			1		1	1	1						1		1			
Viola filicaule			1	1				1		1								
Parahebe decora				1		1		1										
Geranium sessiliflora				1	1					4	4	1			1			
Chionochloa flavescens				1		1	1	3	2	1		1	1	1	1	2	1	1
Aciphylla aurea				1	1			2	1			1	1		1	1		1
Anisotome haastii					1					1	1		1					
Coriaria angustissima					1													
Cyathodes fraseri					1	1		1				1			1			
Hydrocotyle novae-zelandiae					1		1		1									
Celmisia walkeri						1	1	1										
Pimelea traversii						1		1		1	1		1		1	1	1	
Gentiana corymbifera						1	1	1	1	1	1	1	1	2		1	1	1
Celmisia coriacea								1	1			1	1	1	1		1	
Hebe subalpina								1	2	1	2	2	1	1	1	1	1	1
Coprosma rigida								1	2	1	2	2	1	1	1	1	1	1
Olearia nummularifolia									2			2	1	1		1	1	1
Ranunculus lyallii									1	1	1	1	4	1		1	1	1
Coprosma rugosa										1	1				1			
Myrsine nummularia										1				2	2	2	1	2
Podocarpus nivalis											1					1		
Cardamine debilis											1							
Carmichaelia grandiflora												1	1	1	1			
Blechnum fluviatile												1	1		1			
Anisotome flexuosa												1	1	1		1	1	1
Celmisia petiolata												1	1					
Dracophyllum longifolium												1					1	1
Phyllocladus alpinus												1	3	1		1	1	1
Pseudopanax colensoi												2	2	2			4	2
Hebe treadwellii														1		1		
Myrsine divaricatum														1				
Polystichum vestitum														1		1		1
Cassinia vauvilliersii															1			
Coprosma parviflora															1			

Present Vegetation of the Hooker Glacier, Terminal Moraines,
Transect II, Quadrats 19-33.

QUADRAT NUMBER	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE °	3	5	0	0	6	0	3	9	2	0	4	11	15	9	7
ASPECT	S	S	-	-	S	-	S	S	S	-	S	S	S	SW	NW
AGE yr B.P.	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	2540	3350	3350
VEGETATION GROUPS	*Chionochloa flavescens* Seral Shrubland										*Dracophyllum-Olearia* Scrub				
SPECIES															
Cyathodes fraseri	1				1	1					1				
Luzula rufa	1														
Bareground	3	4	1		1	2	1	2	4	1					
Aciphylla aurea	1	2	1	1	1	1	1	1	1	1		1		1	1
Celmisia coriacea	1	1	1	1	1	1	1		1	1				1	
Chionochloa flavescens	2	1	3	1	3	2	2	1	1	2	1	1		1	1
Coprosma rigida	1	1		1		1		1	1		1	1	1		
Gaultheria crassa	1	1	1	1		1	3	1	1	1	1	1	1	1	1
Hebe subalpina	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Olearia nummularifolia	1	2				1	1	2	1	2		2	4		1
Pimelea traversii	1	1	1	1		1			1						1
Racomitrium lanuginosum	1	1	1	3	1	1	2	1		1	1		1	1	2
Ranunculus lyallii	2	1	2	1	3	1					1	2	1	1	1
Hymenanthera alpina		1													
Lycopodium fastigiatum		1					1	1				1	1		
Usnea cilifera		1		1								1	1		1
Viola filicaule		1		1	1	1						1	1		
Wahlenbergia albomarginata		1	1			1					1			1	1
Dracophyllum uniflorum		1	1	1						2	2	1		2	
Hieracium praealtum		1	1	1	1						1	1			
Celmisia gracilenta			1												
Plantago novae-zelandiae			1												
Polystichum vestitum			1	1	1								1		
Anisotome flexuosa				1											
Geum parviflorum				1								1			
Hydrocotyle novae-zelandiae				1	1	1						1	1	1	1
Dracophyllum longifolium				3			1				1	3	1	2	3
Parahebe decora					1									1	1
Celmisia petiolata					1	1		1	1	1	2	1	1	1	
Epilobium melanocaulon						1					1	1			
Muehlenbeckia axillaris						1									
Podocarpus nivalis							1	3					1	1	1
Pittosporum anomalum								1						1	
Anisotome haastii									1		1	1	1	1	1
Coriaria angustissima										1					
Taraxacum magellanicum											1		1	1	1
Blechnum fluviatile											1	1	1		1
Brachycome sinclairii											1				
Cassinia vauvilliersii											3			2	
Celmisia walkeri											1			1	
Dracophyllum kirkii											1				
Hypochoeris radicata											1				
Blechnum penna-marina												1			1
Carmichaelia grandiflora												1			
Geranium sessiliflorum												1			
Phyllocladus alpinus													2		1
Pygmeae pulvinaris													1	1	1
Senecio bennettii													1		
Colobanthus buchananii														1	1
Craspedia sp. large														1	

Present Vegetation of the Classen Glacier, Terminal Moraines

Transect III, Quadrats 1-25

QUADRAT NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE^o	0	2	5	5	5	0	0	3	5	6	5	6	6	2	0	7	7	11	9	14	12	11	8	9	13
ASPECT	-	SE	SE	NW	N	SE	SE	SE	S	SE	SW	N	NW	S	-	S	S	S	S	S	E	E	E	E	NE
AGE yr B.P.	60	60	60	60	60	60	60	60	60	100	100	100	100	100	100	100	100	135	135	135	135	135	135	135	135
VEGETATION GROUPS	New Moraine, Boulder Surface																	Closing Plant Cover							
SPECIES																									
Blechnum penna-marina	1	1		1				1	1	1	1			1				1	1	1	1	1	1	1	1
Celmisia petiolata	1	1	1	1	1	1	1		1	1	1		1				1								
Celmisia walkeri	1				1	1	1	1		1			1					1		1					
Gaultheria crassa	1		1					2	1	1								1	1	1	1		1	1	1
Gaultheria depressa	2	1		1		1	2													1		1			
Parahebe lyallii	1		1		1	1	1	1	1	1							1	1	1	1	1	1	1	1	1
Bareground	4	3	5	5	2	3	4	2	5	5	3	3	5	5	5	5	3	2	3	4	2	3	2	5	5
Viola cunninghamii	1		1		1	1			1	1			1	1			1								
Cyathodes fraseri		1			1	3	1		1				1	1			1								
Luzula rufa		1				1				1								1	1	1	1	1	1	1	1
Racomitrium lanuginosum		2				2		1	3	1	2	2	1	2	2		2	2	2	2	3	2	3	1	1
Dracophyllum uniflorum			1			1	3	1		1				1			1								
Myosotis macrantha			1					1		1								1		1	1	1		1	
Ranunculus cheesemanii			1																						
Raoulia haastii									1	1					1	1	1	1				1			
Muehlenbeckia axillaris											1	1	1	1				1		1	1	1			
Aciphylla aurea																		1							
Celmisia coriacea																		1							
Hebe subalpina																		1		1					
Hieracium praealtum																		1	1				1	1	1
Lycopodium fastigiatum																		1	1	1	1		1	1	
Wahlenbergia albomarginata																			1	1					1
Epilobium spp.																						1			
Acaena inermis																								1	
Dracophyllum kirkii																								1	

Present Vegetation of the Classen Glacier, Terminal Moraines,

Transect III, Quadrats 26-50.

QUADRAT NUMBER	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE °	21	15	16	17	13	8	8	8	16	17	17	17	17	4	8	19	11	15	14	15	5	23	28	19	9
ASPECT	E	E	S	S	S	S	S	S	S	S	S	S	W	W	E	E	SW	SW	NE	NE	NE	NE	E	E	E
AGE yr B.P.	135	135	840	840	840	840	840	840	840	840	840	840	3350	3350	3350	3350	3350	3350	3350	3350	3350	3350	4200	4200	4200
VEGETATION GROUPS	Closing Plant Cover		Closed Plant Cover						*Cassinia*-*Poa* Shrub -land				*Gaultheria*-*Dracophyllum* Scrub				*Gaultheria crassa* *Chionochloa* Grassland						*Dracophyllum* Scrub		
SPECIES																									
Blechnum penna-marina	1	1	1		1				1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Gaultheria crassa	1																	3	2	2			1	1	1
Gaultheria depressa			1		1	1		1					2	2	2	1	2				2		1	1	1
Parahebe lyallii	1	1																							
Bareground	4	4	1										2	1	1	2	1	1	1	2					
Viola cunninghamii			1	1						1											1	1			
Cyathodes fraseri					1	1	1						1		1	1				1				1	1
Luzula rufa	1	1	1								1	1	1												
Racomitrium lanuginosum	1	1	1							3	1	1	1	2	2	1	1	1	1	1					
Myosotis macrantha	1																								
Raoulia haastii		1	1	1	1	1	1																		
Muehlenbeckia axillaris			1						1	1	1	1	1	1	1	1			1				2	1	1
Aciphylla aurea					1		1		1	3	1	1	2	1	1	1	1	1	1	1					
Celmisia coriacea			3	3	3	4	2	3	1		1	1	1	1	1	1	1	1	2	1		1		1	1
Hebe subalpina	1								3	4	3	3	1	1	1	1	1	1	1	1	1	1			
Hieracium praealtum			2	1	1	1	1	1																	
Lycopodium fastigiatum	1	1						1	1	1	1	1					1	1			1	2	1	1	1
Wahlenbergia albomarginata		1						1		1	1														
Epilobium spp.			1							1															
Dracophyllum kirkii		1																							
Olearia nummularifolia	1		2	3	3	2	1			1	1														
Cassinia vauvilliersii	1						3		3	2	2	2	1		1	1		1	1	1		1	1	1	1
Phyllocladus alpinus			1																						
Anisotome aromatica			1		1					1	1	1						1	1	1					
Geranium sessiliflora			1			1																			
Hymenanthera alpina			3	3	1		1		1																
Poa spp.				1	1		1		1	1	2	1									1				1
Cyathodes colensoi				1	1		1																		
Rumex acetosella						1	3	2	1	1	1													2	
Podocarpus nivalis								3	1									2							
Aristotelia fruticosa								2															1	1	
Dacrydium bidwilli								1																	
Dracophyllum longifolium								1	2		3	1	1	2	2	2	2	1		1			1		1
Coprosma ciliata								1	1		1	1			1			1		1	1				1
Gentiana corymbifera									1			3								1	1	2	2	2	2
Pimelea traversii									1								1					1			
Celmisia gracilenta										1													1		
Senecio cassinioides										1	2	1													
Geranium microphyllum											1												1		
Celmisia lyallii															1							1	1	1	
Chionochloa pallens																		1	1						
Coprosma serrulata																		1	1			1			
Chionochloa flavescens																			3	2	2		1	1	1
Hebe treadwellii																			1			1	2	1	1
Polystichum vestitum																			1						
Coprosma parviflora																					1		1	1	1
Celmisia petiolata																							1		1
Usnea cilifera																							1	1	
Aristotelia fruticosa																								1	1
Forstera sedifolia																								1	

Present Vegetation of the Classen Glacier Terminal Moraines,

Transect III, Quadrats 51-75.

QUADRAT NUMBER	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
PLOT AREA m^2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SLOPE °	13	14	13	8	26	22	23	24	22	16	16	23	19	17	18	17	23	22	17	9	7	14	9	25	22
ASPECT	E	E	SE	SE	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
AGE yr B.P.	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200
VEGETATION GROUPS	*Dracophyllum* Scrub				*Dracophyllum longifolium* Scrub									*Cassinia- Senecio* Tall Scrub											
SPECIES																									
Blechnum penna-marina	1	1	1		1	1	1	1	1	1	1	1	2	1		1	1		1	1	1	1			1
Cassinia vauvilliersii	1	1	1	1	1	1	1	2	1		1	1	1	1	1	1		1	2	2	1	1	2		1
Celmisia coriacea		1	1		1	1	1		1	1	1	1		1	1	1	1	1	1	2	2	1	1	1	2
Coprosma ciliata	1	1					1		1	1	1	1	1	1	1	1			1	1	1	1			1
Dracophyllum longifolium	1				2	3	2	2	3	3	3	5	2	3		1	1	1	1	1		1	1	1	1
Hebe subalpina	1		1																						
Lycopodium fastigiatum	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1						1	1	1
Muehlenbeckia axillaris	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1		1	1	
Pimelea traversii			1	1		1					1														
Podocarpus nivalis	1	1												1	1	2	1	2	1	1		1			
Epilobium spp.	1																								
Racomitrium lanuginosum					1	1			1	1					1		1				1	1	1	1	
Viola cunninghamii					1				1																
Senecio cassinioides							1		1																
Cyathodes fraseri					1					1	1					1									
Dracophyllum uniflorum	2	2	2	2												1		2							
Gaultheria depressa			1														1		1						
Bareground	1	1			1	1		2	1	1		1		1								1			
Coprosma serrulata					1						1	1													
Gaultheria crassa			1	1										1	1	1	1	1		1	1	1		1	
Hebe treadwellii			1												1			1						2	
Coprosma parviflora	1	1																			2	1			
Usnea cilifera	1	1	1	1													1	1							
Aristotelia fruticosa			1	1															1					1	
Forstera sedifolia	1																								
Senecio schorzonoroides	1																								
Raoulia glabra	1																								
Craspedia sp.large				1	1			1	1																
Hebe ciliolata					1																				
Hypochoeris radicata					1		1	1	1	1	1	1	1	1											
Dracophyllum kirkii						1			1				1												
Brachycome sinclairii							1			2		1	1												
Celmisia walkeri									1	1	1	1			1	1	1	1	1	1					1
Aciphylla aurea														1	1	1	1	1	1	2	1		1	1	1
Olearia nummularifolia														1	1	1	1			1	1	1	1	2	1
Rumex acetosella														1	1	1	1	1	3		1	3	2	1	2
Phyllocladus alpinus															2		2		1	1	1	1	1		1
Poa sp.															1	1					1	1		1	
Polystichum vestitum															1	1	1	1	1	1	1	1	1	1	2
Aciphylla scott-thompsonii																1	2		1				1		
Myosotis macrantha																1	1	1		1	1			1	
Acaena inermis																	1	1							
Anisotome aromatica																	1		1			1	1		1
Cyathodes colensoi																	1					1		1	
Ranunculus lyallii																		1			1	1	1	1	1
Coprosma pumila																		2	1						
Helichrysum bellidioides																			1	1					
Ourisia caespitosa																			1	1					
Ranunculus cheesemanii																				1				1	
Celmisia lyallii																					1				
Brachycome sinclairii																						1			

Present Vegetation of the Classen Glacier Terminal Moraines,

Transect III, Quadrats 76-84.

QUADRAT NUMBER	76	77	78	79	80	81	82	83	84
PLOT AREA m^2	4	4	4	4	4	4	4	4	4
SLOPE °	23	17	25	22	23	16	17	10	18
ASPECT	S	S	S	S	S	S	S	S	S
AGE yr B.P.	4200	4200	4200	4200	4200	4200	4200	4200	4200
VEGETATION GROUP	*Cassinia* - *Senecio* Tall Scrub								
SPECIES									
Aciphylla aurea	1	1	1	1		1	1	1	1
Blechnum penna-marina	1	1	1		1	1		1	1
Cassinia vauvilliersii	1	1	1	2	2	2	1	1	
Celmisia walkeri	1	1		1					
Coprosma ciliata	1	1	1		1		1	1	
Dracophyllum longifolium	1	1	1	1	1			1	
Gaultheria crassa		1	1	1	1	1	1	1	1
Hebe subalpina	1	1	1	1		1	1	1	2
Lycopodium fastigiatum		1		1	1	1	1	1	
Muehlenbeckia axillaris									1
Olearia nummularifolia	1	1	1	1	1		1	2	1
Podocarpus nivalis	1		1		1		1	1	
Bareground			2		1				
Rumex acetosella		1			1			1	1
Celmisia coriacea	1	1	1	1	1	1	1		1
Hebe treadwellii		2			1	2			
Phyllocladus alpinus			1	1					
Poa sp.					1				
Racomitrium lanuginosum	1	2	2	1	2	2	2	3	3
Anisotome aromatica		1			1			1	1
Cyathodes colensoi					1				1
Gaultheria depressa				1	1				
Ranunculus lyallii	2	1	2	2	1	2	2	2	3
Coprosma pumila					1				
Helichrysum bellidioides			1						
Ranunculus cheesemanii			1			1			
Celmisia lyallii					1			2	
Geranium microphyllum		1	1		1	1	1		
Luzula rufa		1					1		
Hymenanthera alpina	1	1					1		
Viola cunninghamii	1								1
Pimelea traversii	1	1							
Hypolepsis millefolium				1		1			1

Holocene glacier activity in New Zealand

COLIN J. BURROWS and ANNE F. GELLATLY

Burrows, C.J., and Gellatly, A.F., 1982 07 01: Holocene glacier activity in New Zealand. – In *Holocene Glaciers* (W. Karlén, Ed.). *Striae*. Vol. *18*. pp. 41—47. Uppsala. ISBN 91-7388-036-1. ISSN 0345-0074.

STRIAE

XI КОНГРЕСС
INQUA
МОСКВА 1982

Radiocarbon dates show that the last main Pleistocene glacial event in New Zealand ended before about 14 000 yr B.P. In the interval 14 000—9000 yr B.P. there is evidence for several events during which, although glaciers were much smaller than those of the Pleistocene, they were much greater than at any subsequent time. More data are needed to establish a clear chronology for this period. A lesser glacial advance is dated about 8000 yr B.P.

There are no definite dates for glacier activity, then, until about 4500 yr B.P. Then some glaciers advanced several kilometres beyond their modern terminal positions. Smaller advances (generally of decreasing magnitude) occurred about 3500, 2300, 1800, 1600, 1000, 860, 660, 530 and 340 yr B.P. There were subsequent small advances for which there are no radiocarbon dates.

Relative dating, by rock weathering rinds, indicated that there were advances about 300, 550, 800, 1000, 1800, 2500, 4500 and 8000 years ago. The dates obtained by this method for some older surfaces, with the presently available calibration curve, are too young.

Dr. C.J. Burrows and Miss A.F. Gellatly, Botany Department, University of Canterbury, Christchurch, New Zealand.

Holocene glacial deposits in New Zealand are found mainly in the mountain system on either side of the Southern Alps, South Island, between 43°S. and 44°S. latitude (Fig 1). The mountain peaks are generally 1800 m–2000 m high, a few rising to more than 3000 m. The mountains experience a temperate, oceanic climate with a strong westerly component and precipitation is 250 cm–500 cm (or more), per annum. Present glaciers are almost all confined to the central, highest part of the Alps and glacier termini descend to 310—400 m on the west (Westland) and 760—850 m on the east (Canterbury).

During the Pleistocene large glaciers filled all the valleys in this part of the Alps. They receded earlier than about 14 000 years ago (Suggate 1965, Burrows, unpublished data). In the period 12 000–9000 years ago there were readvances, with some glaciers reaching about a third the length of the glaciers during the last main Pleistocene maximum (Porter 1975, Burrows 1977). Subsequently (5000–90 years ago) there were several much smaller episodes of glacial activity during which moraines were formed successively nearer the positions of the present glaciers. At most the glaciers then extended no further than 5 kilometres, and in some instances no more than one kilometre, beyond present terminal positions. The existing glaciers are much reduced; some mountain valleys, now lacking ice, have moraines or rock glaciers from earlier episodes (Birkeland 1981).

The New Zealand glacial chronology for the Holocene, (and the two thousand years immediately preceding it), has been established by means of relatively few radiocarbon dates and a range of relative dating methods of which the most useful has been rock weathering rind thickness. In addition direct observations of some glacier termini have been made, from 1862 A.D. The older radiocarbon dates are from scattered localities but some very useful younger sequences, from superimposed deposits, are available.

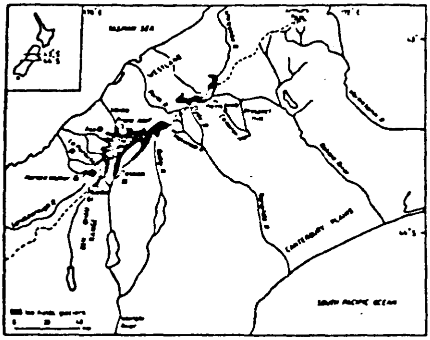


Figure 1. Central South Island, New Zealand, showing ice-fields and glaciers and places mentioned in the text.

The first work of any consequence on the Holocene glacial record was that of McGregor (1967) in the Ben Ohau Range, South Canterbury (Fig. 1, 2, Tab. 1). McGregor had available only imprecise relative methods for dating the moraine sets which he recognized. Burrows and Lucas (1967), Burrows (1973, 1975), Burrows and Maunder (1975), Burrows and Russell (1975) and Burrows, Chinn and Kelly (1976) attempted to date moraines in several localities in Canterbury using the relative method lichenometry for the younger deposits and a few radiocarbon dates for some of the older deposits. Historic records of the glaciers are noted in some of these references. Lawrence and Lawrence (1965) used tree rings to obtain some ages and Wardle (1973, 1978) dated some young moraines by tree rings and radiocarbon dates. One old moraine was dated by radiocarbon and Wardle also reviewed historic records.

Although the radiocarbon dates provided a basic framework for a more precise chronology there were problems of correlation because the dates often could not be related, stratigraphically, to specific moraine surfaces and because they were few, and of sporadic occurrence. Thus local name systems were established for the rock-stratigraphic units in different valleys. Attempts were made to compare sequences in the different valleys (Burrows and Russell 1975, Burrows 1975, 1977, 1980). On reflection, it would have been better to wait until more dates were available, before this was done.

In 1976 T.J. Chinn completed a study of the use of the relative dating method, rock weathering rind thickness measurement, for aging moraines in the Waimakariri Valley, Canterbury. His work was refined and published in 1981. In 1978 P. Birkeland (1981) used Chinn's calibration curve for weathering rind thickness, and several other relative dating methods, to construct a chronology for the Ben Ohau Range. He also re-examined the Cameron, Rakaia and Mount Cook sequences which had been described by Burrows.

Most recently Anne F. Gellatly, using weathering rind and other criteria, has fully re-examined the Mount Cook sequence. She has found the tree ring chronology of Lawrence and Lawrence (1965) and the lichen chronology of Burrows (1973) to be in error. Radiocarbon dating by Burrows (1980) had already shown that the older part of it was suspect. The younger Cameron and Rakaia moraines (Burrows 1975, Burrows and Maunder 1975) also require revision of their dating. Birkeland (1981) indicates approximate time ranges of some moraines in these localities.

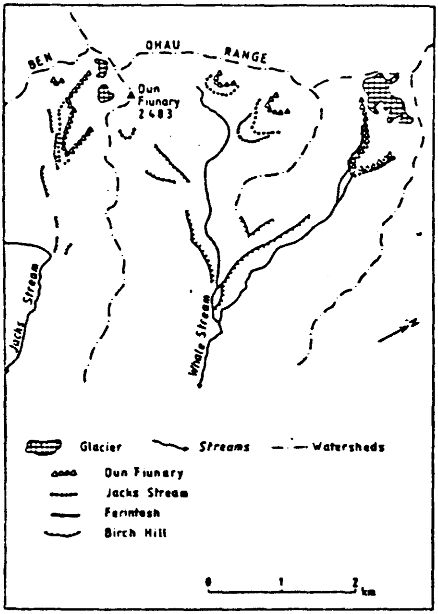


Figure 2. Part of the Ben Ohau Range, Canterbury, showing moraine groups mapped by McGregor (1967).

Table 1. McGregor's (1967) Moraine Groups of the Ben Ohau Range.

Moraine Group	Criteria for Recognition
Dun Fiunary (youngest)	Sharp-crested, probably ice-cored; almost no vegetation; dark grey colour.
Jacks Stream	Rounded crests; no loess; rarely breached by streams; only scattered low plants; some rocks pink-weathered.
Fenntosh	Rounded crests; no loess; breached by streams in some valleys; twenty to fifty percent vegetation cover.
Birch Hill (oldest)	Smooth surfaces; loess-covered; partially erodedby streams; completely vegetation covered except projecting blocks.

The Birch Hill moraines are usually well-separated from the other groups which are arranged, concentrically, near the Dun Fiunary moraines invalley heads.

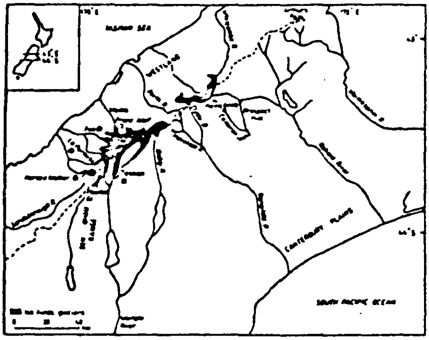


Figure 1. Central South Island, New Zealand, showing ice-fields and glaciers and places mentioned in the text.

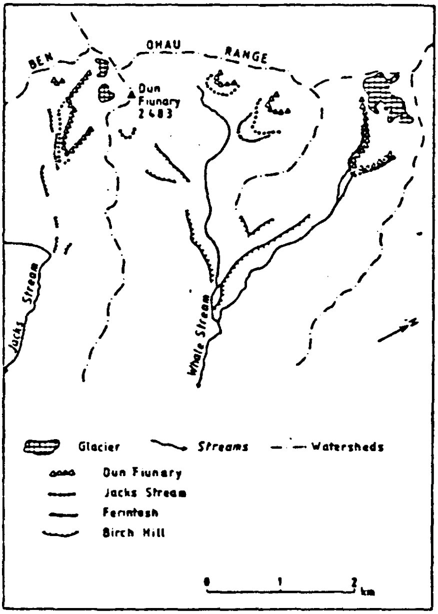


Figure 2. Part of the Ben Ohau Range, Canterbury, showing moraine groups mapped by McGregor (1967).

Table 1. McGregor's (1967) Moraine Groups of the Ben Ohau Range.

Moraine Group	Criteria for Recognition
Dun Fiunary (youngest)	Sharp-crested, probably ice-cored; almost no vegetation; dark grey colour.
Jacks Stream	Rounded crests; no loess; rarely breached by streams; only scattered low plants; some rocks pink-weathered.
Ferintosh	Rounded crests; no loess; breached by streams in some valleys; twenty to fifty percent vegetation cover.
Birch Hill (oldest)	Smooth surfaces; loess-covered; partially erodedby streams; completely vegetation covered except projecting blocks.

The Birch Hill moraines are usually well-separated from the other groups which are arranged, concentrically, near the Dun Fiunary moraines invalley heads.

The first work of any consequence on the Holocene glacial record was that of McGregor (1967) in the Ben Ohau Range, South Canterbury (Fig. 1, 2, Tab. 1). McGregor had available only imprecise relative methods for dating the moraine sets which he recognized. Burrows and Lucas (1967), Burrows (1973, 1975), Burrows and Maunder (1975), Burrows and Russell (1975) and Burrows, Chinn and Kelly (1976) attempted to date moraines in several localities in Canterbury using the relative method lichenometry for the younger deposits and a few radiocarbon dates for some of the older deposits. Historic records of the glaciers are noted in some of these references. Lawrence and Lawrence (1965) used tree rings to obtain some ages and Wardle (1973, 1978) dated some young moraines by tree rings and radiocarbon dates. One old moraine was dated by radiocarbon and Wardle also reviewed historic records.

Although the radiocarbon dates provided a basic framework for a more precise chronology there were problems of correlation because the dates often could not be related, stratigraphically, to specific moraine surfaces and because they were few, and of sporadic occurrence. Thus local name systems were established for the rock-stratigraphic units in different valleys. Attempts were made to compare sequences in the different valleys (Burrows and Russell 1975, Burrows 1975, 1977, 1980). On reflection, it would have been better to wait until more dates were available, before this was done.

In 1976 T.J. Chinn completed a study of the use of the relative dating method, rock weathering rind thickness measurement, for aging moraines in the Waimakariri Valley, Canterbury. His work was refined and published in 1981. In 1978 P. Birkeland (1981) used Chinn's calibration curve for weathering rind thickness, and several other relative dating methods, to construct a chronology for the Ben Ohau Range. He also re-examined the Cameron, Rakaia and Mount Cook sequences which had been described by Burrows.

Most recently Anne F. Gellatly, using weathering rind and other criteria, has fully re-examined the Mount Cook sequence. She has found the tree ring chronology of Lawrence and Lawrence (1965) and the lichen chronology of Burrows (1973) to be in error. Radiocarbon dating by Burrows (1980) had already shown that the older part of it was suspect. The younger Cameron and Rakaia moraines (Burrows 1975, Burrows and Maunder 1975) also require revision of their dating. Birkeland (1981) indicates approximate time ranges of some moraines in these localities.

It is intended to outline the current state of knowledge of Holocene (and immediately pre-Holocene) glacial chronology by means of tables. Radiocarbon dates and the relative dating results are tabulated separately. Presentation and discussion of the results will cover the time periods 12 000—8000 yr B.P., and 5000-present. In this account McGregor's terminology (Tab. 1) is used as a basis for comparison. Dates for moraines in other localities are given as relating to named moraines or moraine sets; the names are used in an informal way.

Radiocarbon Date Chronology

Only those dates which are judged to be unambiguously related to glacial or proglacial deposits are listed here. Numbers of dates from other kinds of deposits, believed to be related to periods of cool climate, were listed by Burrows (1979). In the tables below (Tab. 2, 3) an indication of whether the date is minimal, maximal and/or proximate to a glacial event is given. Dates for material on soils, buried by till, record processes near the beginning of glacier expansion. Dates judged (on ancillary evidence) to be too young or too old by large factors are excluded. All dates are according to the half life 5568 yr for radiocarbon.

Relative Dating Chronology

Rock Weathering Rinds

The most generally useful method so far developed, one which can be used on the sandstone rocks occurring widely in Canterbury, but not on Westland schists, is the measurement of weathering rind thickness. T.J. Chinn (1981) constructed a calibration curve for this method mainly from surface rocks on radiocarbon-dated landslides. This curve has been used, also, by Birkeland (1981) and Gellatly (1981, in preparation). Problems with the calibration and consequent interpretation of some results on older Holocene surfaces are mentioned in the Discussion.

Birkeland worked in the Ben Ohau Range, Canterbury, on the same deposits which McGregor (1967) had studied (Fig. 2). His results (Tab. 4) show that five groups of moraines are recognizable and, at least in places, are well-separated, spatially. Four of these groups had been recognized by McGregor, on more subjective criteria (Tab. 1).

Chinn's (1981) results from the Waimakariri Valley (Fig. 3), Canterbury, are given, not as mean measurements, but as modes. This seems more appropriate than use of means,

Table 2. Radiocarbon Dates Associated with Glacial Deposits 12 000—8000 yr B.P.

Radiocarbon Date (Yr B.P.)	Laboratory Number	Locality, Latitude, Longitude, Altitude	Moraine	Description of Deposit	Significance	Reference
11450±200	NZ-4234	Canavans Knob, Waiho, Westland 43°23'S, 170°10'E 140 m	Waiho Loop	Wood in lake silt beneath till, judged to be associated with proglacial conditions.	Dates an advanced position of Franz Josef Glacier during recession from an advance which extended 10.5 km beyond the present terminal position.	Wardle (1978)
9730±90	NZ-4772	Sinclair Plateau, Clyde River, Canterbury 43°24'S, 170°48'E 990 m	Sinclair	Organic sediment from bottom of infilled tarn on surface within moraine.	Minimal age for recession of ice from Plateau after an advance of Clyde Glacier which extended 10 km beyond the present terminal position.	C.J. Burrows (unpublished)
9520±100	NZ-688	Cameron Valley, Canterbury 43°24'S, 171°03'E	Wildman 2	Wood from soil on glacial outwash, buried by colluvium.	Minimal age for the younger of two advances of Cameron Glacier, which extended 6 km beyond the present terminal position.	Burrows (1975)
9480±130	NZ-4484	Meins Knob, Rakaia River, Canterbury 43°18'S, 170°55'E 1220 m	Reischek Drift	Peat from bottom of shallow bog on summit of ridge.	Minimal age for recession of Rakaia Glacier which had overtopped a level ridge and left drift on the surfaces beyond. Glacier terminus was then at least 5.5 km down-valley of present terminal position and glacier surface was at least 300 m higher than present valley floor.	Burrows (1979)
8960±150	Birm-523	Arthurs Pass Canterbury-Westland 42°54'S, 171°33'E 914 m	Dobson	Organic sediment from bottom of bog immediately up-valley from moraine.	Minimal age for recession of ice from moraine. Existing glaciers in the area are tiny ice-patches at 1700 m.	Burrow et al. (1976)
7940±70	NZ-4508	Black Birch Creek Mount Cook, Canterbury 43°45'S, 170°06'E 700 m	Sebastopol	Wood imbedded in till.	Dates advance of glacier down a steep, short valley. The existing glacier in the valley now lies at 1800 m.	Burrows (1980)

Table 3. Radiocarbon Dates Associated with Glacial Deposits 5000—300 yr B.P.

Radiocarbon Date (Yr B.P.)	Laboratory Number	Locality, Latitude, Longitude, Altitude	Moraine	Description of Deposit	Significance	Reference
4730±75	NZ-1064	Franz Josef Glacier, Waiho, Westland 43°25'S, 170°11'E 200 m	Unnamed	Wood in laminated lake silt deposited in pro-glacial lake.	Dates an advanced position of glacier at least 4 km beyond the present terminal position.	Wardle (1973)
4540±105	NZ-1287	Meins Knob, Rakaia River, Canterbury 43°17'S, 170°56'E 910 m	Meins Knob	Wood imbedded in till.	Dates advance of glacier at least 4.5 km beyond the present terminal position.	Burrows & Russell (1975)
3980±60	NZ-3176	La Perouse Glacier, Westland 43°34'S, 169°59'E 792 m	Unnamed	Peat from bottom of bog in hollow on moraine.	Minimal age for recession of ice from moraine.	Wardle (1978)
2160±42	NZ-856	as above	Unnamed	Peat from bottom of bog in hollow between moraines.	Minimal age for recession of ice from moraine.	Wardle (1973)
3450±80	NZ-5334	Tasman Galcier, Canterbury Novara Site 43°37'S, 170°13'E 1036 m	Tasman lateral	Wood from soil between layers of till.	Minimal age for a moraine and dates subsequent burial of vegetation by expanding glacier.	A.F. Gellatly (unpublished)
1620±65	NZ-5332	as above	Tasman lateral	as above	as above	A.F. Gellatly (unpublished)
864±58	NZ-5331	as above	Tasman lateral	as above	as above	A.F. Gellatly (unpublished)
343±56	NZ-5330	as above	Tasman lateral	as above	as above	A.F. Gellatly (unpublished)
3660±100	NZ-1095	Horace Walker Glacier, Westland 43°41'S, 169°55'E 1036 m	Horace Walker	Bottom of peat on gravel over till.	Minimal age for underlying till.	Wardle (1973)
2570±75	NZ-1094	as above	Horace Walker	Top of peat buried by outwash silt.	Maximal age, close to time of glacial expansion.	Wardle (1973, 1978)
2380±90	NZ-3175	as above	Horace Walker	Bottom of peat overlying outwash silt.	Minimal age for glacial expansion period.	Wardle (1978)
1800±50	NZ-3930	as above	Horace Walker	as above	as above	Wardle (1978)
1510±60	NZ-1438	as above	Horace Walker	Top of peat buried by outwash gravel.	Maximal age, close to time of glacial expansion.	Wardle (1973)
1095±60	NZ-1436	as above	Horace Walker	Bottom of peat overlying outwash gravel.	Minimal age for glacial expansion period.	Wardle (1973)
940±50	NZ-3929	as above	Horace Walker	Top of peat overlain by till.	Maximal age for glacial expansion period (some peat may have been eroded).	Wardle (1973, 1978)
2280±50	NZ-5335	Tasman Glacier, Canterbury Ball Hut Site 43°37'S, 170°12'E 1065 m	Tasman-Ball	Wood from soil between layers of till.	Minimal age for a moraine and dates subsequent burial of vegetation by expanding glacier.	A.F. Gellatly (unpublished)
1800±50	NZ-4402	as above	Tasman-Ball	as above	as above	Burrows (1979)
1740±60	NZ-4406	as above	Tasman-Ball	as above	as above	Burrows (1979)
1100±50	NZ-4404	as above	Tasman-Ball	as above	as above	Burrows (1979)
970±60	NZ-4509	as above	Tasman-Ball	as above	as above	Burrows (1979)
684±48	NZ-711	as above	Tasman-Ball	as above	as above	C.J. Burrows (1973, 1979)

Table 3. Continued.

Radiocarbon Date (Yr B.P.)	Laboratory Number	Locality, Latitude, Longitude, Altitude	Moraine	Description of Deposit	Significance	Reference
1010±50	NZ-4507	Mueller Glacier, Canterbury 43°42'S, 170°05'E 920 m	Mueller lateral	as above	as above	Burrows (1979)
664±57	NZ-4774	McCoy Glacier, Rangitata River, Canterbury 43°20'S, 170°48'E 1200 m	McCoy	Plant roots, leaves from soil between layers of till.	as above	C.J. Burrows (unpublished)
650±60	NZ-4015	Colin Campbell Glacier, Rangitata River, Canterbury 43°21'S, 170°45'E 1066 m	Acland's Ladder	Wood from soil between layers of till.	as above	Burrows & Greenland (1979)
520±60	NZ-4016	as above	Acland's Ladder	as above	as above	Burrows & Greenland (1979)
537±42	NZ-1413	Cameron Glacier Canterbury 43°22'S, 171°01'E 1265 m	Unnamed	Wood from soil on outwash, buried by till or outwash.	Minimal age for outwash; dates subsequent glacial advance.	Burrows (1975)

Table 4. Data for Moraine Groups in Ben Ohau Range, Canterbury.

Moraine Group	Mean Weathering Rind Thickness (mm)	Mean Quartz Vein Height	Approximate Age (yr B.P.)
Dun Fiunary	0	0	100
Whale Stream	0.32±0.08	0	250
Jacks Stream	2.39±0.44	2.59±0.86	3000
Ferintosh	3.03±0.46	4.30±1.32	4000
Birch Hill	5.67±0.64	7.30±1.82	9000

because the distributions are sometimes skewed towards the younger side. Mean and mode are similar in Birkeland's and Chinn's studies, however. A margin of error, ± 20%, is considered appropriate for his dates, by Chinn.

Table 5. Data for Moraine Groups in Waimakariri Valley, Canterbury.

Moraine Group	Range of Modal Weathering Rind Thickness (mm)	Approximate Age (yr B.P.)
Barker	0–0.5	0 to 430±100
O'Malley	1–2.0	1000±240 to 2500±600
Arthurs Pass*	3.0	4000±950
McGrath	5.0–6.0	7600±1800 to 9500±1900

* As noted in Discussion these are much older and should be grouped with McGrath moraines.
McGrath moraines themselves are older than the age indicated.

The most detailed results so far available, using the method, are those of Gellatly (1981, in preparation) for the Mount Cook district (Fig. 4). Since the study is not complete, only representative data are given here, for Tasman and Mueller Glaciers.

Table 6. Data for Moraine Groups in the Mount Cook District.

Moraine Group	Range of Modal Weathering Rind Thickness (mm) Tasman Glacier	Mueller Glacier	Approximate Age (yr B.P.)
1	0.0–0.75	0.0–0.75	<100–500
2	1.0–1.75	1.0–1.75	840–1800
3	2.0–2.75	2.0–2.75	2200–3500
4		3.0–3.75	4000–5000
5		5.0	8000

The Birch Hill moraines are older than the 8000 yr B.P. moraines and, because of the relative differences in ice volumes and lengths of glaciers, are most likely to be several thousand years older (cf. Burrows 1980, Porter 1975).

Other Relative Dating Methods

Although Birkeland and Gellatly have used other relative dating methods such as lichenometry or changes in soil chemistry, they too should be calibrated independently. Ultimately the rock weathering rind results may be useful for this, but the resolution possible will be even less fine than by use of rock weathering rinds.

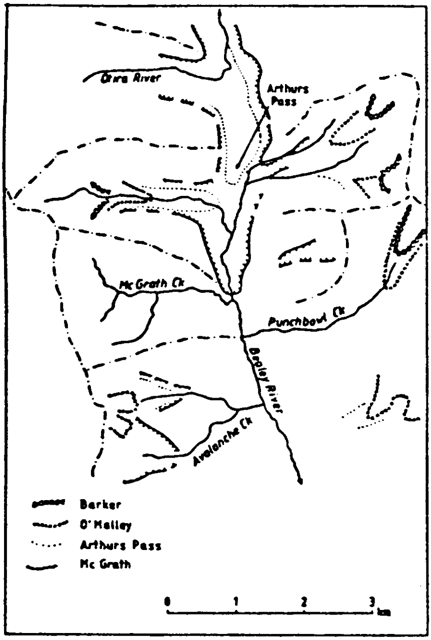


Figure 3. Arthurs Pass region, Waimakariri Valley, Canterbury, showing moraine groups mapped by Chinn (1975).

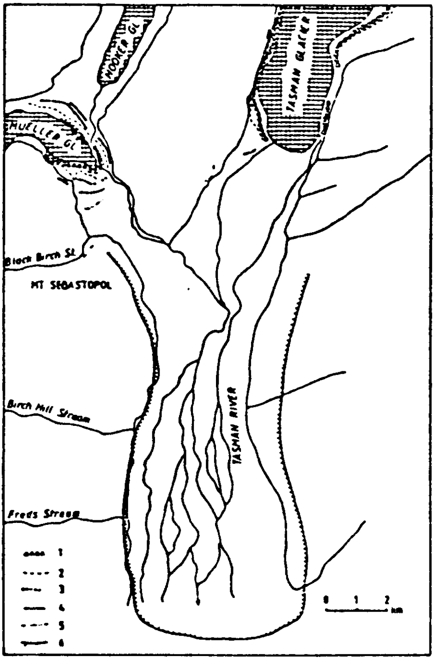


Figure 4. Mount Cook region, Canterbury, showing moraine groups mapped by Gellatly (1981) (in preparation).
1. <100-500; 2. 840-1800; 3. 2200-3500;
4. 4000-5000; 5. 8000 6. c 11500 (Birch Hill);
(dates, years B.P.)

Results have been obtained, by the use of tree ages, for some moraines, e.g. in Westland, by Wardle (1973). Moraines have been dated to the 17th and 18th centuries A.D. by this method, but, until further testing is done, they must be regarded as minimal estimates.

Historic Observations

References to many historic observations are summarized by Wardle (1973), Burrows (1973, 1975), Burrows and Maunder (1975), Heine and Burrows (1980) and Gellatly (1981, in preparation). These show that many New Zealand glaciers were relatively enlarged in the 1860s A.D. They probably shrank a little before expanding again about 1890 A.D. Since then there has been steady and extensive shrinkage, broken by minor advances of a few steep glaciers.

Discussion

Radiocarbon Dates 12 000–8000 yr B.P.

The Canavan's Knob date, 11 450 yr B.P. in Westland (Tab. 2) is believed to be close to the time of a large advance during which the Waiho Loop moraine was formed, but the Waiho Loop could be older. The date is the best direct indication of an enlarged glacier at this time. The type Birch Hill moraines in Canterbury are 18 km downvalley from the present terminus of the Tasman Glacier, so they are comparable to the Waiho Loop, allowing for differences in relative sizes of the glaciers. It has been assumed from this that Birch Hill moraines correlate with the Waiho Loop. The same applies to all other moraines listed in Table 2, except the Sebastopol moraine. These moraines might not be absolute correlatives of one another, nor of the Waiho Loop, but they are likely to be no younger than about 10 000 years (or 9000 years for the Arthurs Pass, Dobson moraine). Ancillary indicators (Burrows 1979, 1980) suggest that there were cool climate events about 11 900, 10 900 and 9500 yr B.P. but more data are needed to establish a clear chronology for the time 12 000–9000 yr B.P.

A small glacial advance occurred about 8000 yr B.P. (Table 2). It formed moraines, the outermost loops near some glaciers in Canterbury. Other indicators (Burrows 1979, McGlone and Topping 1977) show that from 10 000–5000 conditions were relatively warm in New Zealand. There is no further direct indication of glacial activity from 8000 yr B.P. until about 4500 yr B.P.

Relative Dating 12 000–8000 yr B.P.

There are problems with the use of the weathering rind thickness curve for surfaces older than about 8000 years. The oldest date used for calibration is 9520 ± 100, a minimal age for a moraine which could be at least 2000 years older. On grounds of distance from existing glaciers and the radiocarbon age 8960 ± 150 yr B.P. inside it, Chinn's (1981) Arthurs Pass moraine is likely to be at least 9000 years old, rather than the 4000 ± 950 years which he assigns to it. These difficulties remain to be resolved.

Projecting quartz veins show that material has been lost from many surface boulders on old moraines. Birkeland's (1981) approach to this problem was to measure the distance that the resistant quartz veins project above the present rock surface (Table 5). The combined measurements may give the best estimate of age but there is no appropriate calibration curve for this, nor is there a consistent distribution of projecting quartz veins on all boulders.

Radiocarbon Dates 5000-present

There is evidence for glacial episodes which may be grouped into at least seven periods c. 4500 yr B.P., c. 3500 yr B.P., c. 2300 yr B.P., c., 1800 yr B.P., c. 1600 yr B.P., c. 1000 yr B.P. and c. 860–340 yr B.P. There are hardly enough data to distinguish sub-groups within any of these periods except the last, in which events about 860, 660, 530 and 340 yr B.P. are evident. There are several moraines at some glaciers younger than those which are about 340 yr B.P. in age.

Relative Dating 5000 yr B.P.-Present

The rock weathering rind results, particularly those from Gellatly's Mount Cook work, seem to be reliable and consistent for this period. There, they are also consistent with the radiocarbon chronology and discriminate quite well between individual moraines or moraine groups.

Conclusion

Much progress has been made in establishing a chronology for Holocene glacial events in New Zealand. Further refinement will be possible in the future and we will then be in a good position to compare our results with those from Northern Hemisphere localities and to examine, in more detail, the climatic causes of glacier expansion and contraction.

REFERENCES

Birkeland, P., 1982: Multiparameter relative dating methods to differentiate Holocene glacial deposits, Ben Ohau Range, N.Z. *United States Geological Survey Bulletin* (in press).

Burrows, C.J., 1973: Studies on some glacial moraines 2. Ages of moraines of the Mueller, Hooker and Tasman Glaciers. *N.Z. J. Geol. Geophys. 16:* 831–55.

Burrows, C.J., 1975: Late-Pleistocene and Holocene moraines of the Cameron Valley, Arrowsmith Range, Canterbury, N.Z. *Arc. Alp. Res. 7*: 125–40.

Burrows, C.J., 1977: Late Pleistocene and Holocene glacial episodes in the South Island, N.Z. and some climatic implications. *N.Z. Geogr. 33*: 34–39.

Burrows, C.J., 1979: A chronology for cool-climate episodes in the Southern Hemisphere 12 000–1000 yr B.P. *Palaeogeogr., Palaeoclim., Palaeoecol. 27*: 287–347.

Burrows, C.J., 1980: Radiocarbon dates for post-Otiran glacial activity in the Mount Cook region, N.Z. *N.Z. J. Geol. Geophys. 23*: 239–48.

Burrows, C.J., Chinn, T., Kelly, M., 1976: A note on implications of new radiocarbon dates for glacial activity in N.Z. near the Pleistocene-Holocene boundary. *Boreas 5*: 57–60.

Burrows, C.J., Greenland, D.E., 1979: An analysis of the evidence for climatic change in N.Z. in the last thousand years: evidence from diverse natural phenomena and from instrumental records. *J. Royal Soc. N.Z. 9*: 321–73.

Burrows, C.J., Lucas, J., 1967: Variations in two N.Z. glaciers during the past 800 years. *Nature 216*: 467–8.

Burrows, C.J., Maunder, B.R., 1975: The recent moraines of the Lyell and Ramsay Glaciers, Rakaia Valley, Canterbury. *J. Royal Soc. N.Z. 5*: 479–91.

Burrows, C.J., Russell, J.B., 1975: Moraines of the upper Rakaia Valley. *J. Royal Soc. N.Z. 5*: 463–77.

Chinn, T.J.H., 1976: Late Quaternary snowlines in the Waimakariri Catchment and their associated cirque and upper valley deposits. *M.Sc. Thesis, University of Canterbury* (N.Z.).

Chinn, T.J.H., 1981: Use of rock weathering-rind thickness for Holocene absolute age-dating in N.Z. *Arct. Alp. Res. 13*: 33–45.

Gellatly, A.F., 1981: Moraine chronology in Mount Cook National Park. *Ph.D. thesis, University of Canterbury (N.Z.)* (in preparation).

Heine, M., Burrows, C.J., 1980: Who fills the Stocking? *N.Z. Alp. J. 33*: 68–71.

Lawrence, D.B., Lawrence, E.G., 1965: Glacier studies in N.Z. *Mazama 47*: 17–27.

McGlone, M.S., Topping, W.W., 1977: Aranuian (post-glacial) pollen diagrams from the Tongariro region, North Island, N.Z. *N.Z. J. Bot. 15*: 749–60.

McGregor, V.R., 1967: Holocene moraines and rock glaciers in the Central Ben Ohau Range, South Canterbury, N.Z. *J. Glaciol. 6*: 737–48.

Porter, S.C., 1975: Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, N.Z. *Quat. Res. 5*: 27–67.

Suggate, R.P., 1965: Late Pleistocene geology of the northern part of the South Island, N.Z. *N.Z. Geol. Surv. Bull.*, n.s. *77*: 91pp.

Wardle, P., 1973: Variations of the glaciers of Westland National Park and the Hooker Range, N.Z. *N.Z. J. Bot. 11*: 349–88.

Wardle, P., 1978: Further radiocarbon dates from Westland National Park and the Hooker Range, N.Z. *N.Z. J. Bot. 16*: 147–52.

ADDENDUM

A CRITICAL REVIEW OF ROCK WEATHERING RIND MEASUREMENTS

Too great an importance has been placed on the use of rock weathering rind thickness within this study without sufficient regard to the limitations and errors associated with the method. The following account examines the technique from a more critical standpoint with reference to the sampling procedure, calibration and relationship between rind thickness and radiocarbon-dated surface.

The present study makes use of a dating technique involving the use of rock weathering rind measurements. The method adopted in this thesis follows the procedure outlined by Chinn (1981). Chinn presents a calibration curve for rates of weathering rind development in New Zealand. The measurements are derived from surface deposits of the Torlesse Sandstone. Dating techniques were selected according to five main criteria (see Section 3.1.1 p.27). In the absence of more persuasive data, the approach used provides a provisional indication of the pattern of surface ageing during the Holocene period. It has the advantage that it is inexpensive and can be used extensively throughout the Eastern Ranges of the Southern Alps.

The decision to adopt the sampling and analytical procedures described by Chinn (1981) in their entirety arises from several considerations:

- deviations away from the original procedure would restrict the reliance on the existing calibration curve, and ultimately impair future comparisons with other studies in New Zealand.
- no suitable sample sites were identified within the Mt Cook region other than those previously used by Chinn (1981) which would have enabled a separate regional calibration curve to be fitted.

The method is based on a number of assumptions, some of them critical to the acceptance of this technique.

- Lithological uniformity The lithological background for the Mt Cook region is summarised in Section 2.2.2 (p.6). The 'uniformity' of this lithological facies is described in detail by Whitehouse, McSaveney, Chinn & Knuepher (unpubl.). The term Torlesse sandstone is used to describe all the 'undifferentiated Permian-Jurassic rocks of the South Island east of the main outcrop of the Haast Schist Group' (Suggate, Stevens & Te Punga, 1978, p.271). The status of 'Supergroup' arises from the recognition of great thicknesses of sediments and significant local lithological differences within the Torlesse terrane, (Suggate *et.al*. 1978). Warren notes how: 'On a small scale, there is great petrographic diversity, within a relatively limited range of rock types, both stratigraphically and laterally; on a regional scale, however, the Supergroup is notable for, and indeed exists as a still virtually undivided unit because of,the overall uniformity both between widely separated areas and between parts of the stratigraphic column of widely different ages'. (Warren 1978, p.273). Mackinnon (1983) presents evidence for five major petrofacies within the Torlesse Supergroup. The whole of the Mt Cook region lies within one petrofacies - the Lower Upper Triassic. Chinn (1981) and Whitehouse *et.al*. (unpubl.) describe weathering rind thickness measurements from clasts of Mid to Upper Triassic sandstone. The sample sites used in the construction of the rind growth curve extend across two recognised petrofacies. Within the Torlesse Supergroup, selective sampling concentrates on the fine-grained members for accurate measurements.*

---

* For further information on 'Non-temporal' environmental factors and their possible influence on weathering rind thickness measurements see Chinn (1981) and Whitehouse *et.al*. (unpubl.).

-Climatic variability Chinn (1975, 1981) describes no significant variation in rates of rind thickness growth with altitude and thereby deduces that temperature variations do not complicate the calibration of rates of weathering. Birkeland(1982) describes the use of weathering rinds in the Ben Ohau Range with no allowance for variation in altitude. No information is available at present on the influence of lichen and moss cover on rind development on the Torlesse Sandstone in New Zealand although several studies overseas have examined this possibility.

-Calibration of the Rind Growth Curve The weathering rind growth curve is described by Chinn (1981) and is reproduced in Fig.5.2b (p.67). The accuracy of this curve has recently been improved (Whitehouse *et.al.* unpubl.). The points shown on the curve are derived from a number of different locations and different aged surfaces and the details are presented in Table 5.1 (p.66). Burrows (written comm. 1982, 1983) notes that the older part of the weathering rind curve is insecurely dated as the radiocarbon date on the curve (9520±95 years) is a minimal age for an outwash surface. Using an empirically calibrated structural relationship, Whitehouse *et.al.*(unpubl.) have demonstrated that the 'best fit' for the growth curve implies that the present interpretation of the oldest point is reliable. Of less reliability is the youngest point on the curve which is derived from studies of lichen dating in the Cameron Valley employing a lichen growth curve now superseded (Gellatly 1982).

The Accuracy of Age Values Derived from the Rind Thickness Growth Curve

The growth curve presented by Chinn (1981) describes the error in sample age of ±26%. This is a constant relative error (McSaveney pers.comm. 1983). The age measurements given in this thesis resulting from this method should have all included an indication of the error range - their exclusion was an oversight. The extent of the error margins on each age value is indicated in Table 5.2 (p.77).

Weathering rinds are perceptible on extremely young surfaces (c.50-80 years). The most precise measurements are obtained from surfaces less than c 2000 years old. The greatest practical limitation on the technique is the use of size class intervals as opposed to continuous measurement. For this reason it is suggested that the technique cannot be regarded as 'absolute'. Strictly speaking it is not merely a relative dating tool either and it is perhaps best to regard it, with reservations, as a 'crudely absolute' dating method. The accuracy of all the measurements depends to a large extent on the sampling techniques. To increase the reliability of the method it is suggested that workers (unless they have strong reasons for doing otherwise) follow the sampling and analytical procedures adopted by Chinn (1981). These include the nature of the clasts, sample size and the use of the modal size group. It is to these points which I now turn.

Criteria for Field Sampling

A number of criteria were adopted for the selection of suitable material for rock weathering rind thickness sampling in the field. Chinn(1981,pers.comm. 1979) suggests the following directions;

a. All measurements should be taken from clasts of fine-grained, low grade metamorphic clasts of the Torlesse Sandstone group.
b. Rinds may be measured on clasts of varying size provided that the material has remained on the surface of the deposit since the duration of the period of deposition.

c. Rock fragments are chipped off the large boulders avoiding both angular corners and weathered mineral veins.
d. No measurements are possible on wet rock, or during periods of excessive rain.
e. The sample size varies according to the availability of suitable material but should in all situations exceed 30 rind counts.

Interpretation of Rock Weathering Rind Thickness Histograms

The interpretation of the data collected in the field and presented in this study requires clarification. Initially information was collected from one site on each surface, the sample size normally exceeding 30 individual rock chips. Later, additional sites were examined on the same surface and comparisons made between the modal value of each separate site's sample. The selection of the modal value is a contentious issue (see 3.1.2 p.49). Within this study the modal values used to describe any one surface are a reflection of all the sites examined on any one individual surface. That is to say, only if all the separate sites indicated a dominant mode was the surface assigned a tentative age. It should be noted that only in one instance during the course of the field work did a surface provide two conflicting rind width measurements and the surface remained undated. The modal values from each site throughout any one deposit were then presented as evidence of the relative position of that surface in a moraine sequence and a 'crudely absolute' age assigned to that surface according to earlier work by Chinn (1981). Appendix C presents all of the sample sites examined. The mode for most histograms should be apparent and can be cross-checked with the alphabetical lettering system described in Table 5.2 (p.77). Referral to these ages in the text should have included the error ranges shown in this table.

The selection of modal values from the separate rind count sites reduces the error that could be expected from post-depositional contamination, or the inclusion of pre-weathered clasts. It is likely that such events would manifest themselves in the form of multiple modes rather than actual shift in the position of the mode in the same way as the mean value is altered. This invites the argument that the actual mode may describe a major secondary event and that the actual surface age is described by a smaller peak in the histogram. This situation can only be overcome by careful geomorphic interpretation in the field. No standard deviations were calculated for the individual rind count distributions due to the absence of normality in the histograms.

Finally it should be reiterated that the measurements presented here are based on the rind thickness growth model presented by Chinn (1981) and to interpret the age of a surface using a parameter other than the mode using his calibration curve would be to invite additional error.

The restrictions placed on the interpretation of weathering rind thickness values of surface age arise from a variety of sources:

- the initial accuracy of correlation between radiocarbon dates and rind thickness values
- units of measurement and sampling technique
- selection of the mode corresponding to the deposition event of any one surface, and
- the inability to eliminate spurious values (e.g. pre-weathered clasts, differential weathering, spalling, introduction of fresh material, etc.)

In view of the restriction placed on the dating method by the use of unit measurements as opposed to continuous measurements, the apparent glacial sequence in each valley appears to conform exactly to the same general pattern. It should be emphasised that this is an artifical grouping of events which would have appeared differently had another unit of measurements been selected (measurements to the nearest 0.5mm, or 1.0mm). In the absence of the error terms (which should have accompanied each reference to a surface age), the unnatural grouping of deposits into 'events' identical to within 10 years between valleys gives the reader a false impression of regional uniformity.

There is no compelling evidence to suggest that glacial events occurred with absolute synchroneity between valleys and the presentation of data as an unvarying age-sequence over such a large area is clearly misleading. It may be possible to continue to group depositional events on the basis of their relative stratigraphic positions but attempts to superimpose a crudely absolute age sequence whilst ignoring the generally recognised error terms are wrong.

The Relationship between Weathering Rind and Radiocarbon Dated Moraine Sequences

The problem of interpreting the rock weathering rind thickness values is complicated by the suggestion that the weathering rind chronology is correlated with a separate radiocarbon-dated chronology. The radiocarbon dates are not stratigraphically related to the surfaces dated using other methods (except in a very few circumstances and only for the young surfaces). Using statistical manipulation a 'best fit' for a sequence of events identified by both dating methods is shown. The value of this correlation is greatly diminished in view of the range of errors present with both dating methods.

The radiocarbon-dated chronology is more reliable than that described by rock weathering rinds. Detailed geomorphic analysis carried out in the field with Dr F. Rothlisberger identified the major trends and relationships before they could be confirmed by laboratory analysis. The interpretations and subsequent groupings of the radiocarbon dates are strengthened in view of such detailed field examination (F.Rothlisberger,pers.comm. 1981, written comm. 1982).

Identification of Geomorphic Criteria for Cross-Correlation

In order to interpret the data fully it is frequently necessary to describe the geomorphic features pertaining to that site. These can be identified by surface and subsurface examination and the principal features to identify include the following:

a. Surface Geomorphic Features:-

- Overlapping (Accretion) moraine surfaces
- Rockfall and avalanche deposits
- Meltwater deposits
- Tarn sites
- Ephemeral drainage channels
- Ice-cored surfaces and collapse features implying an unstable deposit for an unknown period of time subsequent to deposition
- Human interference such as tracks and road building

b. Subsurface Geomorphic Indicators:-

- Loess deposition
- Polygenetic soils indicating events such as vegetation burning, truncation through aggradation etc.
- Monogenetic soils indicating a relatively stable period of development

The overall stratigraphy, position and size of moraines within a region are of limited use in cross-correlation. The variable response by different glaciers within a small area results in marked variations in depositional characteristics. These may be attributed to:

- Valley assymetry
- Size of the glacier
- Available depositional material
- Gradient of the glacier
- Nature of till deposition
- Post-depositional working of the till including erosion, re-deposition and subsidence.

Sites with recognised geomorphic irregularities should be avoided because it is unlikely that sampling could be sufficiently selective to be accurate, and it is more than likely that it would become subjective. Because of inter-valley and intra-valley variations correlations may become complex. Overlapping of moraine sequence, or the complete removal of a deposit due to melt-water aggradation or landslide events can prevent direct comparisons of depositional sequences. The number and position of deposits reflect more than just the response of the glacier to climatic change. Furthermore, surfaces may be formed at different stages in any one event and can yield significantly different age values (*c.f.*section 2.4.1 p.15). Because of this, it may be possible to outline more 'events' than actually occurred.

Geomorphic interpretations may conceivably be used to help group the events to provide a general model of glacial events in the region. At this stage such a step would involve considerable subjective judgement (see section 11.3 p.190). In valleys where the moraine sequence is incomplete the problem of grouping barely exists. Within the Mueller Valley, and to a lesser degree within the Hooker Valley, the decision to group several geomorphic events would be difficult, if not impossible. A series of well defined, clearly demarcated deposits give an impression of several, closely spaced glacial oscillations.

References

Birkeland, P.W. 1982 Subdivision of Holocene glacial deposits, Ben Ohau Range, New Zealand using relative dating methods. *Geological Society of America Bulletin* 93: 433-449

Chinn,T.J.H. 1975 Late Quaternary snowlines and cirque moraines within the Waimakariri watershed. MSc.Thesis University of Canterbury, New Zealand, 213 pp.

Chinn,T.J.H. 1981 Use of rock weathering rind thickness for Holocene absolute age-dating. *Arctic and Alpine Research* 13: 33-45

Gellatly,A.F. 1982 The use of lichenometry as a relative-age dating method with specific reference to Mount Cook National Park, New Zealand. *New Zealand Journal of Botany* 20: 343-353

MacKinnon,T.C. (in press) Origin of Torlesse and related rocks, South Island, New Zealand. *Geological Society of America Bulletin*

Suggate,R.P., Stevens,G.R. & Te Punga, M.T. (Eds.) 1978 'The Geology of New Zealand' Government Printer, Wellington. 2 vols. 820p.

Warren,G.A. 1978 (Carboniferous-Jurassic) Torlesse Supergroup - Eastern South Island pp 271-277 *in* Suggate,R.P., Stevens,G.R. & Te Punga,M.T. (Eds.) The Geology of New Zealand Government Printer, Wellington.

Whitehouse,I.E., McSaveney,M.J., Chinn,T.J.H. & Knuepher,P.L. (in prep.) Growth of weathering rinds on Torlesse Sandstone, Southern Alps, New Zealand. (unpubl.)